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NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Proceedings of the PV Reliability Workshop – Lakewood, Colorado

February 26 – 28, 2019

2019 marks the tenth anniversary of the Photovoltaic Reliability Workshop (PVRW)! This year's workshop continues in the tradition of engaged attendees. Participation requires sharing of a paper—either an oral or poster presentation—by each company at some time during the week. This workshop provides a unique opportunity for group discussions that can yield answers and bring participants to a common understanding for current questions in module and system reliability.

Hot topics during this year's workshop include performance of fielded systems and degradation rates, system analytics and large data sets, durable module materials, structural and site-specific effects, collaborative research, standards and accelerated testing, extended testing beyond design qualification, power electronics, bifacial and glass-glass constructions, new system types, and system end-of-life.

Chair:

Ingrid Repins

Committee:

Teresa Barnes

Michael Bolen

Evelyn Butler

Alessandra Colli

Chris Deline

Tassos Golnas

Nadeem Haque

Dirk Jordan

Sarah Kurtz

Sumanth Lokanath

David Meakin

Andreas Meisel

Nancy Phillips

Tony Sample

Tim Silverman

Josh Stein

Mani G. TamizhMani

Tadanori Tanahashi

John Wohlgemuth

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.

AGENDA – Tuesday, 26 February 2019

7:30-8:00	**Continental breakfast**
8:00-10:00	**Session 1: Performance of fielded systems and degradation rates** **8:00** – Welcome to the PV Reliability Workshop – Ingrid Repins, NREL **8:05 –** Slido Tutorial – Josh Stein, Sandia National Laboratories **8:10** – DC health: field testing and results – Jim Rand, Core Energy **8:30** – Degradation rate case studies – Dirk Jordan, NREL **8:50** – Field observations on module degradation and power loss – Eric Daniels, SunCycle **9:10** – Critical material degradation impact performance of PV modules in the field – Kaushik Roy-Choudhury, DuPont **9:30** – DuraMAT research collaborations and highlights – Teresa Barnes, NREL **9:45** – Discussion – Chairs: Ulrike Jahn, TUV Rheinland, and Ingrid Repins, NREL
10:05-10:25	**Coffee break**
10:25-11:55	**Session 2: System analytics and large data sets** **10:25** – Optimizing PV system asset management using scalable digital models – Nikhil Vadhavkar, Raptor Maps **10:45** – Signal processing on PV time-series data: degradation analysis without physical models – Bennet Meyers, Stanford National Accelerator Laboratory **11:05** – Large-scale electroluminescence inspection: multi-sensor platforms and automated evaluation – Andreas Fladung, AEPVI **11:25** – Discussion – Chairs: Kaushik Roy-Choudhury, DuPont, and Mike Deceglie, NREL
11:55-12:55	**Lunch** (poster viewing/discussion encouraged)
12:55-13:55	**Poster Session I** (see poster agenda)
13:55-15:45	**Session 3: DuraMAT capabilities** **13:55** – Announcement of DOE PV fleet performance data initiative – Inna Kozinsky, US DOE **14:00** – Fleet-scale performance and degradation analysis – Mike Deceglie, NREL **14:15** – Multi-scale, multi-physics modeling for PV reliability – James Hartley, Sandia National Laboratory **14:35** – Combined- and sequential-accelerated stress testing for derisking photovoltaic modules – Peter Hacke, NREL **14:55** – DuraMAT module forensics – Laura Schelhas, Stanford National Accelerator Laboratory **15:15** – Discussion – Chairs: Margaret Gordon, Sandia National Laboratories, and Teresa Barnes, NREL
15:45-16:00	**Coffee break**
16:00-17:30	**Session 4: DuraMAT projects** **16:00** – Characterizing adhesives and edge seals for roll-to-roll photovoltaics packaging – Michael Sulkis, Georgia Institute of Technology **16:20** – A unified constitutive model for electrically-conductive adhesives – Martin Springer, NREL **16:40** – Development of low-cost, crack-tolerant metallization using screen printing – Sang Han, Osazda Energy **17:00** – Discussion – Chairs: Teresa Barnes, NREL, and Margaret Gordon, Sandia National Laboratories **17:25** – Poster Session I poster awards – Ingrid Repins, NREL
17:30	**Adjourn** (poster viewing/discussion encouraged)

POSTER SESSION I: Tuesday, 26 February 2019

1. **K. Sakurai, H. Tomita, D. Schmitz, S. Tokura, K. Ogawa, H. Shibata, A. Masuda**, "Complete recovery of CIGS solar cells from PID stress with light"

4. **B. King**, "DuraMAT Capability 5: field deployment for reliability"

7. **C. Staiger, S. Lopez, E. Elce,** "Development of a spray deposition method for polysilsesquioxane coatings in thin-film photovoltaic applications"

10. **P. Hacke,** "Module-level solutions for cell-front ionization damage"

13. **A. Jain**, **T. Karin, C.B. Jones, M. Deceglie**, "DuraMAT data analytics: clear sky detection and new climate zone classifications"

16. **J. Stein, C. Deline, C. Robinson,** "PV lifetime project: measured PV module degradation over three years"

19. **D. Goossens,** "Using an environmental wind tunnel for PV and CSP applications"

22. **A. Richter,** "Performance investigation of different PV technologies in the field"

25. **M. Springer, K. Han, N. Bosco**, "A unified constitutive model for the degradation of electrically-conductive adhesives"

28. **O. Abudayyeh, A. Chavez, J. Chavez, S. M. Han, F. Zimbardi, B. Rounsaville, V. Upadhyaya, A. Rohatgi, B. McDanold, T. Silverman,** "Development of low-cost, crack-tolerant metallization using screen printing"

31. **M. Sulkis, J. Hah, S. Graham, J. Moon, C.P. Wong, S. Sitaraman, M. Reese, S. Garner, S. Jones, D. Vak**, "Scalable packing materials for roll-to-roll processed thin film solar cells"

34. **A. Shinn, B. Browne**, "Measuring degradation of fielded systems at scale on an ongoing basis with RdTools"

37. **R.H. French, J. Liu, M. Wang, A.J. Curran, W-H Huang, E. Schnabel, M. Köhl, J.L. Braid,** "Glass-backsheet and double-glass PV module degradation across climate zones determined from Suns-VOC, Loss Factors, and I-V steps analysis of eight years of time series I-V datastreams"

40. **S.L. Moffitt, L. Schelhas, M. Gordon, P. Burton, A. Zakutayev, P. Hacke, N. Bosco**, "DuraMAT: materials characterizations and forensics"

43. **Y. Zhu, C. Taubert, K. Chen, B.D. Vogt, H. Fan**, "Low percolation threshold in electrically-conductive adhesives using complex dimensional fillers"

46. **J. Karas, A. Sinha, V. Buddha, A. Augusto, G. TamizhMani, S. Bowden**, "Reliability of modules with high-efficiency solar cells with copper-plated contacts"

49. **M. Mate, L.T. Schelhas, S.L. Moffitt,** "Evaluation of PID chamber and field testing of CIGS modules"

52. **R. White, M. Deceglie, C. Deline,** "Development of PV fleet data acquisition and analysis pipeline"

55. **A. Maes, J.Y. Hartley, C.C. Roberts,** "Thermal and viscoelastic behavior of photovoltaic module encapsulants"

58. **A. Lyons, I. Nayshevsky, QF. Xu, D.C. Miller, J. Newkirk, D. Furhang**, "Self-cleaning coatings for solar cover glass: durability and effect of artificial soilant particle type"

61. **D. Sulas,** "Fill factor loss in fielded photovoltaic modules due to metallization failures, characterized by luminescence and thermal imaging"

64. **B. Strauss, T. Shimpi, C. Moffett, L. Maple, W. Sampath, K. Barth,** "Evaluation of different models to describe reverse breakdown characteristics of CIGS solar cells"

67. **D. Fleming, A. Sahm, J.R. Sherwin, B.H. King, C.S. Thompson,** "Field installations of a high-performance antireflective coating for solar modules"

70. **K. Barth, J. Morgante, W.S. Sampath, T. Shimpi,** "Non-lamination encapsulation technology to improve reliability and reduce costs"

73. **J. Hartley, A. Maes, S. Roberts, J. Stein, L. Schelhas, N. Bosco,** "Multi-scale, multi-physics modeling for PV reliability"

76. **B. Hartweg, K. Fisher, J. Huxel, M. Branch, N. Chawla, Z. Holman,** "Failure mechanisms of electrically-conductive adhesives in shingled solar modules"

79. **R. Andrews,** "Industry reliability benchmarking: DC health data from 6 GW of operational assets"

82. **N. Ramchandani,** "Case study: first year unavailability at solar PV plants"

85. **M. Owen-Bellini,** "Combined-accelerated stress testing for advanced reliability assessment of photovoltaic modules"

88. **M. Owen-Bellini,** "Correlation of advanced accelerated stress testing procedures with field data through advanced characterization and data analytics"

93. **+DEMONSTRATION TABLE: M. Bora,** "Back side defect imaging in crystalline silicon photovoltaic modules"

DuraMAT posters are indicated with green-printed titles

AGENDA – Wednesday, 27 February 2019

7:30-8:00	**Continental breakfast**
8:00-10:05	**Session 5: Structural and site-specific effects** **8:00** – Designing for wind – Alex Roedel, NEXTracker **8:20** – Dynamic wind loads on ground-mounted PV – David Banks, CPP Wind **8:40** – Soil corrosivity testing to maximize useful life – Ed Hernandez, Corrosion Project X **9:00** – Reliability and safety issues observed in flood-affected PV power plants in India – Narendra Shiradkar, IIT Bombay **9:20** – Joint relaxation in PV racking system bolted joints – Jon Ness, Matrix Engineering Consultants **9:30** – Discussion – Chairs: Evelyn Butler, SEIA, and Matt Muller, NREL
10:05-10:25	**Coffee break**
10:20-11:55	**Session 6: Collaborative updates (PVQAT and others)** **10:25** – Collaborative updates: PVQAT TG 3 (Humidity, temperature and voltage [modules]), and TG 11 (PV systems – power electronics) – Peter Hacke, NREL **10:40** – Standardization of non-uniform wind-load test method on PV modules in PVQAT TG 7 – Shu-Tsung (Anderson) Hsu, ITRI **10:50** – Updates on PVQAT TG 5 (UV weathering) and TG 12 (soiling) – David Miller, NREL **11:05** – PVQAT updates: toward further global collaboration – Tadanori Tanahashi, AIST **11:15** – Performance, operation and reliability of IEA PVPS Task 13 – Ulrike Jahn, TUV Rheinland **11:25** – Department of Energy reliability portfolio and motivations – Marie Mapes, US DOE **11:35** – Discussion -- Chairs: Tony Sample, JRC, and Nick Bosco, NREL
11:55-12:55	**Lunch** (poster viewing/discussion encouraged)
12:55-13:55	**Poster Session II** (see poster agenda)
14:00-15:45	**Session 7: Activity in standards and accelerated testing** **13:55** – Quantifying LeTID through in-chamber, light simulator and outdoor testing – Tristan Erion-Lorico, PVEL **14:15** – Status of the IEC 61215 new edition – Tony Sample, JRC **14:35** – Status of TS63126: Guidelines for qualifying PV products for operation at high temperature – Kent Whitfield, UL **14:55** – Changes in solar simulator classification and significance for PV power measurement – Werner Herrmann, TUV Rheinland **15:15** – Discussion – Chairs: Bill Gambogi, DuPont, and Mike Kempe, NREL
15:45-16:00	**Coffee break**
15:40-17:30	**Session 8: Beyond design qualification** **16:00** – CSA/ANSI C450 Sequence B variations: sequential application of static and dynamic mechanical stresses to electrically isolate cracked cell sections – Colin Sillerud, CFV **16:20** – Assessing backsheet durability in PV modules using multiple UV sources and test structures – Bill Gambogi, DuPont **16:40** – Design considerations and evaluations for PV modules – David Okawa, SunPower **17:00** – Discussion – Chairs: Nancy Phillips, DuPont, and Michael Owen-Bellini, NREL **17:25** – Poster Session II awards – Ingrid Repins, NREL
17:30	**Adjourn** (poster viewing/discussion encouraged)

POSTER SESSION II: Wednesday, 27 February 2019

2. **Z. Hammond, T. Curtis, L. Simpson, G. TamizhMani,** "Design advancement of an indoor soil deposition chamber: a road to standardization"

5. **M. Köentopp, F. Kersten, E. Herzog**, "LETID testing in qualification standards. procedures, kinetics and separation of B-O degradation from LETID"

8. **M. Köentopp, E. Herzog, R. Won,** "PID testing of bifacial modules: how to adapt test protocols in qualification standards in order to avoid polarization artifacts"

11. **A. Gabor, R. Lockhart, A. Sanghvi, E.J. Schneller, J. Lincoln, H. Seigneur,** "Cracked up: how should we classify and respond to various electroluminescence defects in silicon PV modules?"

14. **C. Thellen, A. Rothacker, D. Santoleri,** "Characterization of polyamide-ionomer based backsheet after highly-accelerated stress testing (HAST) and acetic acid exposure"

17. **F. Dross, B. Custodio,** "How to valorize the use of high-quality materials**"**

20. **B. Hallam, M. Kim,** "Using numerical simulations to understand BO-LID and LeTID"

23. **H. Wilterdink, R. Sinton, C. Sainsbury, W. Dobson, J. Dinger,** "The bad practice bible: surefire ways to get poor results when power rating PV modules"

26. **T. Sample,** "The European Commission's EcoDesign preparatory study status and outlook"

29. **L. Postak, S. Daroczi,** "Reducing power degradation in c-Si modules by using PIB edge seal"

32. **C. Xiao, C-S. Jiang, S.P. Harvey, D. Sulas, X. Chen, J. Liu, J. Pan, H. Moutinho, A. Norman, P. Hacke, S. Johnston, M. Al-Jassim,** "Large-area material and junction damage in c-Si solar cells by potential-induced degradation"

35. **S. Napoli, A.W. Hauser, G.S. O'Brien, Y. Wang, A. Fairbrother, S. Julien, X. Gu, L. Ji, K.P. Boyce, M.D. Kempe, K-T. Wan, R.H. French, L.S. Bruckman,** "Degradation of commercial photovoltaic backsheets under outdoor and accelerated indoor weathering exposures"

38. **J. Wohlgemuth,** "PV standards activities of the IEC"

41. **J. Qian, M. Ernst, A. Thomson, A. Blakers,** "Hotspots in half-cell modules undetected by current test standards"

44. **B. Paudyal, S. Hackett, M. Bolen,** "DC arc-flash risk in a photovoltaic plant"

47. **W. Hobbs, B. Gilleland,** "Fast acquisition of UV-fluorescence images and automated crack detection"

50. **S. Wendlandt, L. Podlowski,** "Light and temperature-induced degradation of PV modules with PERC technology: result of a benchmark test on commercial products"

53. **Z. Purohit, J. Carolus, H. Chaliyawala, M. Kumar, M. Daenen, B. Tripathi,** "Investigating the degradation kinetics of c-Si and CIGS solar cells under potential induced degradation by various material characterization techniques"

56. **B. Figgis, A. Abdullah,** "Investigation of yield differences of PV technologies in desert climate"

59. **A. Abdullah, B. Figgis,** "Photovoltaic module reliability in desert climates"

62. **A. Meyer, V. LaSalvia, W. Nemeth, M. Page, D. Young, S. Agarwal, P. Stradins,** "Light-induced degradation and regeneration of p-type crystalline silicon solar cells**"**

65. **X. Meng, M. Bertoni, "Imaging deflection and stress in next-generation PV modules"**

68. **P. Robusto**, **B.J.J. Liu, V. Bheemreddy,** "Status of IEC 63163 consumer products specification"

71. **L. Burnham, D. Riley,** "Electroluminescent imaging of multiple module technologies exposed to snow and ice loading"

74. **A. Pavgi, J. Oh, G. Kelly, G. TamizhMani,** "Reductions and climate-specific evaluation of module operating temperatures using thermally-conductive backsheets"

77. **E. Schneller, H. Seigneur, J. Lincoln, A. Gabor,** "Re-evaluating solar module mechanical durability testing"

80. **B.G. Potter, M.R. Dzurick, K. Simmons-Potter,** "Effect of location-specific weather and PV degradation data on PV power prediction using NREL PVWatts"

83. **S. Harvey, S. Johnston, C.P. Muzzillo, L. Mansfield, P. Hacke, M. Al-Jassim,** "Utilizing TOF-SIMS to investigate module degradation mechanisms"

86. **B. Habersberger,** "Encapsulant resistivity is not predictive of PID-s susceptibility"

89. **X. Gu, Y. Lyu, A. Fairbrother, J.H. Kim, M. Kempe, S. Julien, K-T Wan, S. Napoli, A. Hauser, G. O'Brien, Y. Wang, L. Bruckman, R. French, L. Ji, K. Boyce,** "Failure analysis of polyamide-based backsheet for PV modules fielded under different climates"

91. **+ DEMONSTRATION TABLE: J. Sorensen,** "Cell cracking"

95. **R. Descharnais, F. Dross,** "Accelerated testing reproducing backsheet field observations"

97. **G. Robinson,** "Field lessons from storm-damaged arrays"

99. **F. Quartiani,** "Long-term performance of light-emitting diodes in IV curve testing of photovoltaic modules"

101. **J. Gallon,** "EL-Sweep for CdTe modules"

103. **L. Malmgren,** "Statistical analysis of performance differentiation through accelerated stress testing"

104. **F. Lim,** "Module reliability journey"

105. **A. Sinha,** "Comparison of solder bond degradation mechanisms in fielded PV modules at different climates"

106. **P. Arularasu,** "Role of humidity on the degradation of UV-cut and UV-pass encapsulants"

107. **A. Morabito,** "Construction mishaps and long-term problems"

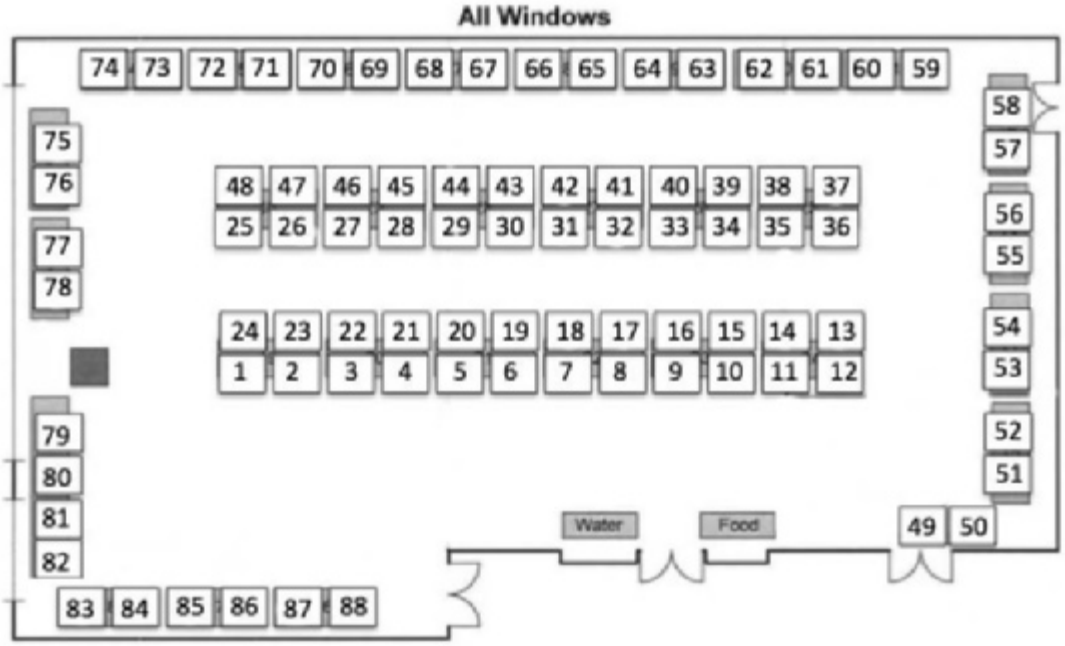
AGENDA – Thursday, 28 February 2019

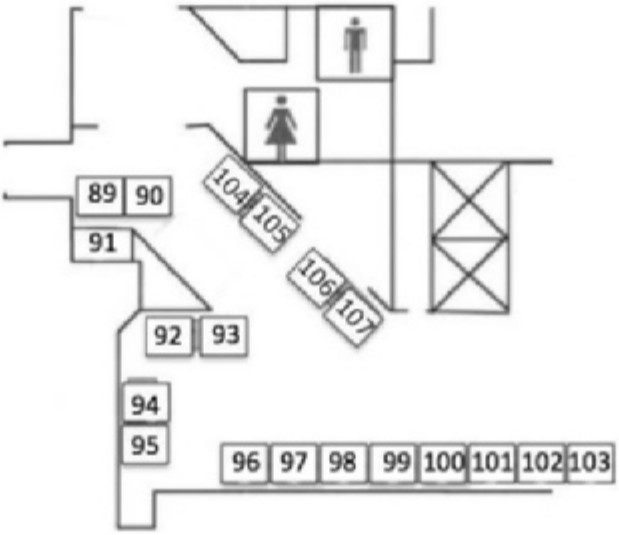
7:30-8:00	**Continental breakfast**
8:00-10:10	**Session 9: Power electronics** **8:00** – Reduce to the max: what makes up a reliable PV inverter – Daniel Clemens, SMA **8:20** – Methods to optimize maintenance in PV plants, starting with inverters – Michael Bolen, EPRI **8:40** – Management of phantom ground faults in a PV plant with high DC circuit-to-ground capacitance – Daniel Cormode, Bay4 Energy **9:00** – Effect of Inverter Failures on the Return on Investment of Solar Photovoltaic Systems - Tyler Formica, Johns Hopkins University **9:20** – Reliability of Electronics for Photovoltaics - Magnus Asbo, SolarEdge **9:40** – Discussion – Chairs: Sumanth Lokanath, First Solar, and Peter Hacke, NREL
10:10-10:25	**Coffee break**
10:25-11:55	**Session 10: Bifacial and glass-glass construction** **10:25** – Evaluating the durability of transparent backsheets for bifacial modules – Mike Kempe, NREL **10:45** – Comparison of glass/glass and glass/backsheet mini-modules by accelerated test – Yuji Ino, AIST **11:05** – The risk/reward of bifacial PV system design – Itai Suez, EDPR **11:25** – Discussion – Chairs: Tadanori Tanahashi, AIST, and Silvana Ayala Pelaez, NREL
11:55-12:55	**Lunch** (poster viewing/discussion encouraged)
12:55-13:55	**Poster Session III** (see poster agenda)
13:55-15:45	**Session 11: New system types** **13:55** – Reliability considerations of floating PV systems: experiences from the world's largest floating PV test bed – Thomas Reindl, SERIS **14:15** – Standardizing the ecosystem: future proofing power plant systems using energy storage – Alex Au, NEXTracker **14:35** – AC-coupled solar plus storage systems – Mohammad Bozchalui, Enphase **14:55** – The new PV hazard control standard (UL 3741): evaluating PV systems for reduced shock hazards during fire-fighting – Tim Zgonena, UL **15:15** – Discussion: – Chairs: Michael Bolen, EPRI, and Dirk Jordan, NREL
15:45-16:00	**Coffee break**
16:00-17:30	**Session 12: System end of life** **16:00** – PV module end-of-life management – Garvin Heath, NREL **16:20** – High-value PV recycling approach – Sumanth Lokanath, First Solar **16:40** – Assessing variability in toxicity testing of PV modules – GovindaSamy TamizhMani, Arizona State University **17:00** – Discussion: – Chairs: Cara Libby, EPRI, and Tim Silverman, NREL **17:25** – Poster Session III awards – Ingrid Repins, NREL
17:30	**Adjourn** – All posters removed

POSTER SESSION III: Thursday, 28 February 2019

3. **F. Faller**, "Bifacial gain relative to different irradiance levels"
6. **Q. Wang, M. Bauer, T. Frech, J. Lindgren,** "Junction-box terminal resistance-welding development"
9. **T. Tanahashi, N. Sakamoto, H. Shibata, A. Masuda,** "Corrosion underneath front electrodes of crystalline silicon photovoltaic cells predominantly contributes to their performance degradation"
12. **K. Bedrich, Y. Wang, A.G. Aberle, Y.S. Khoo,** "Quantitative electroluminescence imaging of PV modules: low-frequency blur removal"
15. **S. Napoli, B. Douglas, A.W. Hauser, G.S. O'Brien, B. Skarbek, S. Lokanath,** "Weathering performance of cable ties for solar wire management"
18. **D. McDougall, Y. Xue, D. Su,** "Application for electrically-conductive adhesives"
21. **Å. Skomedal, H. Haug, E. Marstein,** "Endogenous soiling rate determination and detection of cleaning events in utility-scale PV plants"
24. **L. Kazmerski, S.C. Silva Costa, A.S.A.C. Diniz, C. Brasil Maia, C. Dias Campos, D. Senna Braga, M. Machado Viana, P. P. Brito, V. Camatta, E.M.C. Barboso, F. Costa, L.R. de Oliveira Cruz, S. de Morais Hanriot,** "Comparative studies of the effects of soiling of PV modules and systems in tropical and subtropical climate zones in Brasil"
27. **M. Gostein, B. Stueve,** "CdTe spectrally-matched c-Si PV reference cell for PV plant monitoring"
30. **C. Libby, S. Shaw,** "PV end-of-life management"
33. **D. Fregosi, B. Paudyal, M. Bolen,** "Module, string, array, and plant-level degradations in a PV system"
36. **J. Previtali,** "How to efficiently share data across the solar industry using the orange button standard"
39. **G. Kelly,** "IECRE site inspection demonstration"
42. **H. Kim,** "Modeling thermal and mechanical stress of flexible CIGS solar cells"
45. **D. Kumar,** "Performance optimization of a solar PV hybrid SPV system for telecom applications"
48. **S. Zhou**, "The mechanism and damage of snail trails"
51. **D. Chawla,** "Gaps in bankability of upcoming photovoltaic technologies--PERC, bifacial, glass-glass, half-cell"
54. **S. Pulsford**, "Testing and compliance of PV modules in Australia"
57. **B. Brownell,** "Saving the PV module: repair tape for scratched and cracked backsheets"
60. **B. Marion**, "Albedo data for bifacial PV systems"
63. **H. Gopalakrishna, P. Arularasu, K. Dolia, A. Sinha, G. TamizhMani,** "Degradation comparison of UV-cut and UV-pass encapsulants"
66. **J. Irikawa,** "Analysis of acetic acid generation in PV modules"
69. **D. Friedman,** "Activities, capabilities and services provided by the NREL Cell and Module Performance Group"
72. **L. Simpson,** "Rotary brush test for PV abrasion standard"
75. **S. Kingston, A. Edun, E. Benoit, N.K.T. Jayakumar, M.U. Saleh, C.M. Furse, M.A. Scarpulla, J.B. Harley,** "Simulating the spread spectrum time domain reflectometry responses of photovoltaic cells to detect and locate faults"
78. **E. Benoit, N.K.T. Jayakumar, S. Kingston, M.U. Saleh, M.A. Scarpulla, J.B. Harley, C.M. Furse,** "Spread spectrum time domain reflectometry for complex impedance fault detection"
81. **C. Wolfrom, "**Using satellite albedo data to aid bifacial performance modelling"
84. **M.U. Saleh,** "Detection and localization of disconnections in PV strings using SSTDR"
87. **J. Driesen,** "(Bi)PV power architecture reliability and performance aspects"
90. **H.H. Ng,** "25-year low-cost flexible frontsheet"
92. **S.T. Hsu,** "Non-uniform wind load on floating solar panel under the wind-wave environment"
94. **J. Forbess,** "Daily soiling rates correlated with air quality and other meteorological data in Oakland, CA"
96. **B. Liang,** "Impact of satellite-based solar resource models (SRM) on utility-scale PV system design and project economics"
98. **K. Lu,** "High-speed quantum efficiency measurements of solar panels'
100. **J. Flicker,** "Co-located accelerated testing of module-level power electronics and associated PV panels"
102. **P. Dong,** "A flexible solar cell/supercapacitor-integrated energy device

POSTER LAYOUT – CITY LIGHTS BALLROOM





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February 2019

NREL
Transforming ENERGY

Welcome to the 2019 Photovoltaic Reliability Workshop!

10th Anniversary

Ingrid Repins
February 26-28
Lakewood, Colorado

Special Thanks To….

Program Committee:

Teresa Barnes	David Meakin
Michael Bolen	Andreas Meisel
Evelyn Butler	Nancy Phillips
Alessandra Colli	Tony Sample
Chris Deline	Tim Silverman
Tassos Golnas	Josh Stein
Nadeem Haque	Mani G. TamizhMani
Sarah Kurtz	Tadanori Tanahashi
Dirk Jordan	John Wohlgemuth
Sumanth Lokanath	

Administrative Chair:
Pat Kline

Poster Awards: Xiaohong Gu

2020 General Chair: David Miller
2021 General Chair: Tim Silverman

Slido Masters: Joshua Stein
Silvana Ayala

….. and you!

Jefferson Boardroom
Lookout Mountain Room

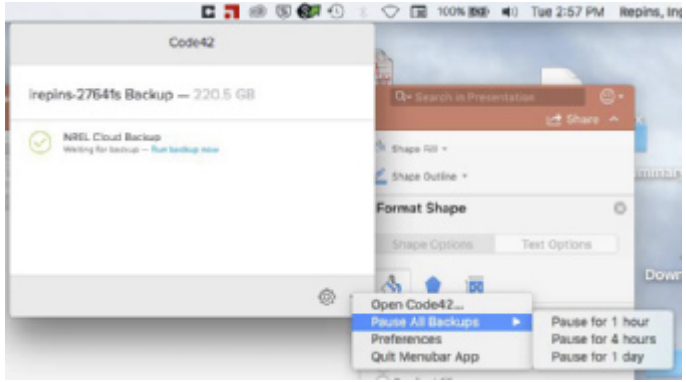
- **Straight out ballroom doors, past bathrooms.**
- **You may reserve by talking to Pat Kline. (Some times already taken.)**
- **Spontaneous use when they are not reserved.**

- Side Meeting Announcement – Initial Gap Analysis – Severe Weather Failure Modes (gtrobinson@lbl.gov) Tuesday 16:00-17:00, Lookout Mountain Room

Audience Questions and Event Feedback Via On-Line Polling

- Sheraton Wifi Network: Meet @ Sheraton
- Wifi User name: sheratonmeeting
- Sheraton wifi password: 360union

- **Please turn off your wifi streaming apps during oral sessions so we have enough bandwidth for audience questions.**
- **NREL people – turn off your cloud back-up**



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Time to take your seats

An Important Video Clip

- You know solar has arrived when super-heroes and super-villains are fighting over modules.
- Nothing I do will ever impress my kids now that 400% efficiency is on the table.
- The super-villain doesn't understand that it's not all about 400% efficiency. It's about long-term energy generation, which means **reliability**.

NREL PV Reliability Workshop

PV Degradation Observations

Robert Flottemesch

February 27, 2019

Constellation.
An Exelon Company

About Exelon

Introduction

Exelon's family of companies represents every stage of the energy value chain.

Generation

Exelon Generation

Generation Capacity:
More than 32,000 MW

Energy Sales & Services

Constellation*

Competitive C&I Load Served:
211 Annualized TWH (power)
1,634 Annualized BCF (natural gas)

Competitive Energy Sales:
Nearly 2 million business & public sector customers
1.4 million residential customers
Wholesale sales, dispatch, and delivery from Exelon's ~33 GW power generation portfolio

Transmission & Delivery

Atlantic City Electric, BGE, ComEd, Delmarva Power, PECO and Pepco

Service:
10 million electric and natural gas customers

**Q1 2019 data*

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Constellation
An Exelon Company

Introduction

Exelon by the Numbers

America's **#1 Zero-Carbon** Nuclear energy provider and **A leading competitive energy provider**

More than **32,000 MW** of owned capacity

Service Territory: **25,590 mi²** Electric Transmission: **11,472 mi**

Named to the **Dow Jones Sustainability North America Index** for the **13th year in a row** in 2018.

Headquarters: **Chicago, IL** Employees: **33,298**

Operates in **48 States**, DC & Canada

Operating Revenues: **$36 Billion**

**Q1 2019 data*

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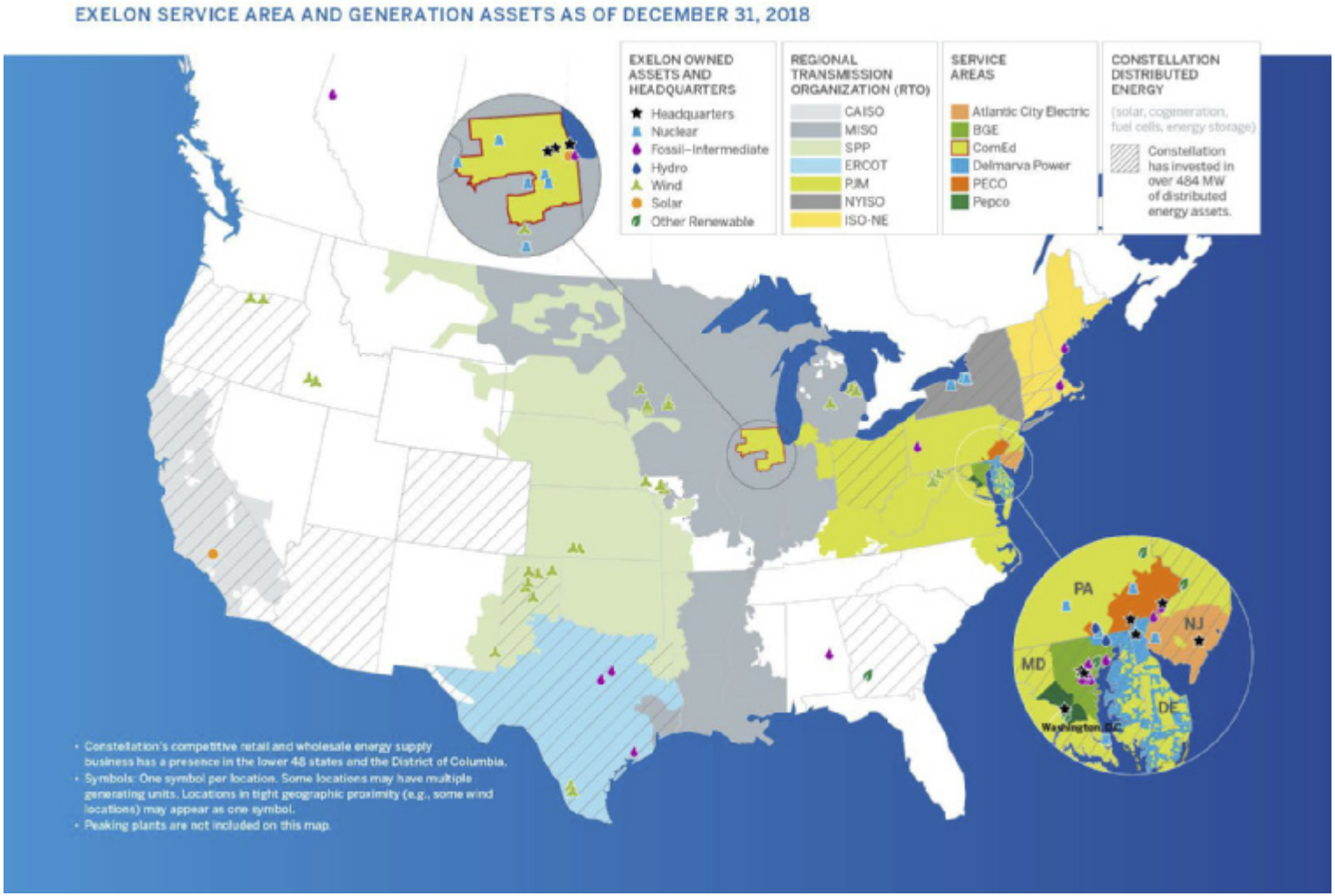
Introduction

Exelon's Footprint



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About Constellation

Introduction

Constellation: Who We Are

Approximately **2 million customers** served

123,561 Commercial & Industrial Power Customers

Continually investing in **emerging energy technologies**

113,325 Commercial & Industrial Natural Gas Customers

Dedicated Team of Regulatory, Market & Wholesale Experts

381 MW of solar projects developed since 2007

In 2018, **procured 8 million RECs** for customers, enabling them to avoid **3.6 million metric tons of GHG** emissions and support the development of renewables power generation

Headquartered in **Baltimore, MD**

**Q1 2019 data*

Power and Gas customer counts are based on commodity served

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Introduction

Constellation: Who, What and Where we Serve

Natural Gas
Approx 787 Bcf
load in C&I markets^

Retail Power
Approx 147 TWh
C&I load under contract^

Energy Efficiency
905,000 MWh
Annual MWH Savings from EE Programs

Solar
381 MW
customer sited, completed or under construction

Distributed Generation
65 MW
customer sited, completed or under construction

We serve approximately
2 million customers,
including
2/3 of the Fortune 100,
approximately **233,000 Business &**
Public Sector customers,
and about *1.4 million unique residential customers.*

We serve Power & Natural Gas across all competitive markets:

**Q1 2019 data*

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Constellation
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Introduction

Distributed Energy Solutions & Features

ENERGY EFFICIENCY

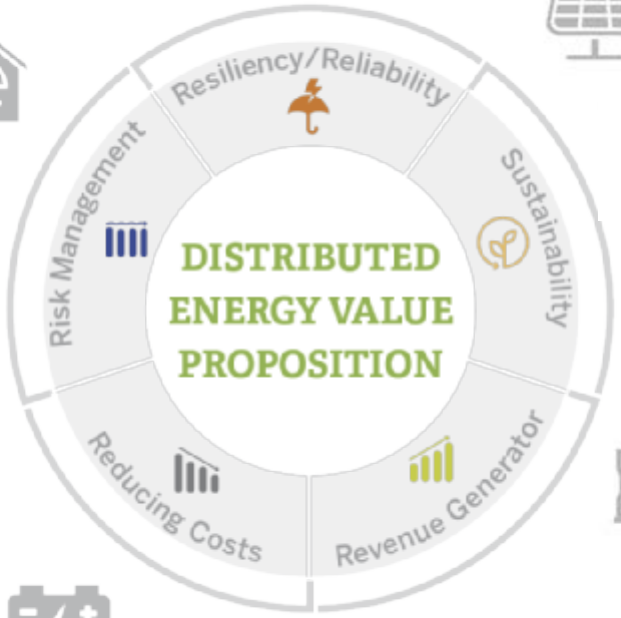
Energy efficiency services improve energy-related equipment, infrastructure and systems with the priority placed on reducing overall energy expenditures.

FUEL CELLS

Fuel cells are devices that convert fuel into electricity through an electro-chemical process (rather than combustion), providing clean, quiet electricity directly at a customer's site.

BATTERY STORAGE

Batteries are energy storage systems that allow customers to take advantage of time-of-use price differences as well as revenue-generating programs in the electricity marketplace.



SOLAR

Solar photovoltaic systems generate electricity from sunlight, and can provide a substantial amount of renewable electricity for your facility at a known rate.

COGENERATION

Cogeneration allows customers with substantial heat and power needs to obtain both from an on-site asset in an economical and reliable manner.

BACKUP GENERATION

An on-site Backup Generation asset allows customers to stay on-line even when grid-based power is interrupted.

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PV Degradation Observations

Timeline

- **Jan 2016** – Sarah Kurtz and Dirk Jordan from NREL lead effort to develop IEC 61724-4;
  - Constellation provides data set to aid standard development;
  - Variation in results observed when implementing draft standard;
- **Jan 2017** – Chris Deline from NREL presents results from early version of Rd Tools;
  - YOY data closely aligns with lab degradation measurements;
- **Q1 2018** – Rd Tools YOY Clear Sky method integration into Also Energy platform complete;
  - NREL validates results from 10 sample sites;
  - Rd Tools run across Constellation Fleet;
- **Q2 2018** – Constellation observed degradation rates that in some cases exceed modeled degradation rates (~0.5%/year);
- **Q2 2018 thru Present** – Constellation conducts deeper investigation to validate results from Rd Tools and to identify root causes of degradation;
- **Present** – development of robust Quality Assurance program.

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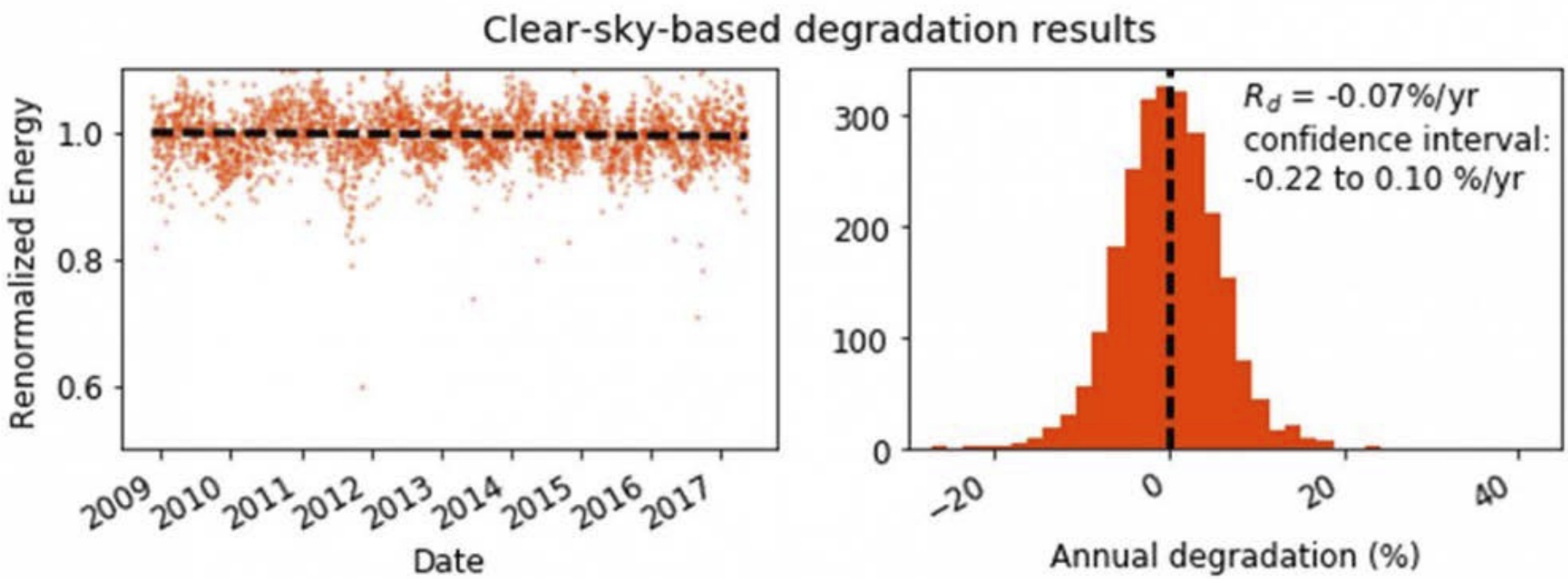
RdTools (2017)

RdTools is a set of Python scripts and software for analysis of photovoltaic time-series data. The open-source tools were developed in collaboration with industry to bring together best practices and years of degradation research from NREL.

Additional details on software methodology and updates can be found on the RdTools info page and on the GitHub software repository.



RdTools system analysis includes filtering, normalization based on measured or modeled irradiance and degradation distribution calculation.

https://www.nrel.gov/pv/lifetime.html

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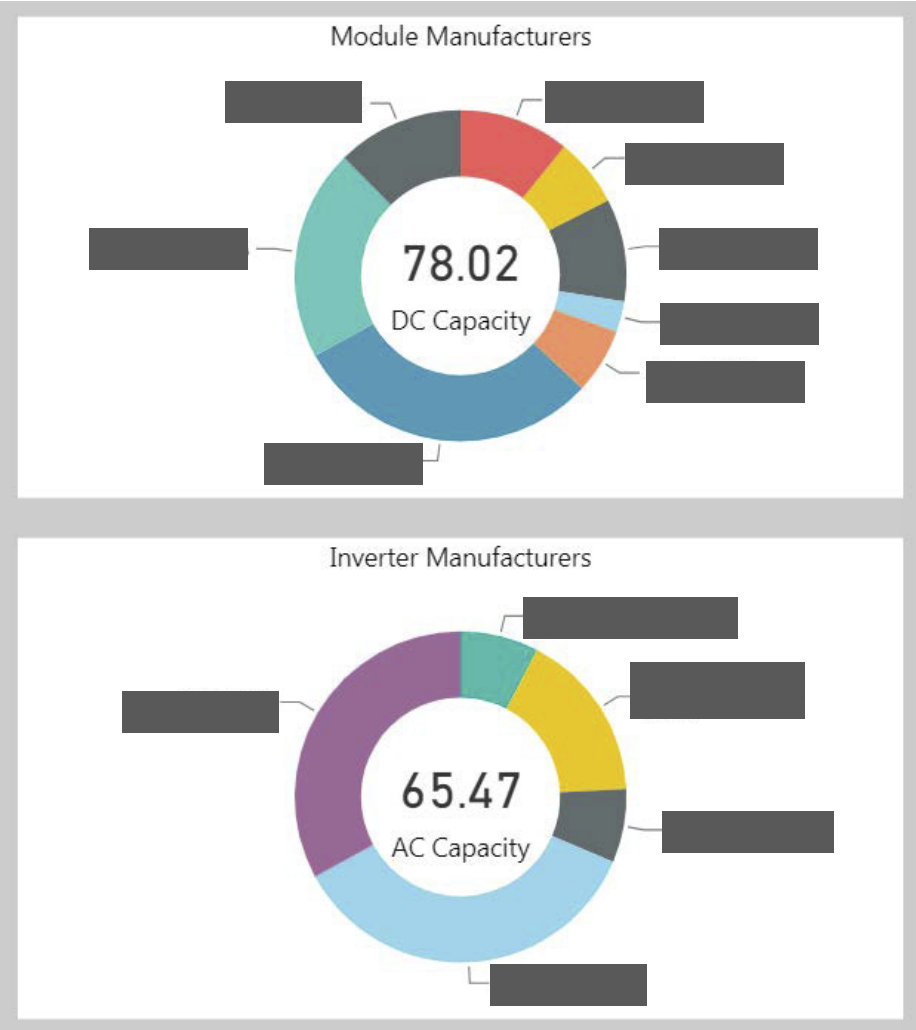
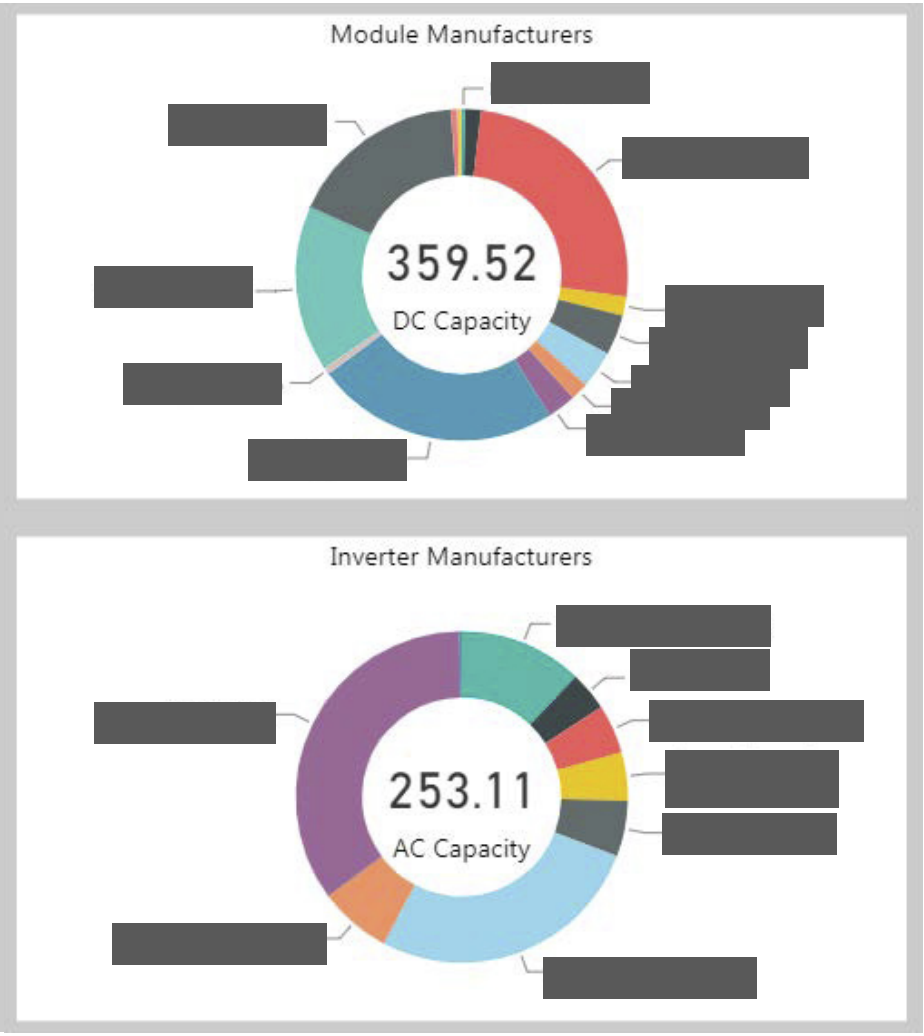
Field Testing



Field Testing Sample



Fleet

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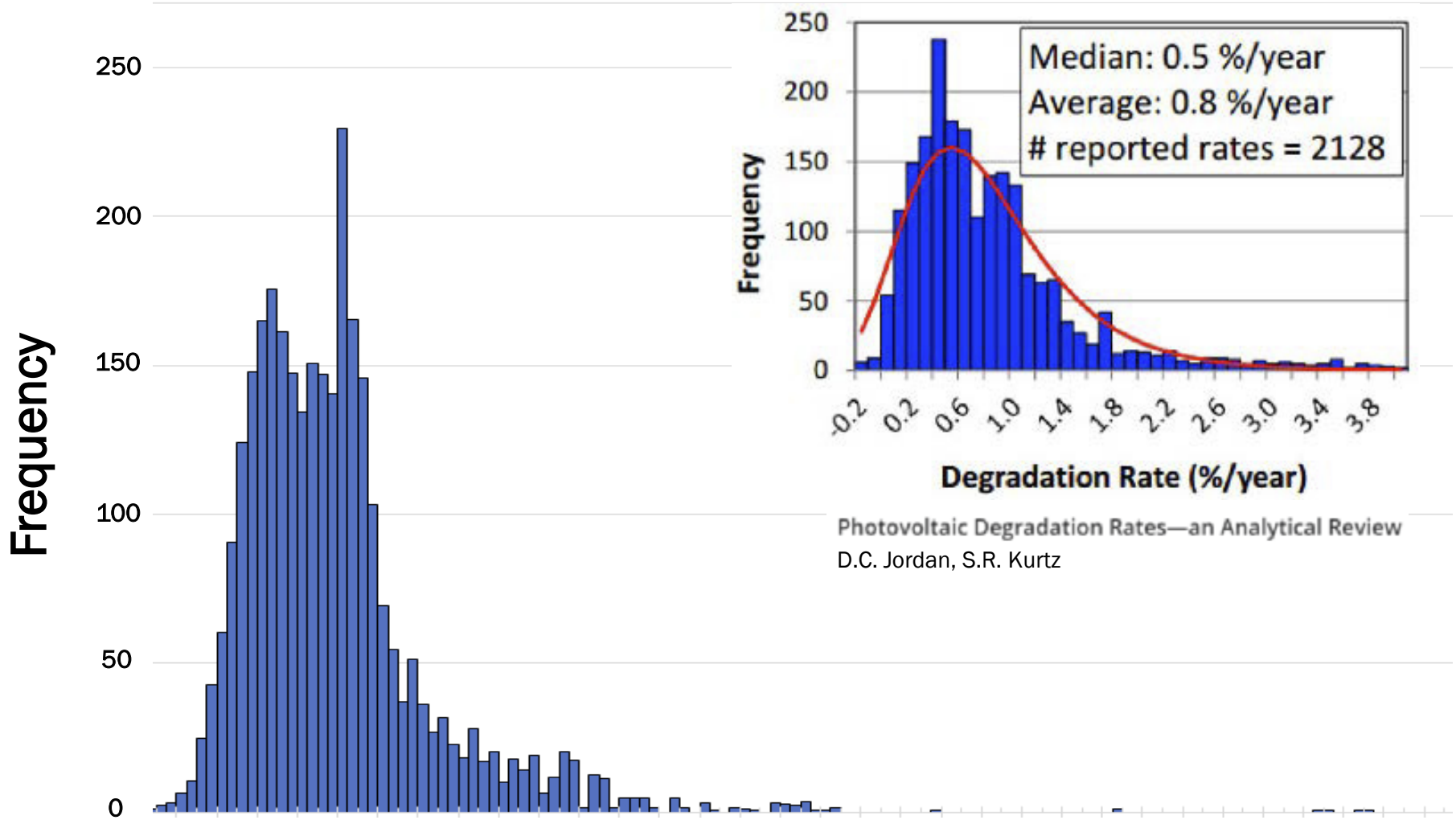
Field Testing Results



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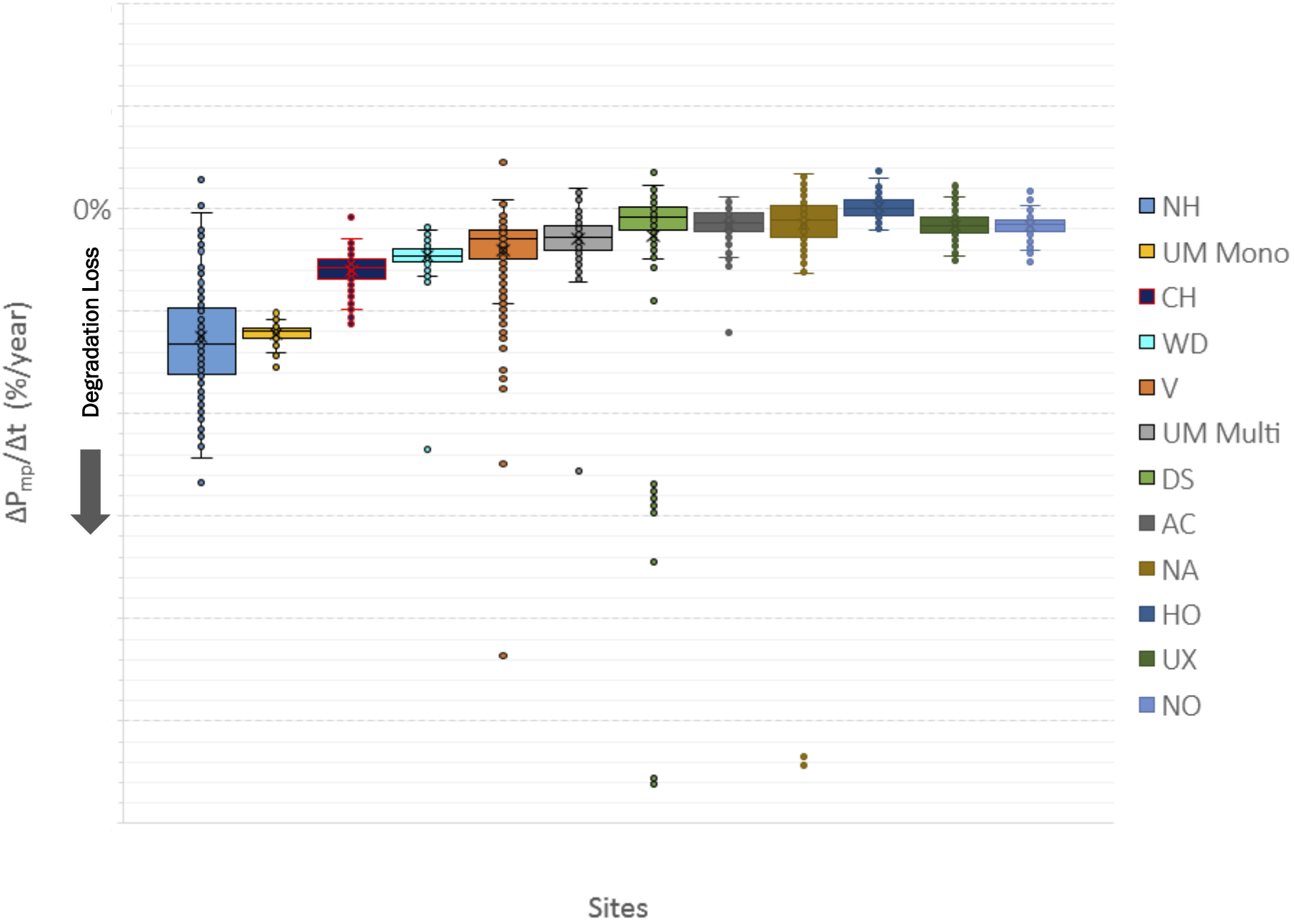

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Thanks for Listening

Robert Flottemesch

robert.flottemesch@constellation.com

410-470-4238

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New Field Testing Protocol

Monitoring DC Health

February 2019

James Rand
Mason Reed
Robert Flottemesch, Constellation

CORE ENERGY WORKS

Core Energy Works' Experience with Field Testing Modules

- Inspected >150MW in the Field at over 50 Sites
- Utility and Commercial Scale Sites
- 20+ Different Module Manufacturers/Technologies
- Ground Mount, Roof Mount, Car Ports, Trackers
- All of the Testing Reported on Today is for Installed Modules

Short Conclusion : They are almost All Good!
....Trust yet Verify

Caveat – Utility scale with no microinverters or power optimizers

Outline

Review from a Field Testing Point of View

- Arial IR Imaging (by Drone)
- Electroluminescence Imaging
- IV Test

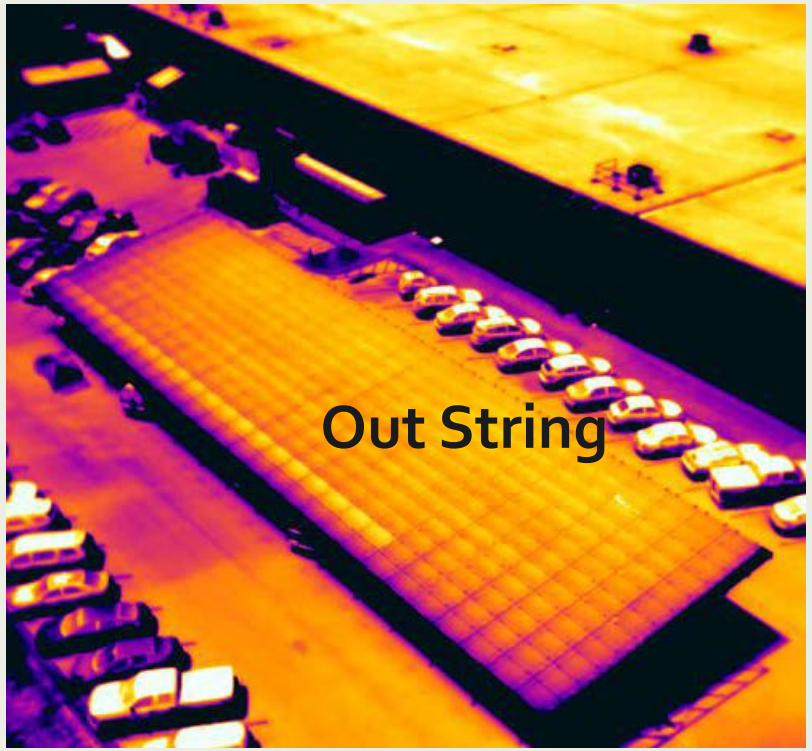
Field Testing Protocol

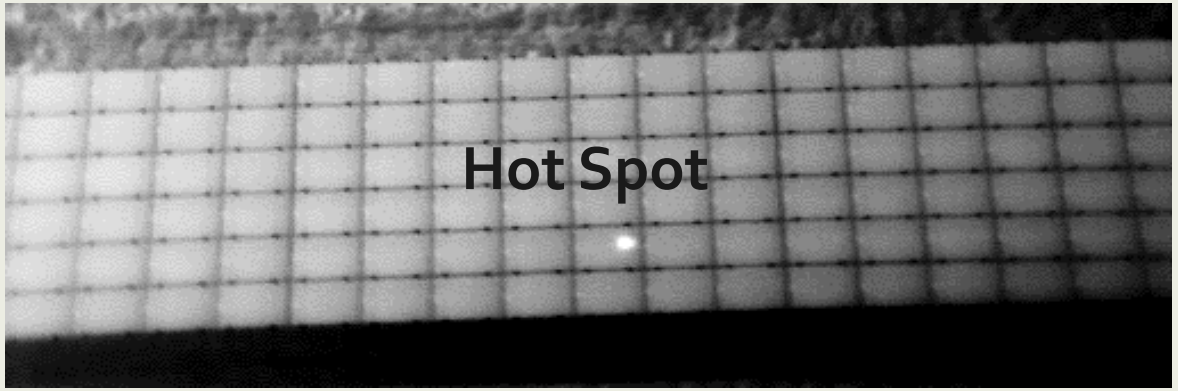
Case Studies

Conclusions

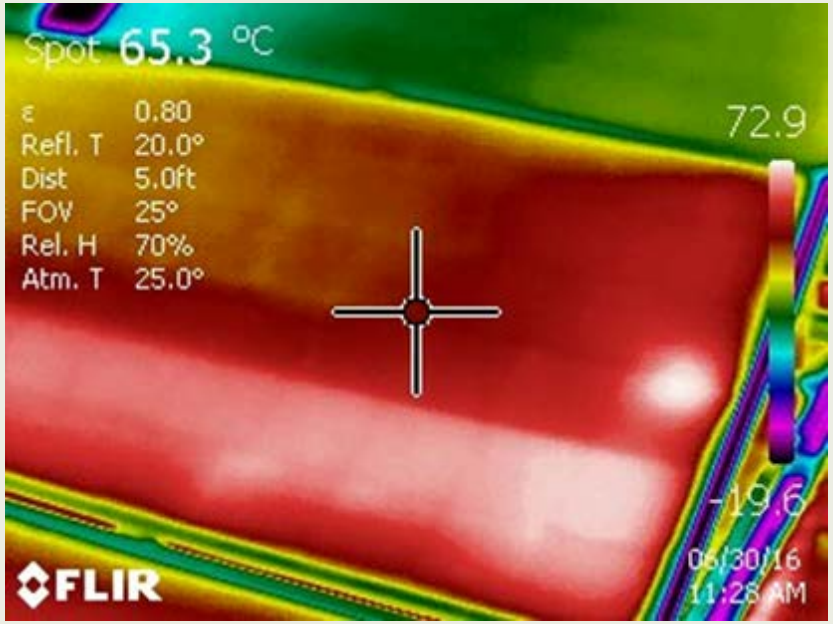
~~Energy Monitoring~~

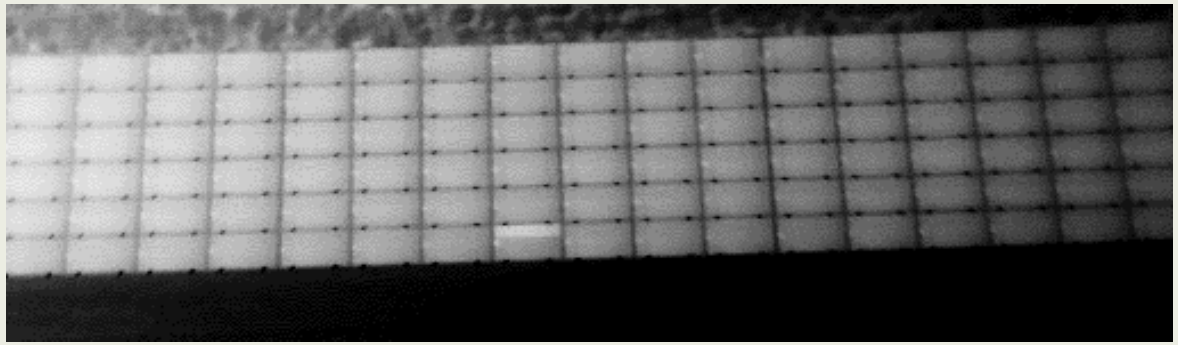
Aerial IR Imaging


Out String

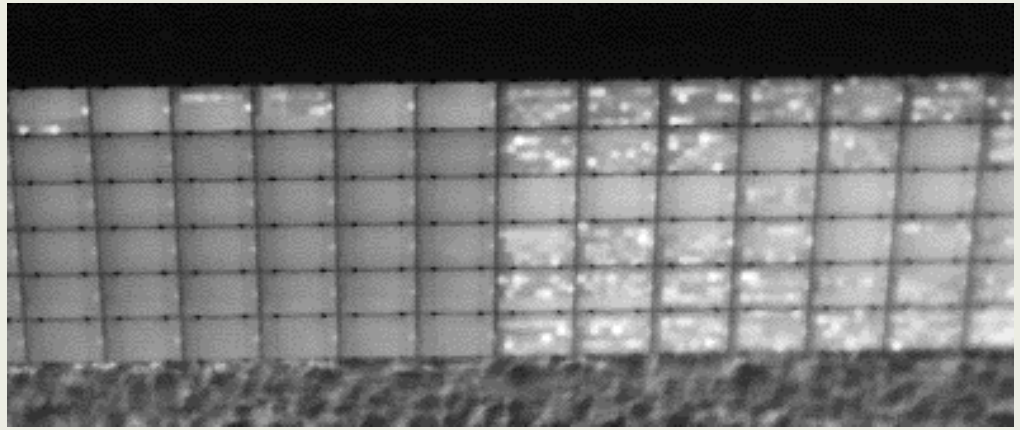

Hot Spot

Aerial IR Imaging





Open Circuited Sub- String (OSS)



Shorted Sub-Strings(SSS) and Open Sub-Strings (OSS)

IR Imaging by Drone

Pros

100% Inspection

Fast (minimal field time)

Forgiving with the Weather

Excellent at Detecting Non-Uniformities

Open Circuits*

Short Circuits*

**Circuits = Substrings up to Whole Inverters*

Cons

Uniform Degradation Mechanisms are Undetectable

Limited Ground Verification

Hot Spots are Common and Can be Hard to Interpret

Electroluminescence (EL)

Pros

Very Useful for Root Cause Determination
Surprising Compatible with Field Testing
You have to Work at Night

Cons

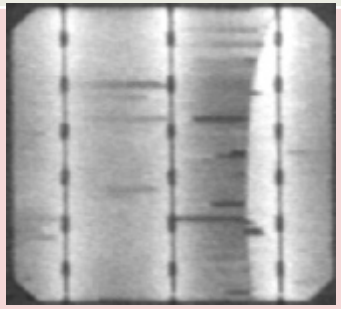
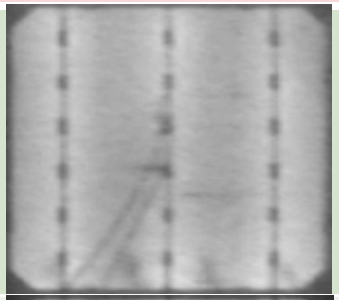
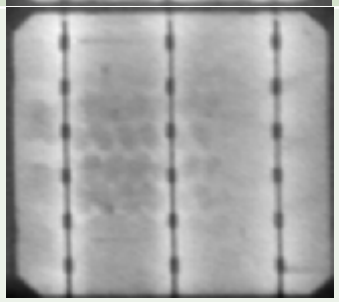
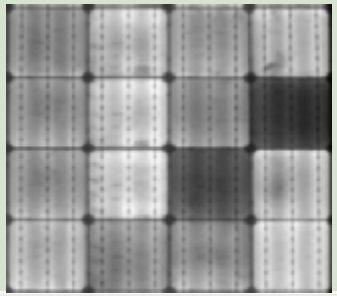
Slow and Therefore Expensive
but getting faster all the time
Experience needed to Interpret the Results

Modified consumer camera

DC power supply

~1-2kW Ac Generator

EL

Non-isolating crack		**Interior cracks where all regions of the cell still have a direct path to a busbar are non-isolating and typically will not significantly degrade performance over time.**
Isolation via multiple cracks		Although not yet isolated in this example, multiple cracks are forming an interior region of the cell that can become isolated as thermal expansion/contraction stress continues
"Tire Track Pattern"		This is a cell processing phenomenon occurring during the metallization firing step due to the belt pattern of the belt furnace "transferring" to the cell (probably due to a thermal shadow from the belt).
Degraded cell efficiency (LID or PID)		The dim cells are less efficient. In this case, an exacerbated form of LID associated with p-type CZ cells is suspected, although PID is possible.

Current-Voltage (IV) Traces

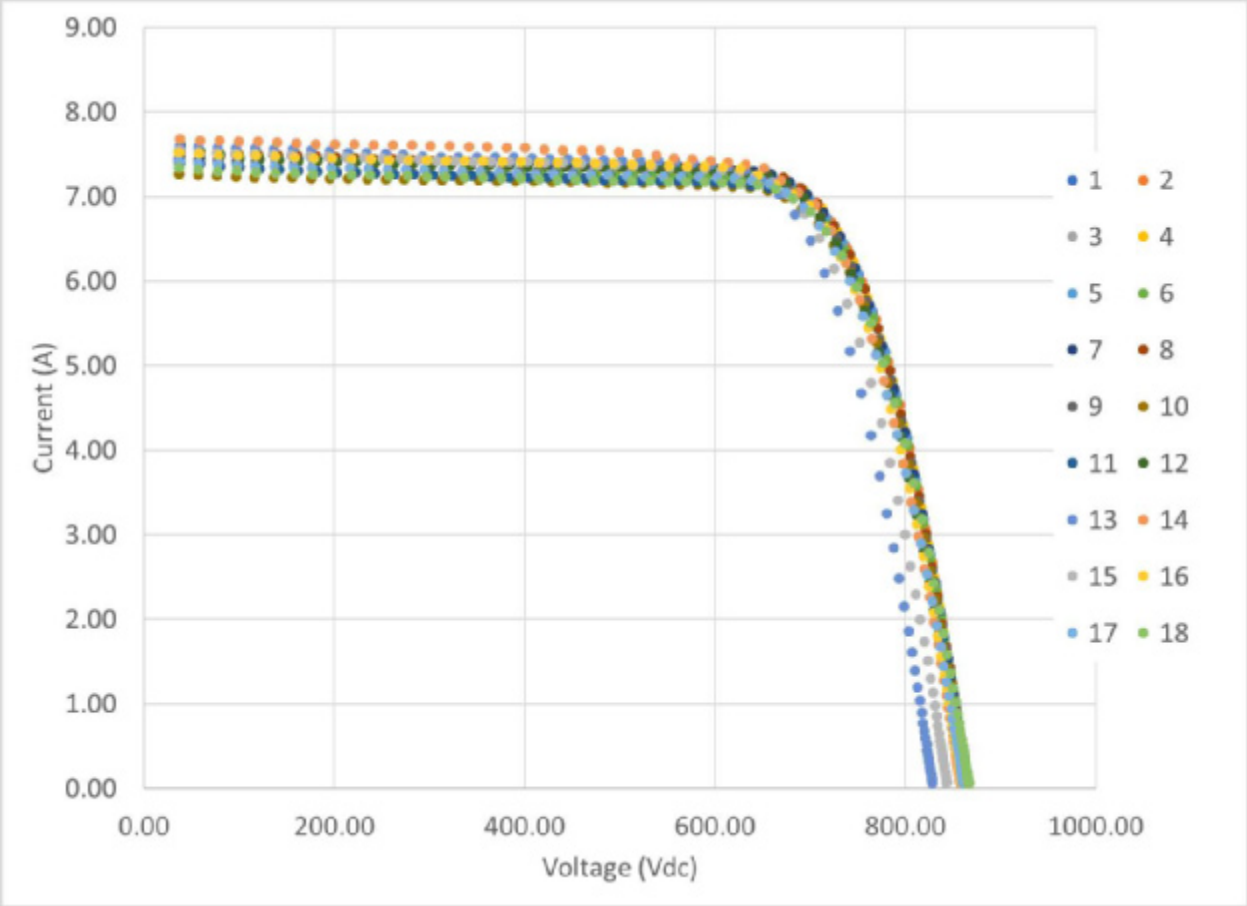
At the String Level (working in the Combiner Box)

Pros

- Useful for Site Acceptance
- Catches Many (Most) Field Wiring Errors
- Reasonable in terms of Cost and Expertise Needed
- Evaluate mismatch loss (if done very carefully)

Cons

- Cannot diagnose module issues
- Weather Dependent
- Translation to STC Expands the Error Bars



Current-Voltage (IV) Traces

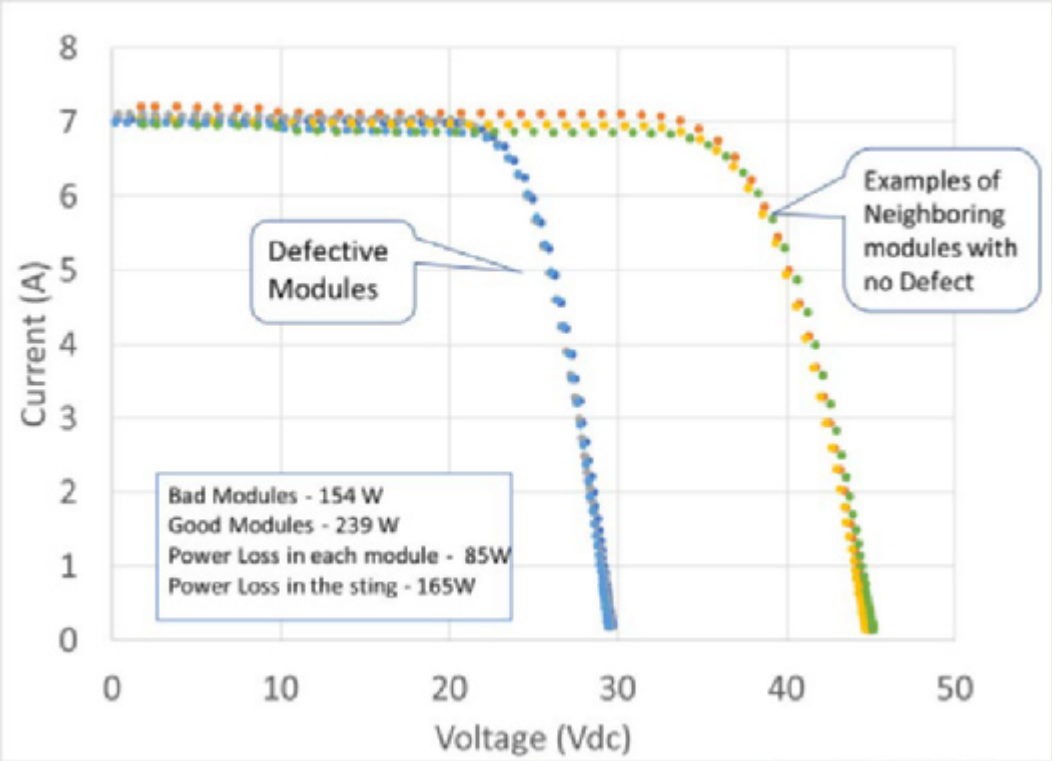
At the Module Level

Pros

Very Good for Diagnosing Module Issues

Cons

Slow and Expensive
Weather Dependent
Expertise Needed
for Translation to STC
for Sufficient Accuracy to Consider Warranty Issues



The Tail of the Distribution has an Out Sized Impact to Overall System Performance

Core Energy Works Field Test Protocol

Test	Sample Size		Key Result
IR Imaging	100%		Thermal non-uniformities at the module level
Visual Inspection	2% (+/-)	300 Minimum	Module package defects such as bubbling, burn marks, delamination, and overheated Jboxes.
Module Level IV	2% (+/-)	300 Typical	Finds degradation mechanisms impacting all modules. Identifies subtle differences in big populations.
String Level IV	Small Sample	<10 Typical	Measures mismatch losses
Impact of Soiling	Small Sample	20-30 Modules	Measures soiling loss. Needed for Translation to STC
EL	Small Sample	30-60+ Modules is Typical	Connects solar cell level defects to module performance

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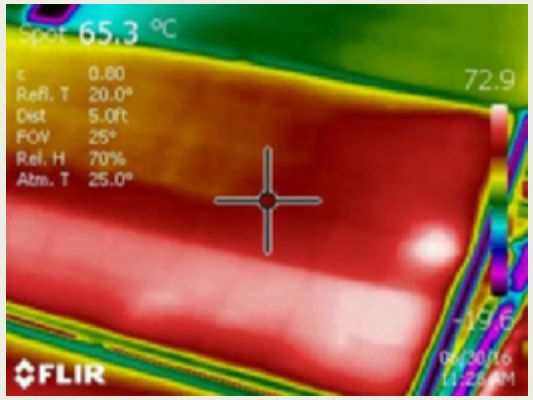
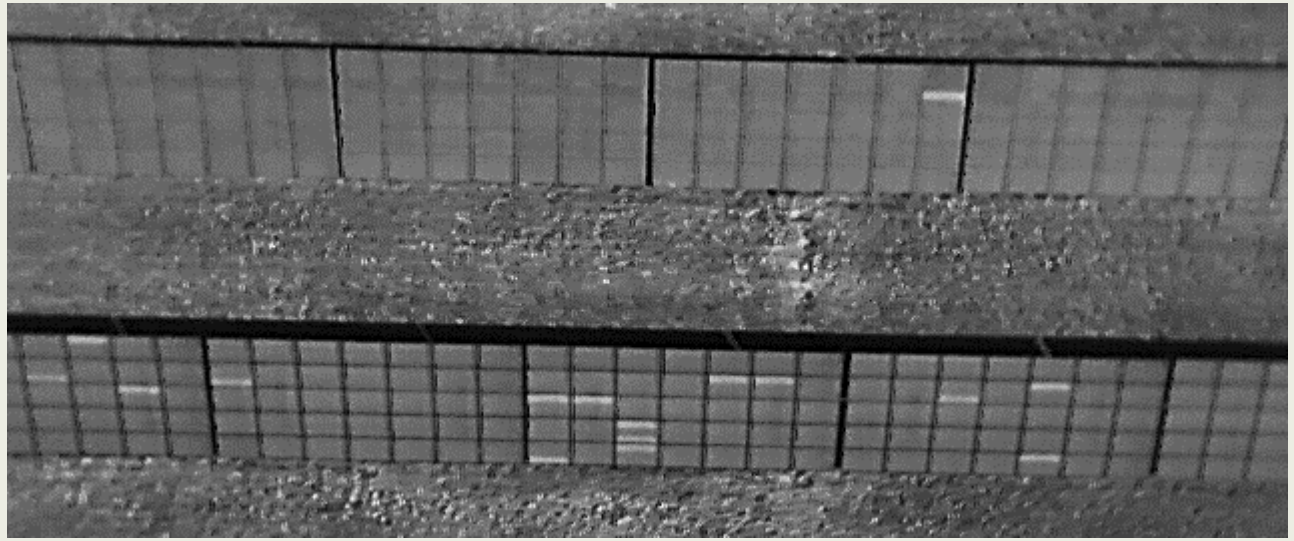
Case Studies 1 to5 Failed Solder/Weld Connections

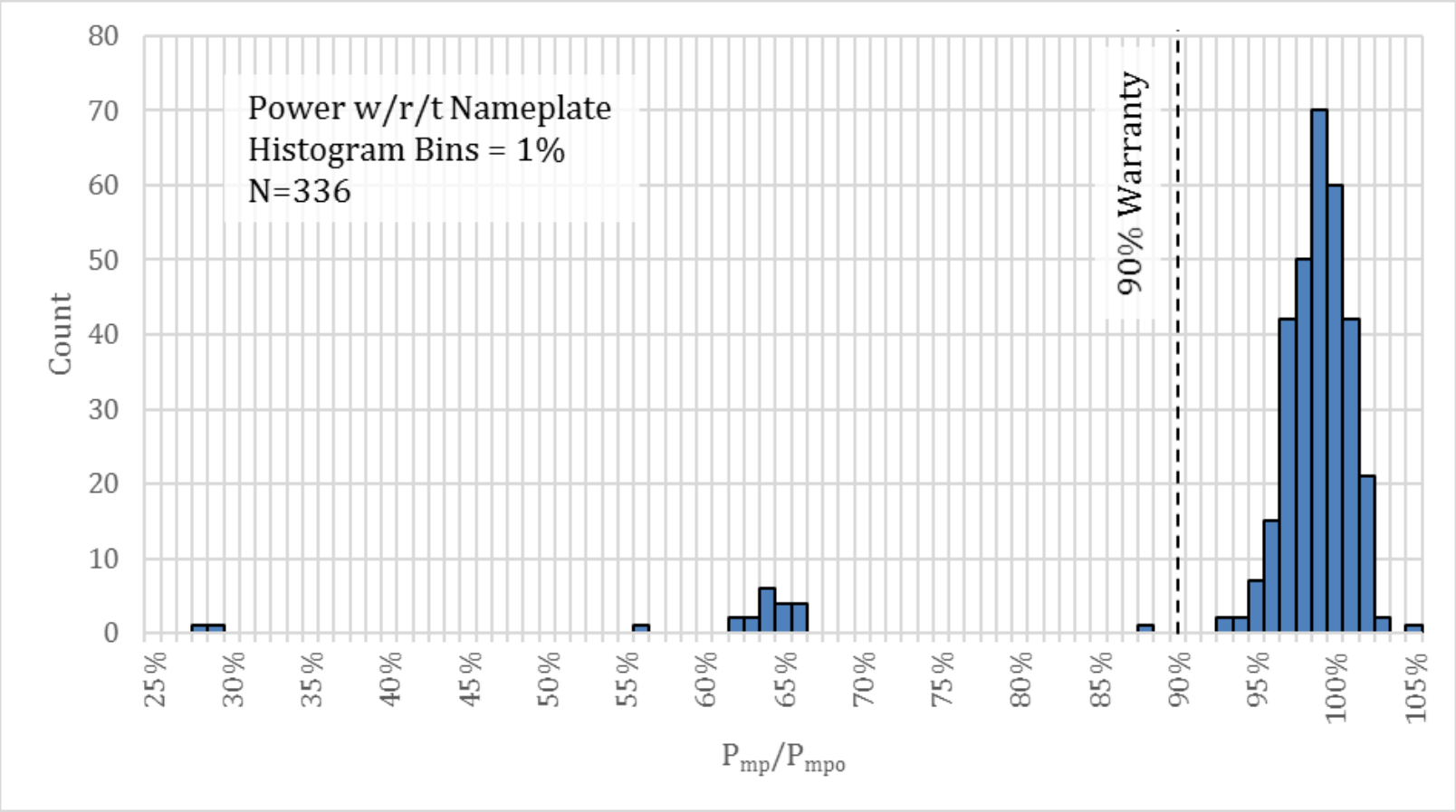
Manufacturer A	8% Modules Impacted	5 Years	Failed **Off Cell** Solder Joints
Manufacturer B	3.9% Modules Impacted	8 Years	Failed **Off Cell** Solder Joints and Diode Failures
Manufacturer C	8% Modules Impacted	5 Years	Failed and Failing **Off Cell** Solder Joints (Running hot)
Manufacturer D	0.7% Modules Impacted	8 Years	Unknown
Manufacturer E	0.4% Modules Impacted	3 Years	Failed Welded Joint in Jbox



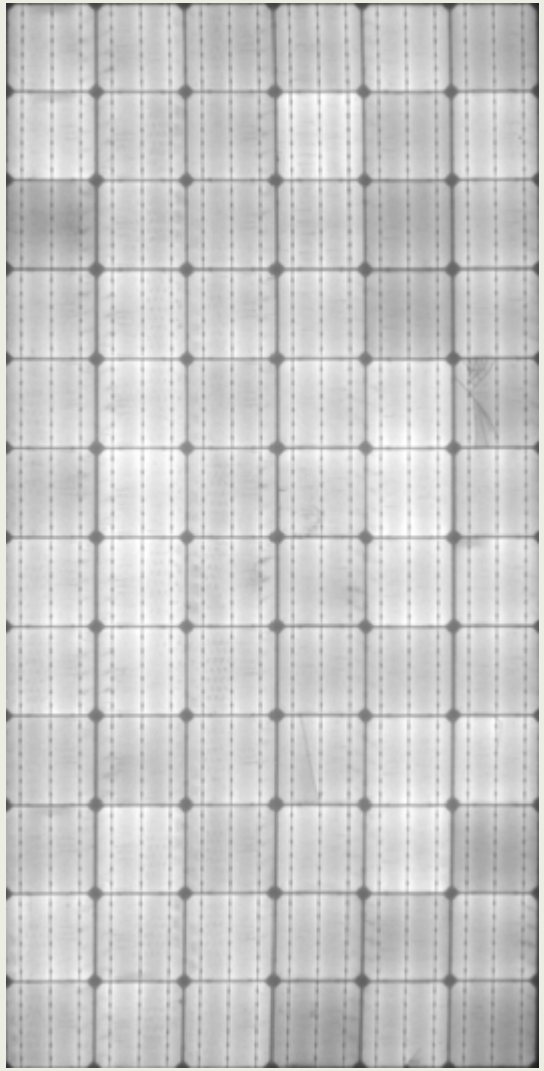


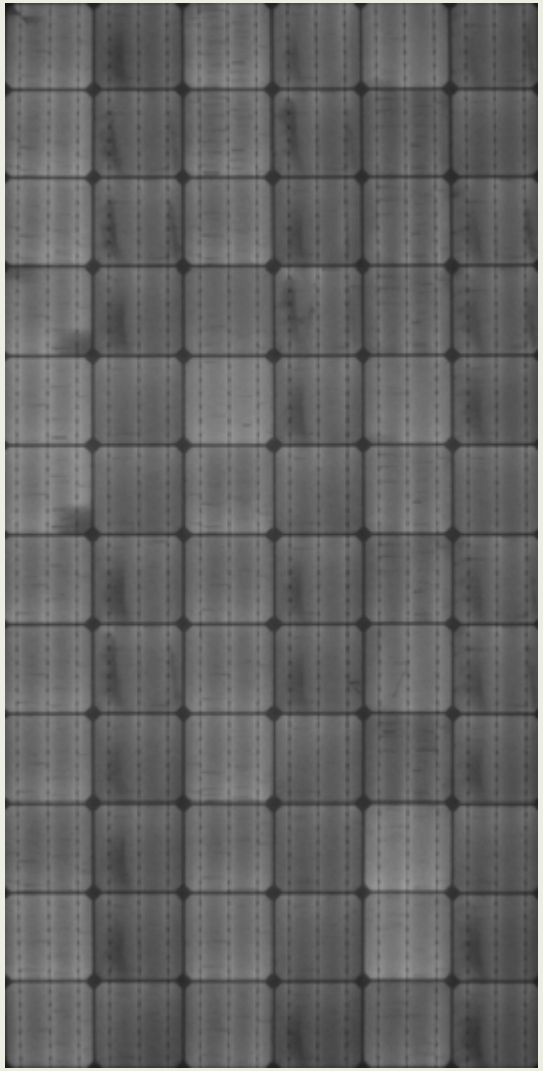
Case Studies 1-5

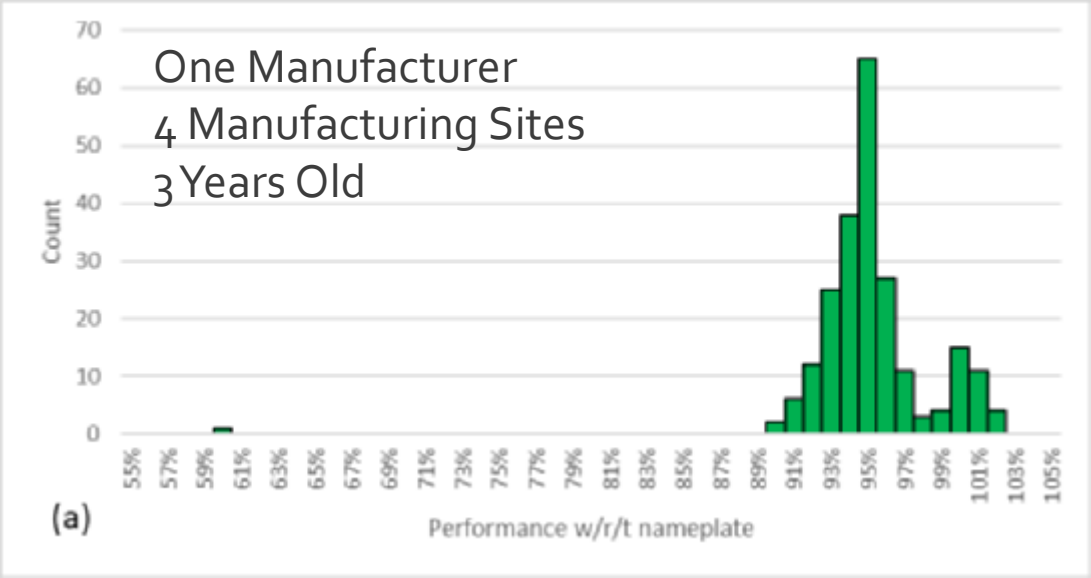
Failed Solder/Weld Connections

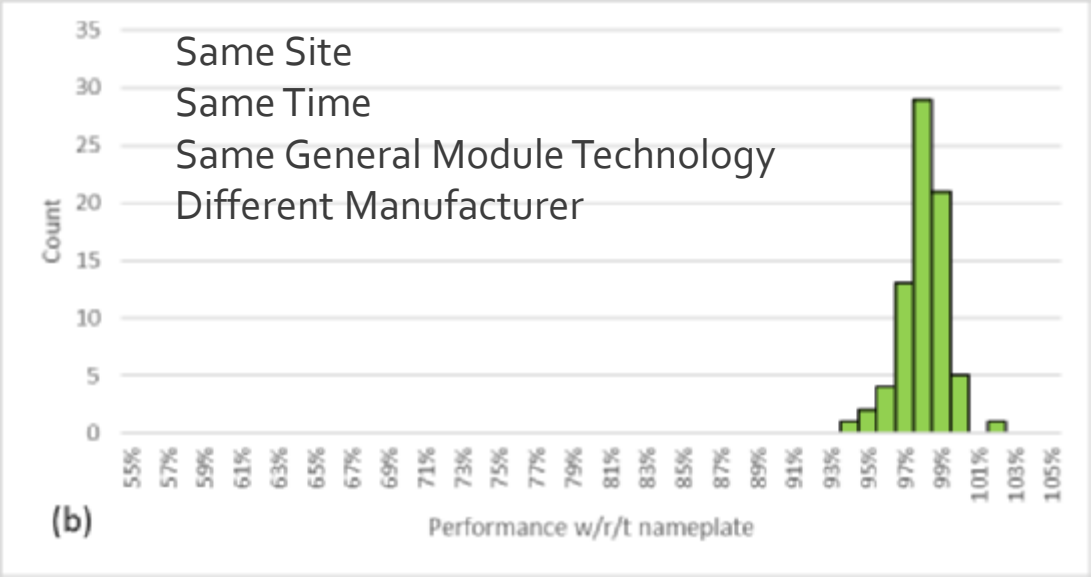


Case Study 6 Discrete Module Level Degradation

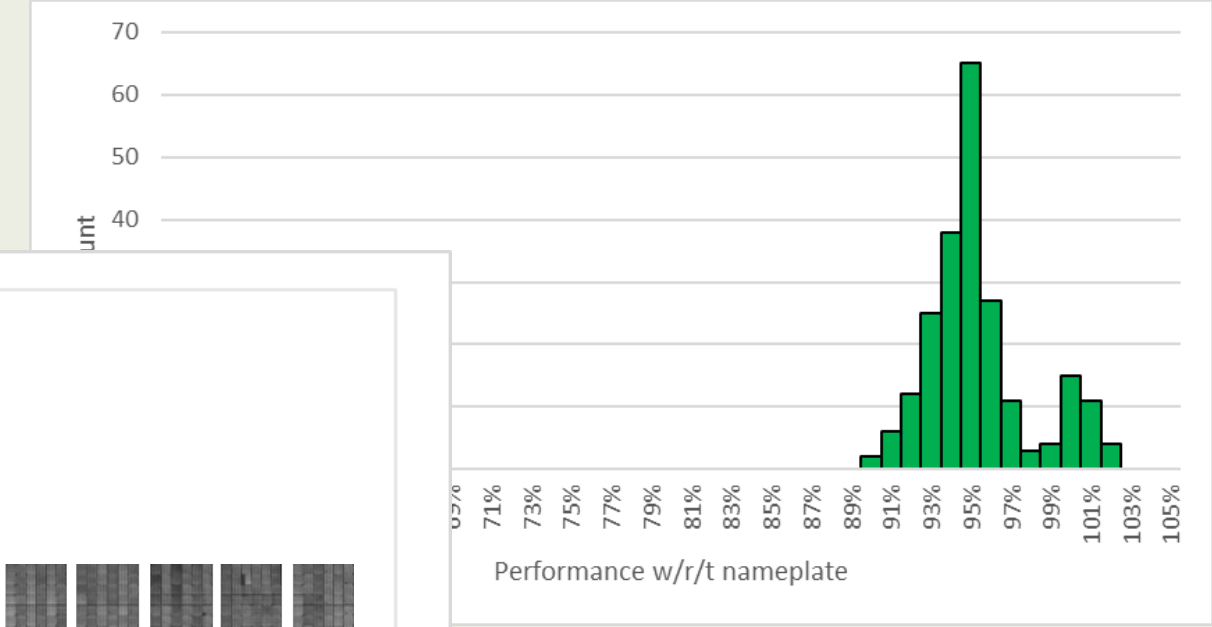


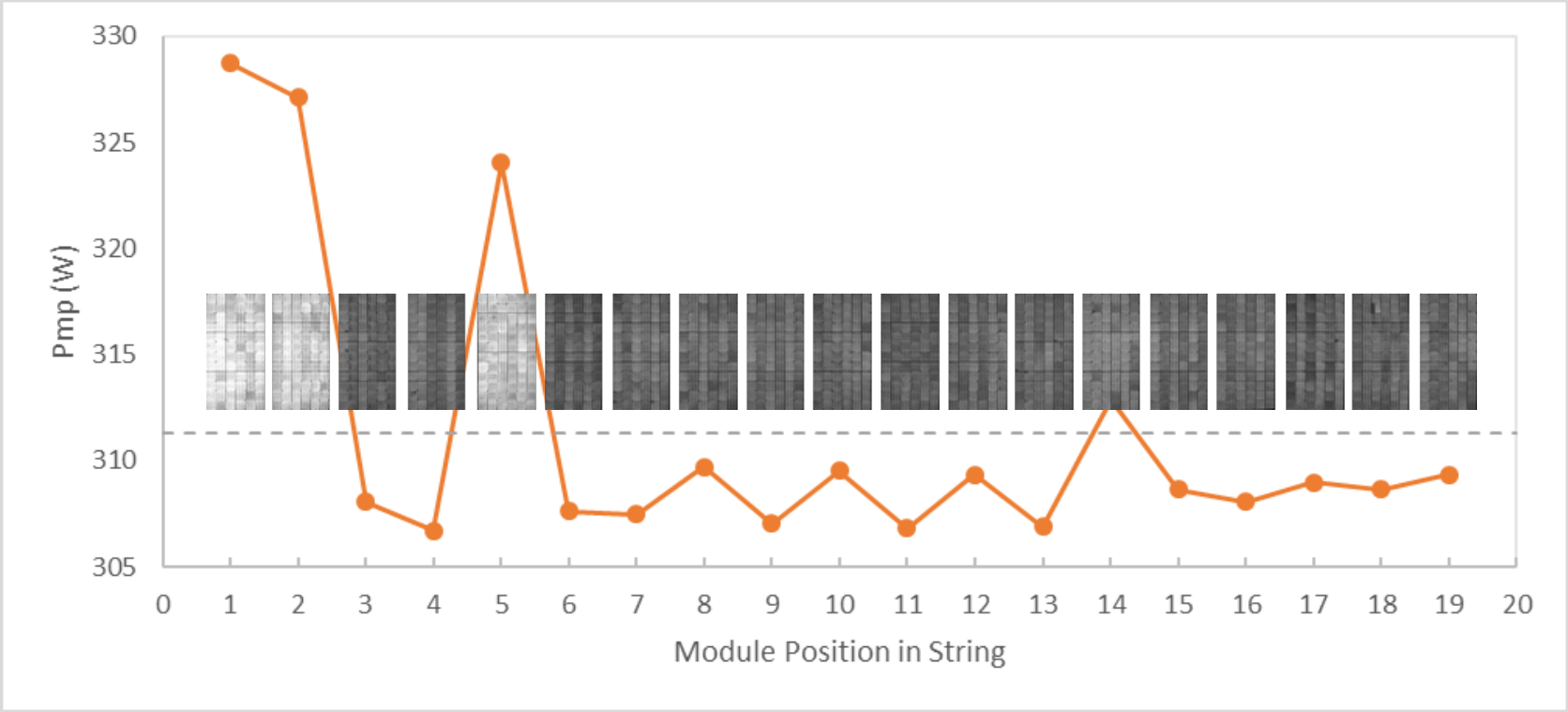




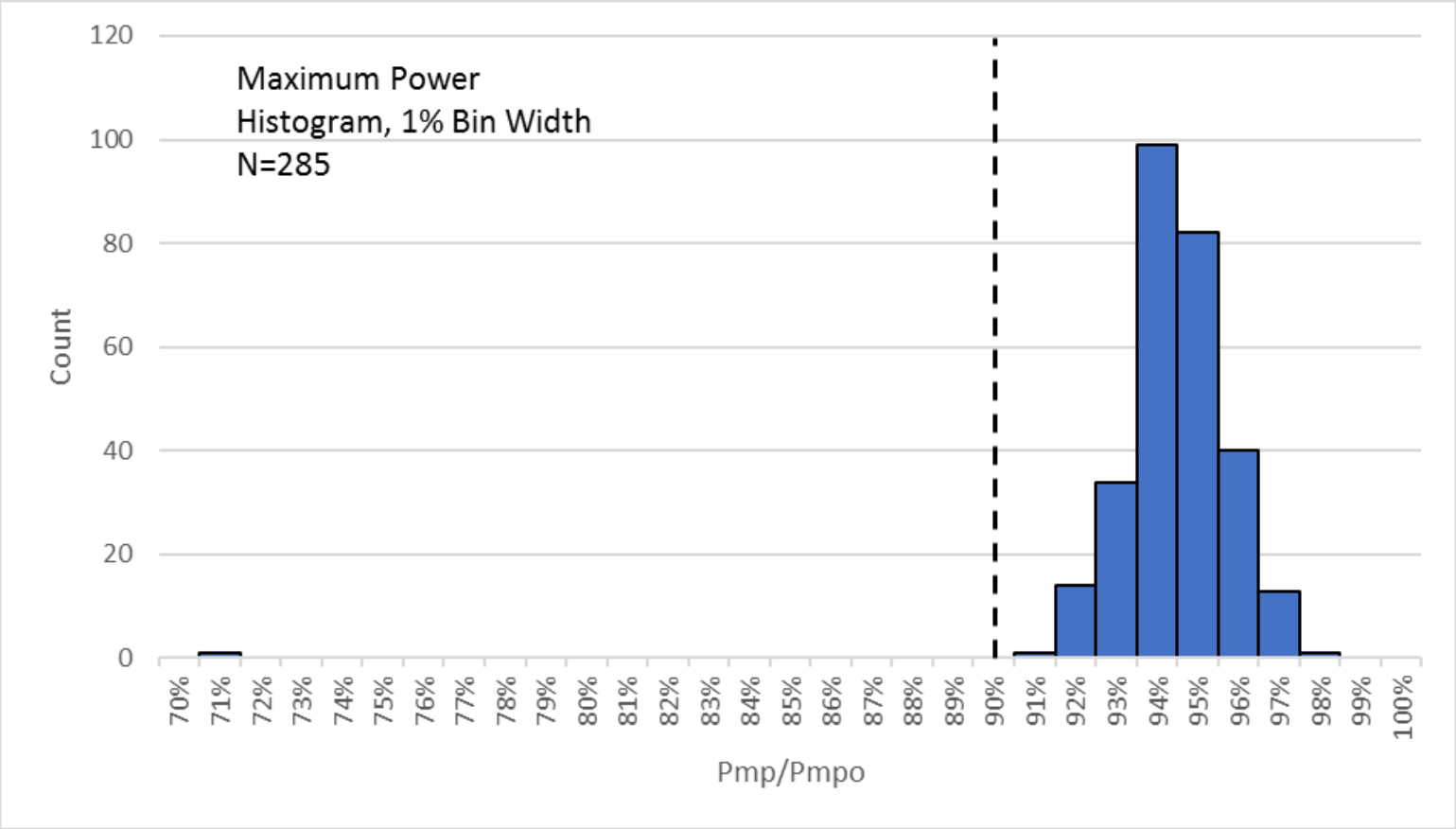


Case Study 6 Discrete Module Level Degradation





Case Study 7 Success!



8 years old

Conclusions

A Field Testing Protocol Has Beed Developed to Better Assess DC Health

Full Field IR Imaging

Required Part of Annual O&M

Although Necessary it is not Sufficient

IV Testing

Modest Sample Sizes are needed at the module level to determine overall DC health

EL Testing

Provides root cause answers when cell level defects are present

Samples can be small if IR and IV are in hand

Expertise is needed to extract meaning information

New Degradation Mechanisms Associated with New Higher Performance Solar Cells

Diagnose Poor Performing Arrays
Root Cause for Module Defects
Warranty Claim Support
Lab or Field Testing

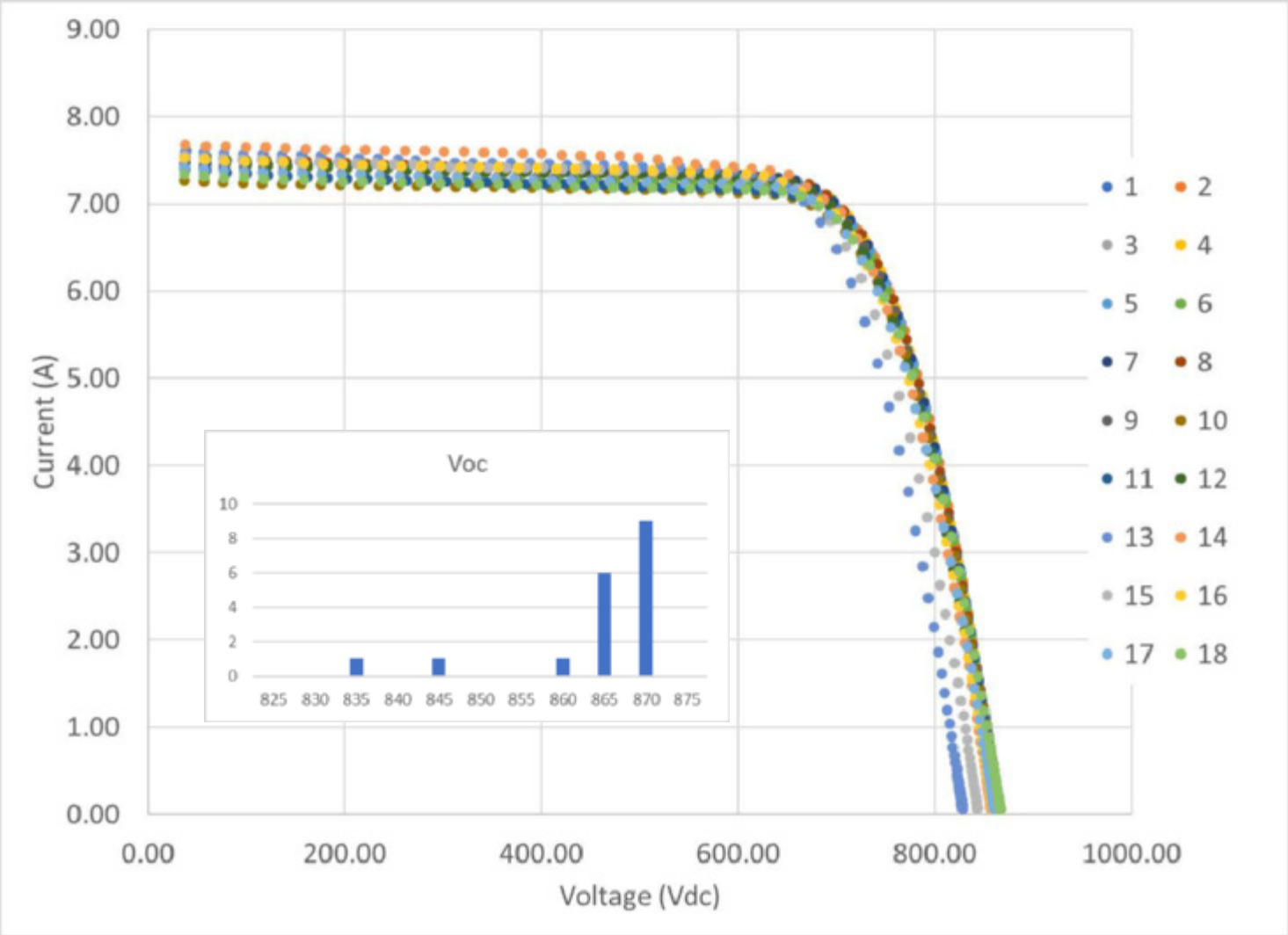
CORE ENERGY WORKS

Jim Rand, jim.rand@CoreEnergyWorks.com

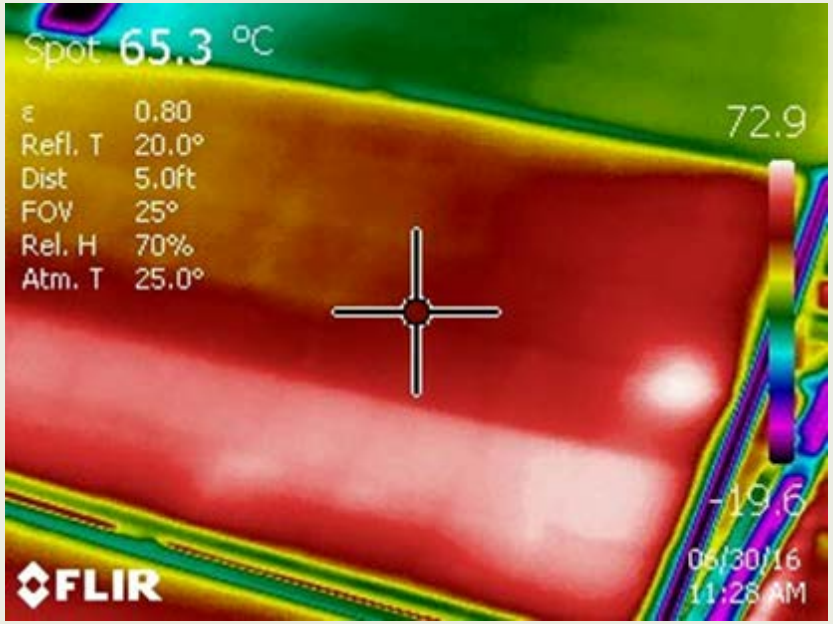
Mason Reed, mason. reed@CoreEnergyWorks.com

Contact us with feedback, questions, or just to talk solar.

Impact of Defective Modules

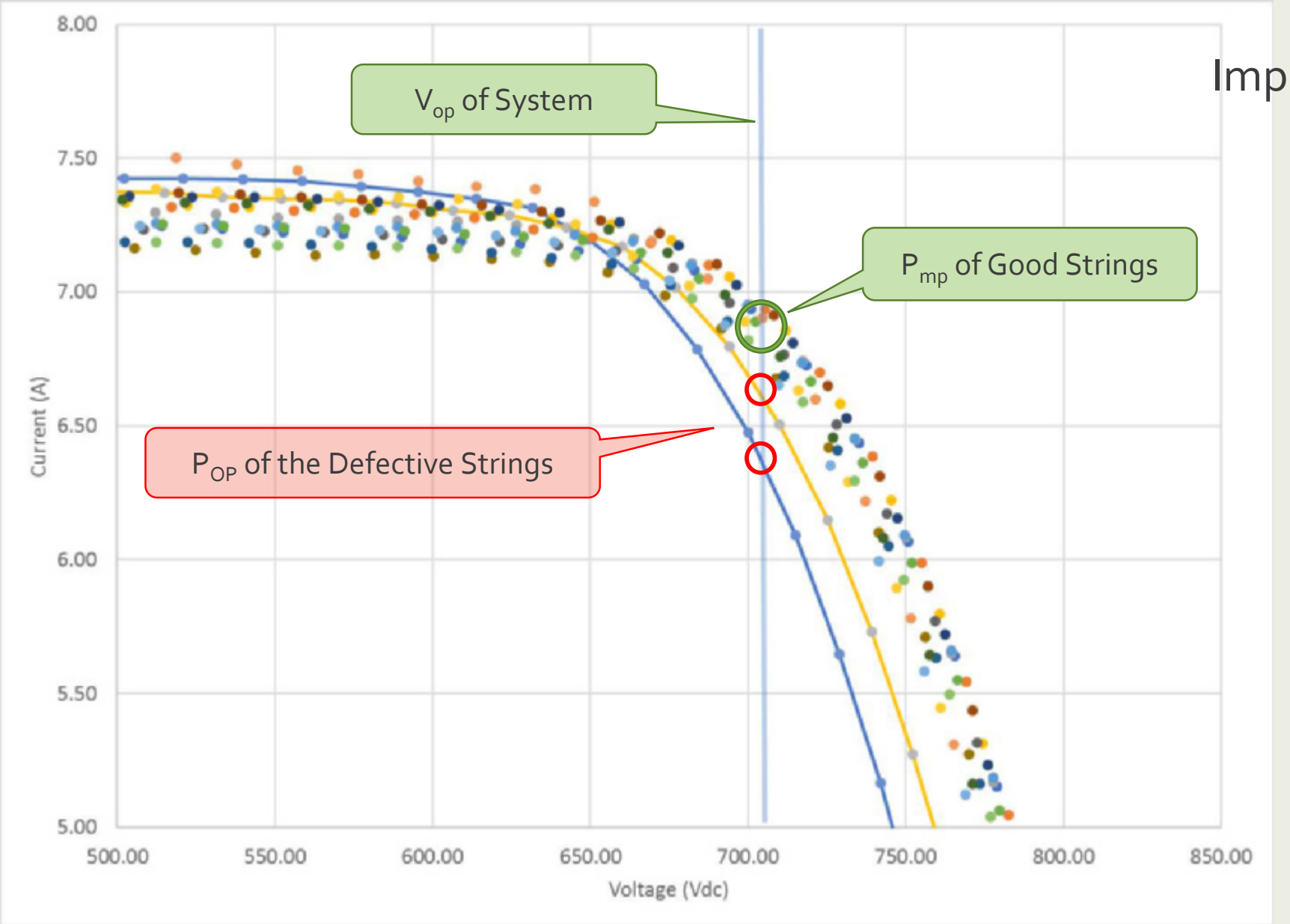


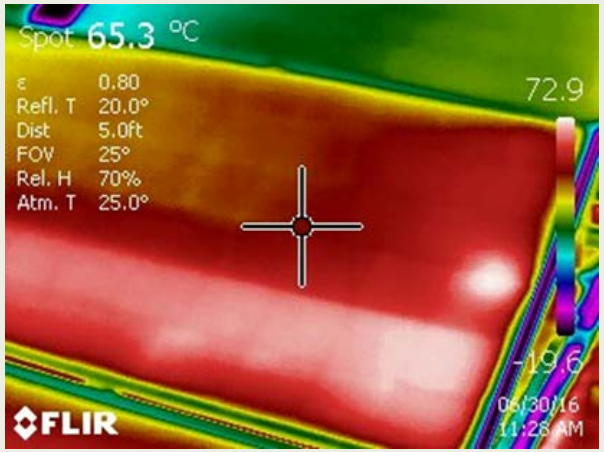
Infrared



Impact of Defective Modules

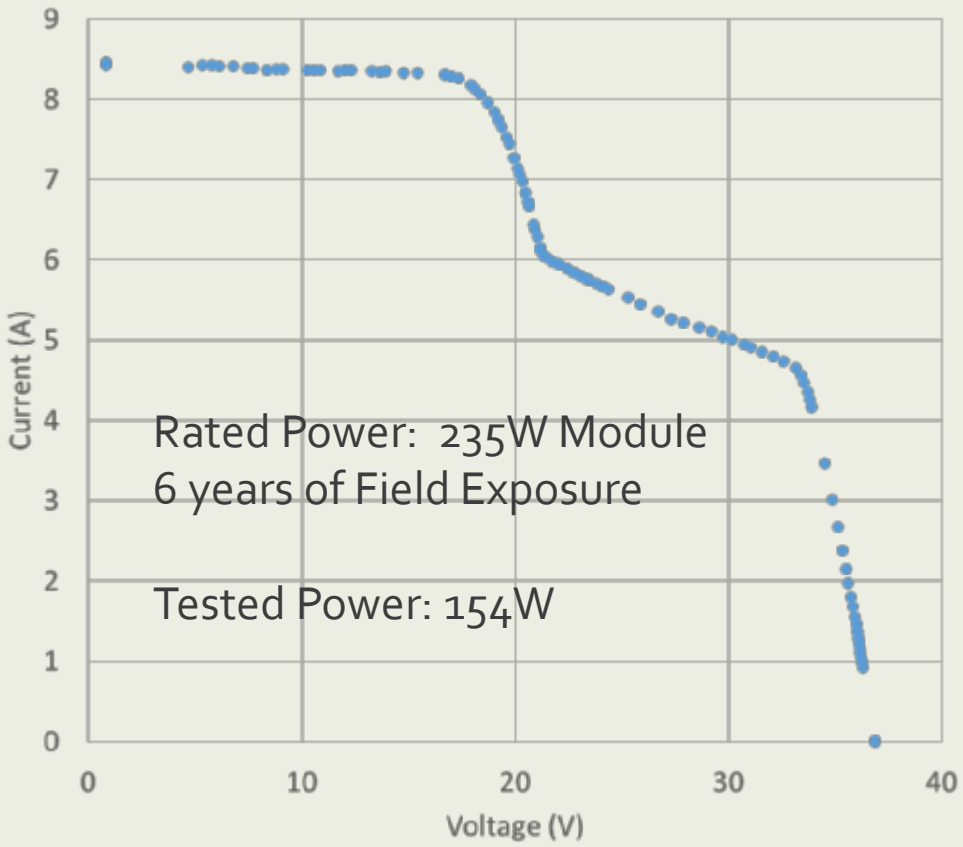
OSS

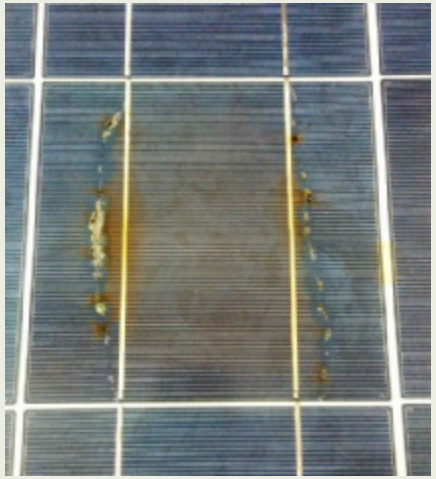


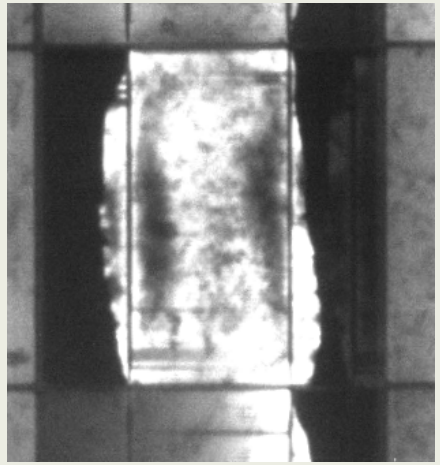


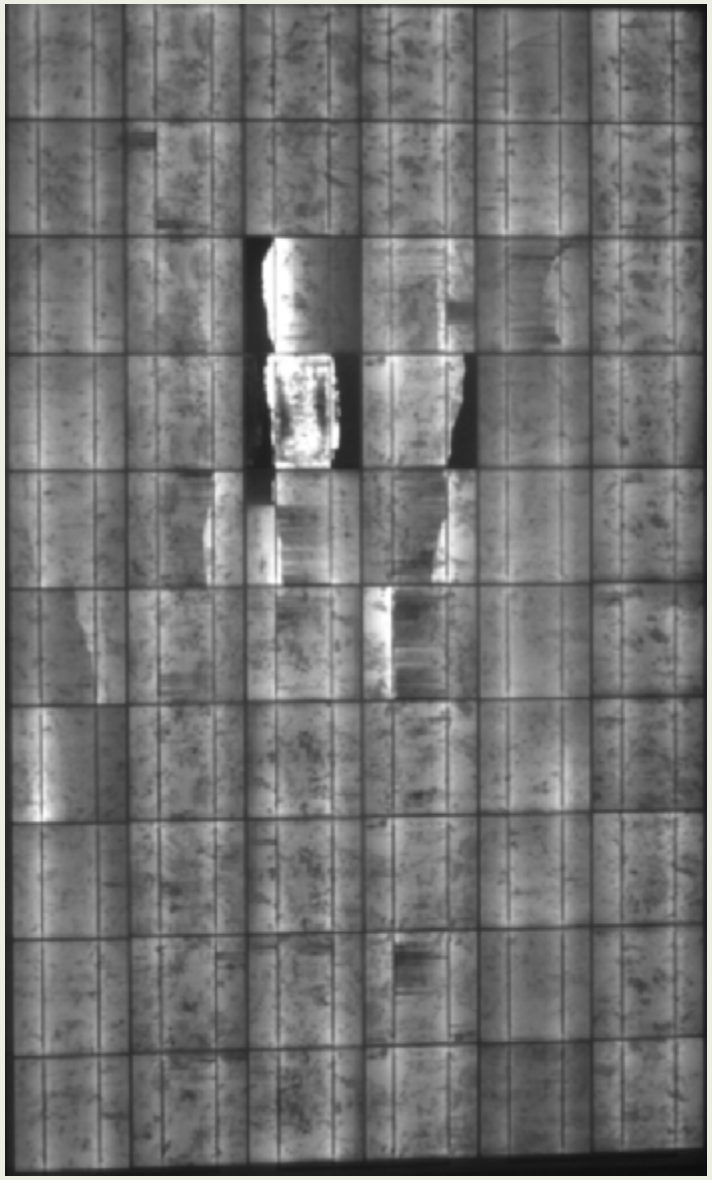
You would expect the power loss to be -33% for this defect.

Include mismatch it is -73%





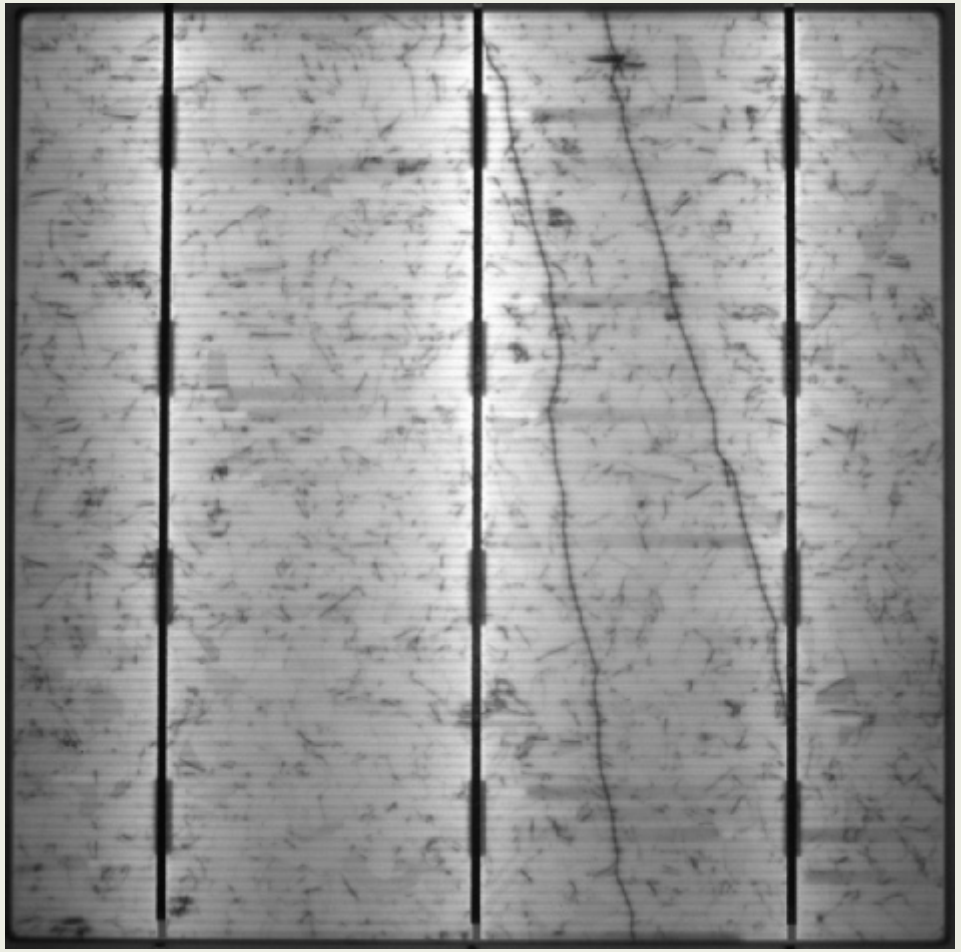




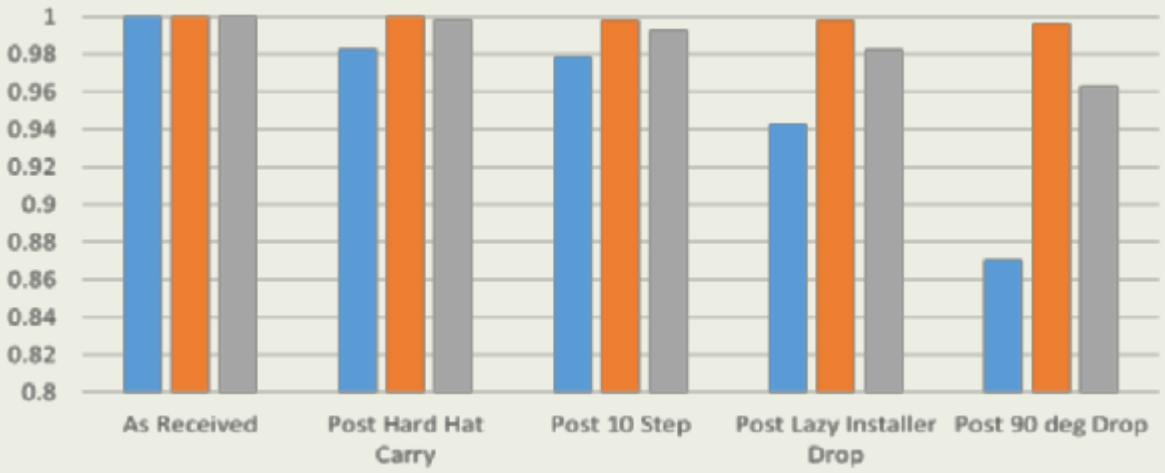
Electroluminescence

Cracked Solar Cells May Not be Bad,

But They Can't Be Good

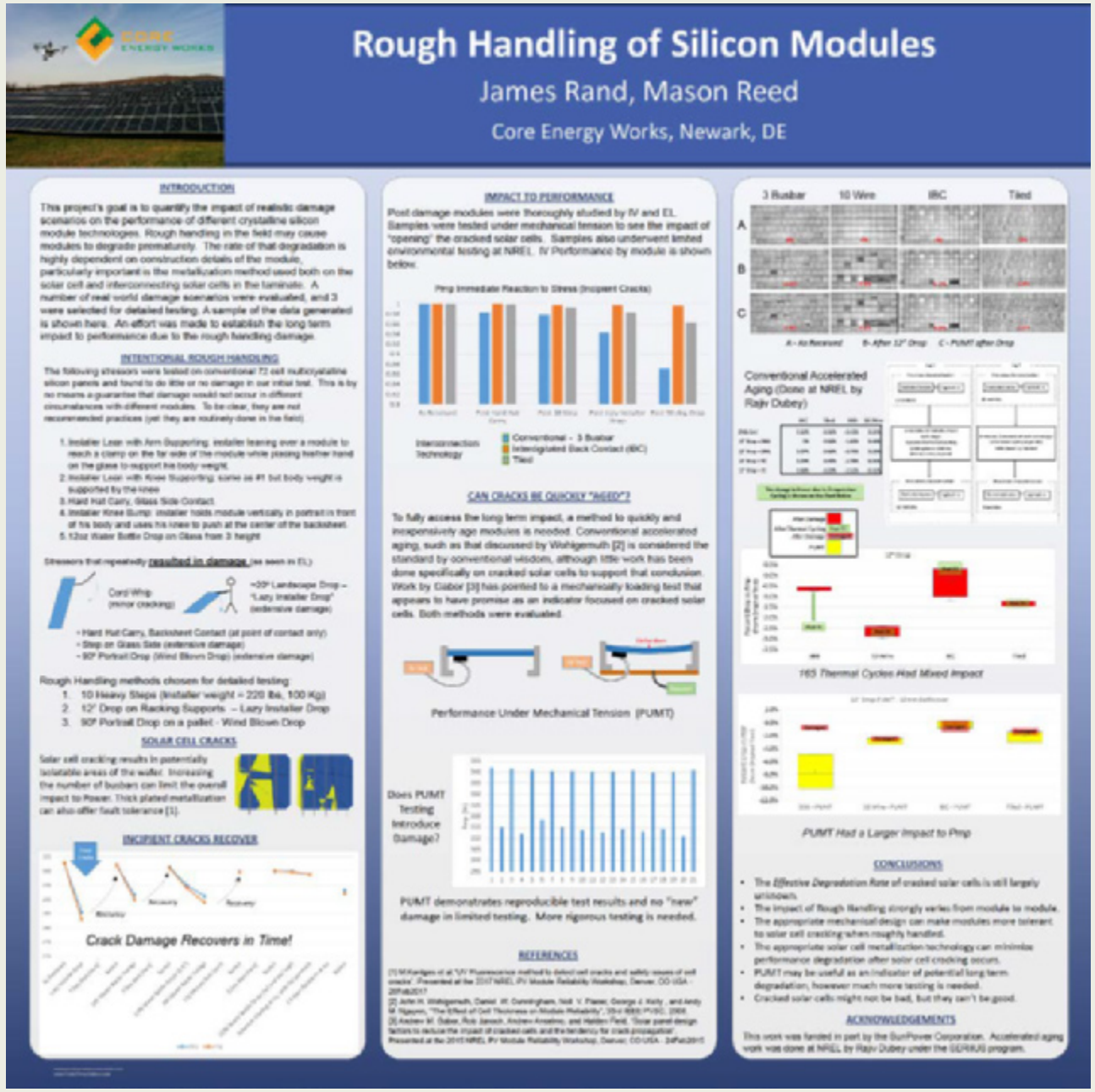


P_{mp} Immediate Reaction to Stress (Incipient Cracks)



Interconnection Technology

- Conventional - 3 Busbar
- Interdigitated Back Contact (IBC)
- Tiled



EL

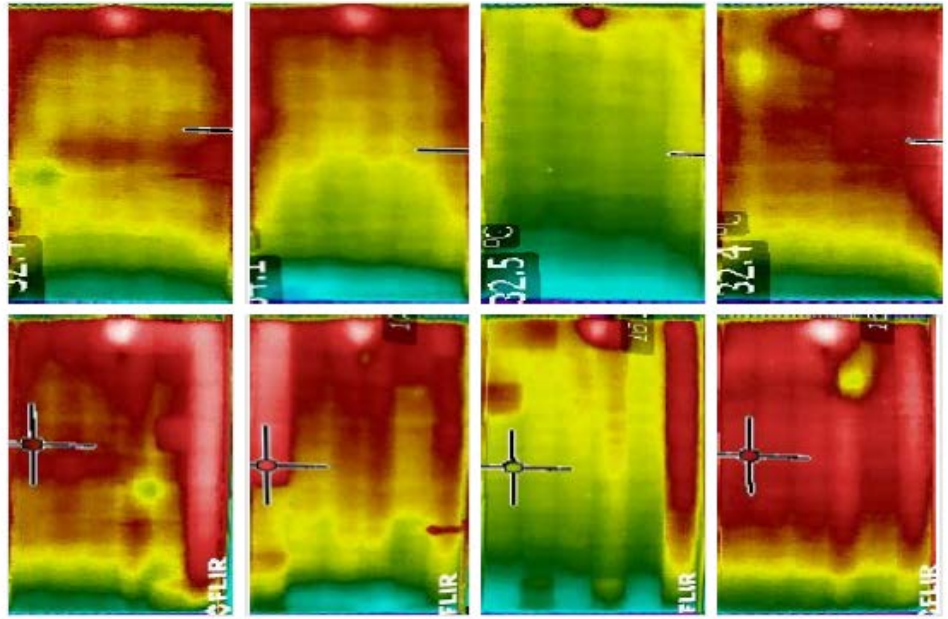
PID

+

Positive End of String

-

Negative End of String

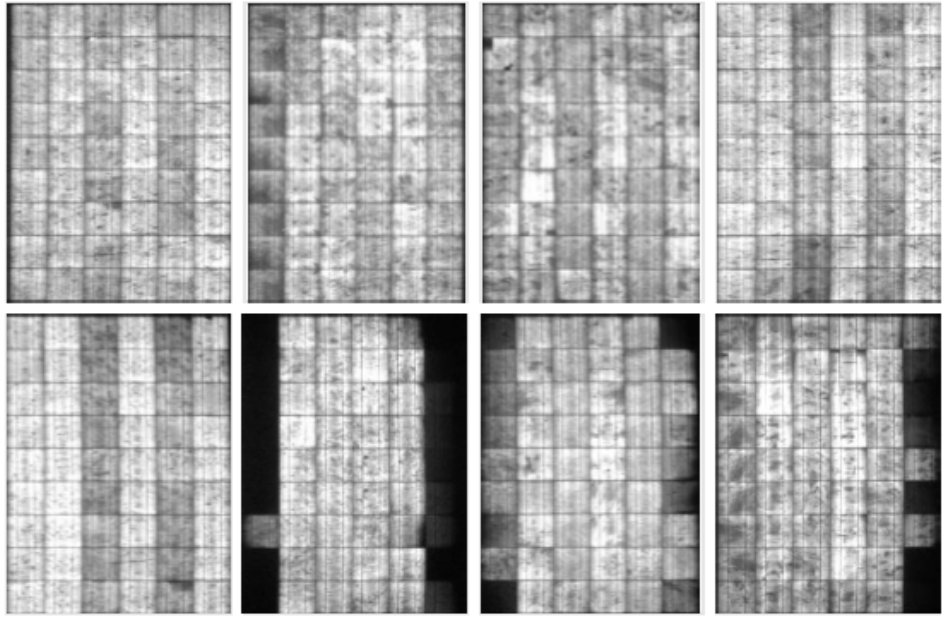


+

Positive End of String

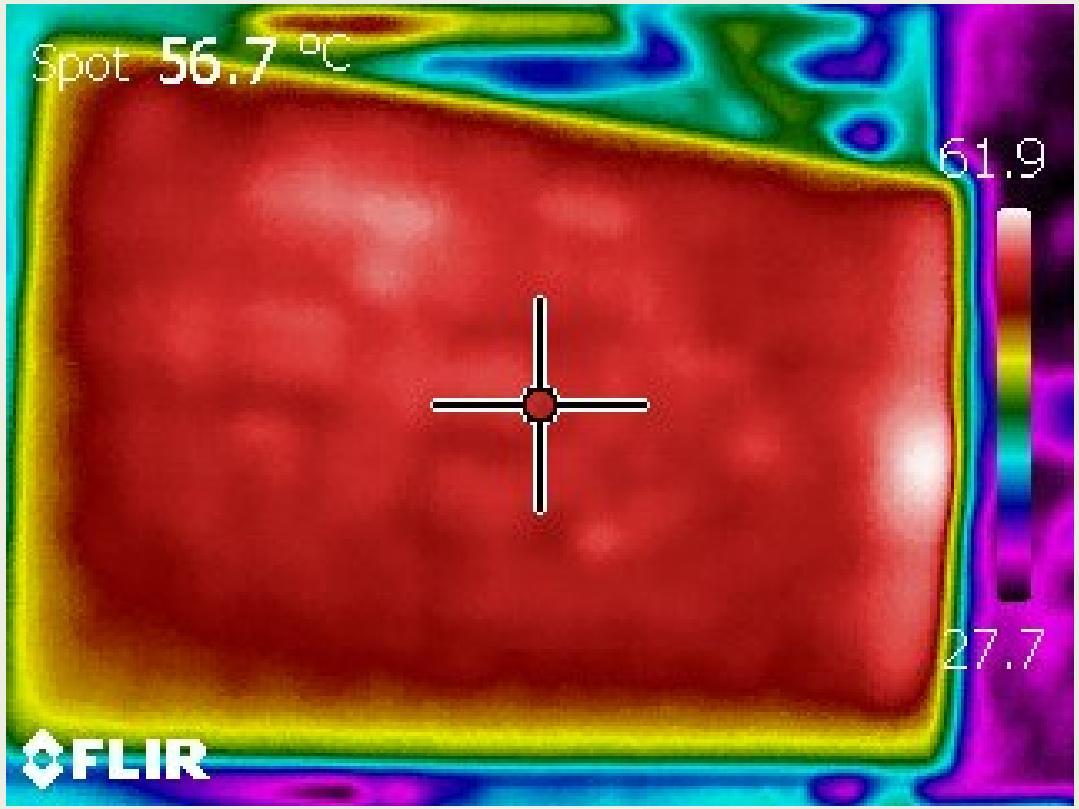
-

Negative End of String

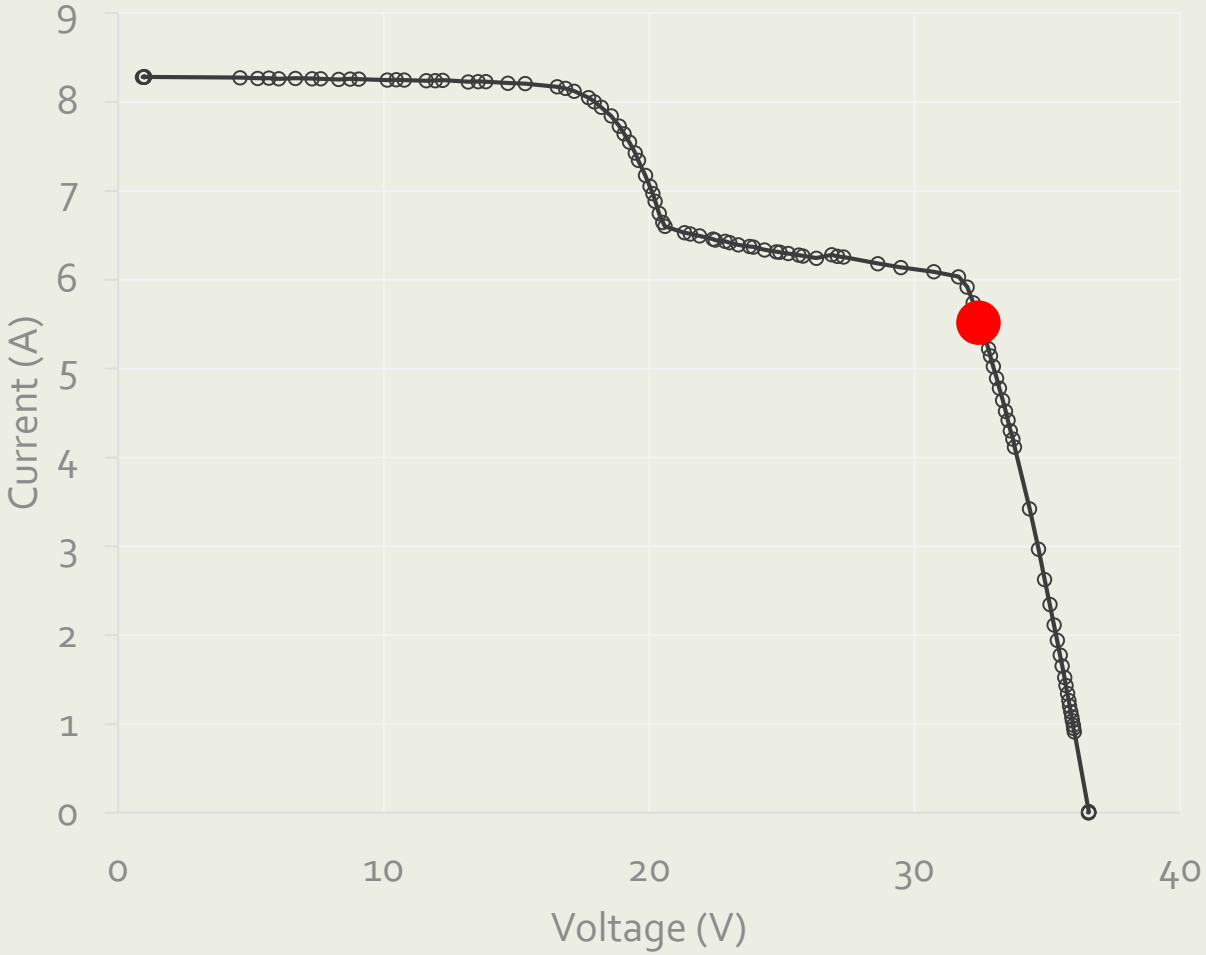


The two ends of a 24 Module String

SN: C201012230710, 60 cell, 2 busbar, multicrystalline silicon , 235 W nameplate



ΔT ≈ 0°C



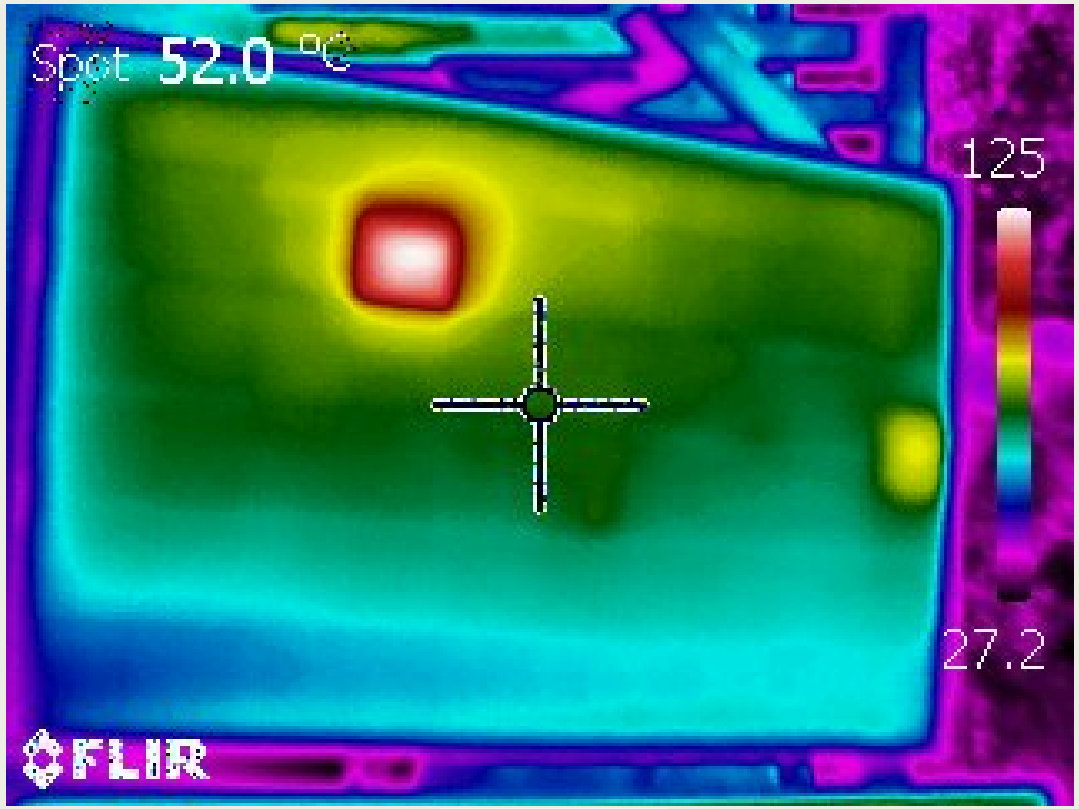
Module History:

Warranty return from a commercial rooftop.

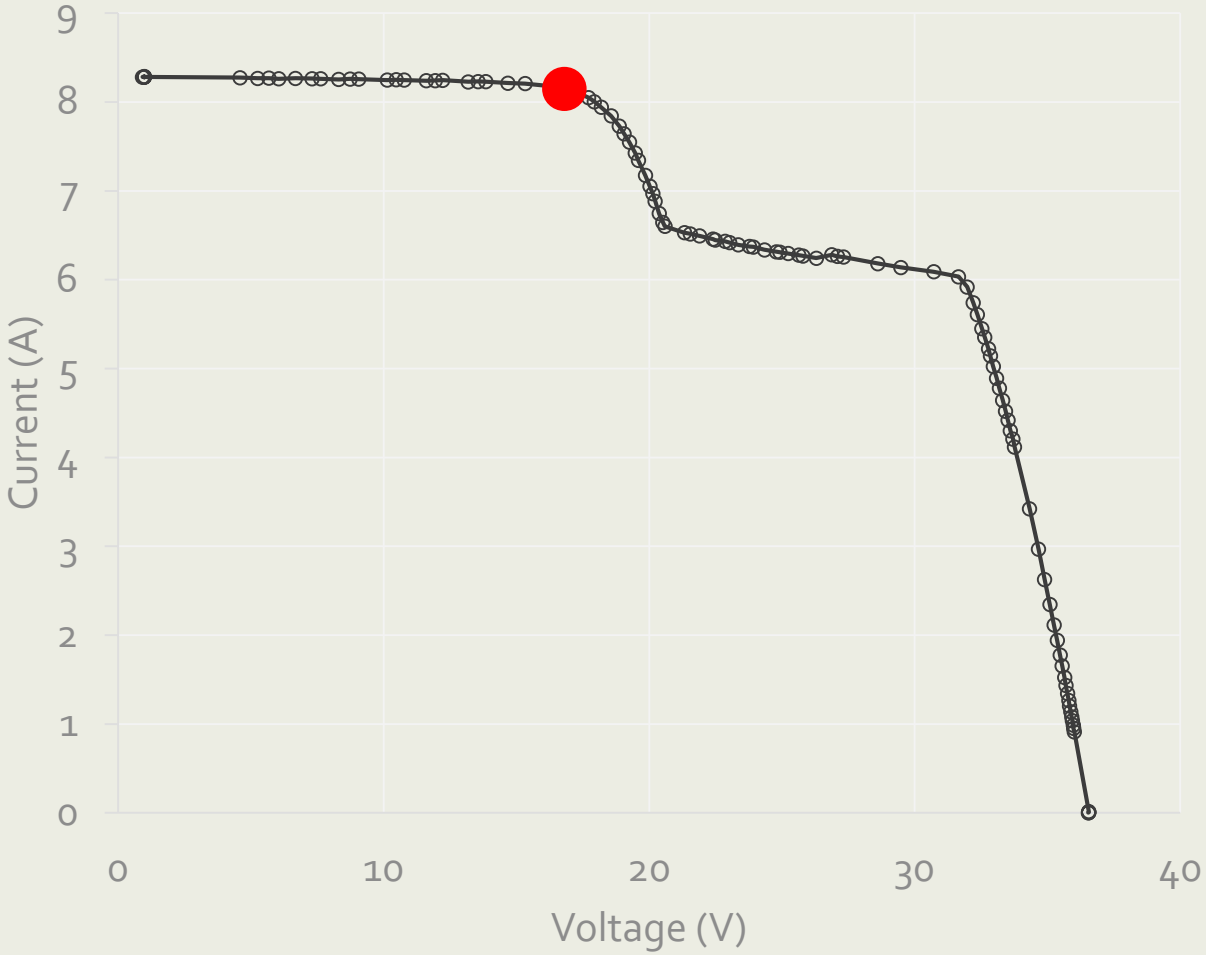
6 years in operation.

~20% Power loss at STC

SN: C201012230710, 60 cell, 2 busbar, multicrystalline silicon , 235 W nameplate



ΔT ≈ 66°C



Module History:

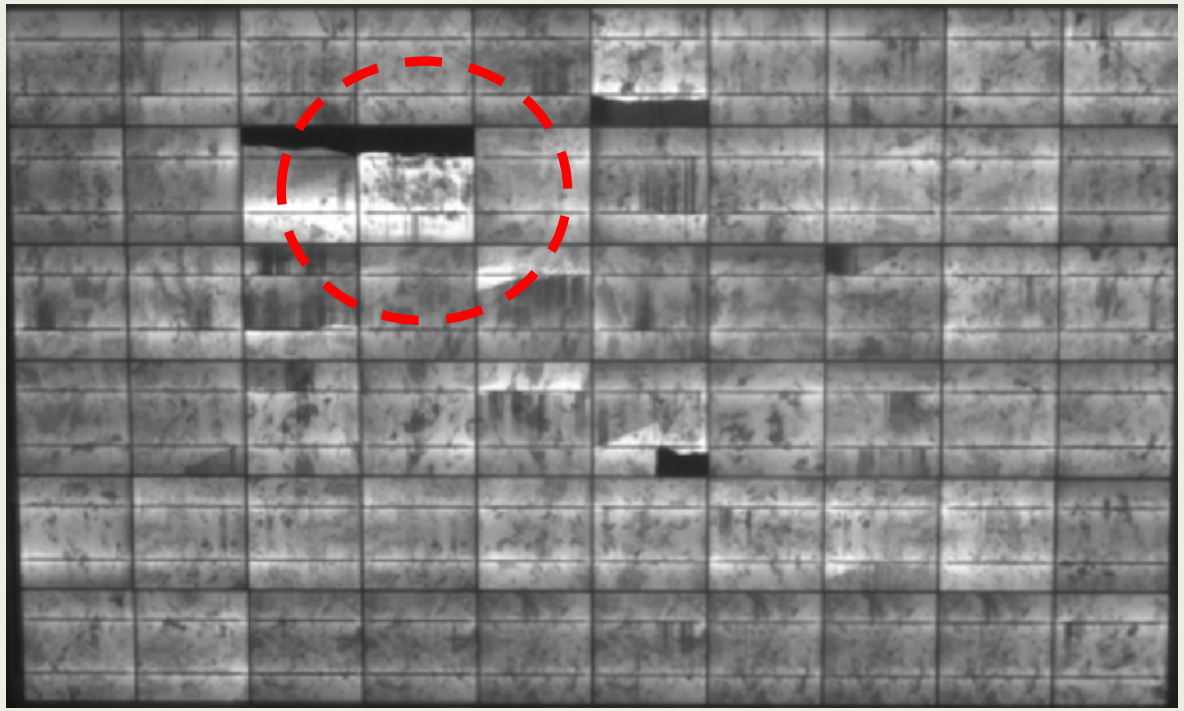
Warranty return from a commercial rooftop.

6 years in operation.

~20% Power loss at STC

SN: C201012230710, 60 cell, 2 busbar, multicrystalline silicon , 235 W nameplate

ΔT ≈ 70°C @ short-circuit



Module History:

Warranty return from a commercial rooftop.

6 years in operation.

~20% Power loss at STC

IR Imaging by Drone

Technical Details

Type of Drone: DJI Inspire 1, Version 2

Type of Camera: Zenmuse XT 30 Hz, 640x512

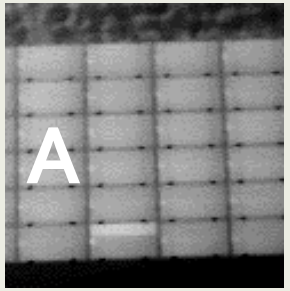
Flight Speed <10 mph; ~20-25 min per battery; winds < 20 mph

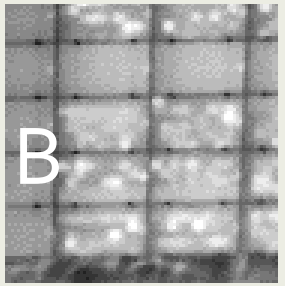
FAA UAS Remote Pilot license required for commercial work. Part 107 waiver required for operation in controlled airspace.

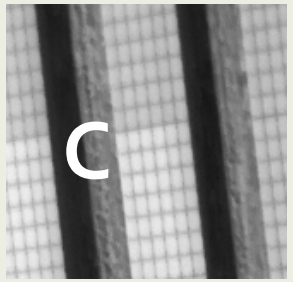
~ 9 minutes of flight time per MW (most time is spent in post flight analysis/interpretation)

Applicable to All Module Technologies

Irradiance >400 W/m^2 recommended.







NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Degradation rate case studies

PV Reliability Workshop

Lakewood, CO

Dirk Jordan, Mike Deceglie, Chris Deline, Tim Silverman, Teresa Barnes– NREL

Luo Wei – SERIS, Singapore

Rajiv Dubey – IIT Bombay, India

2/26/2019

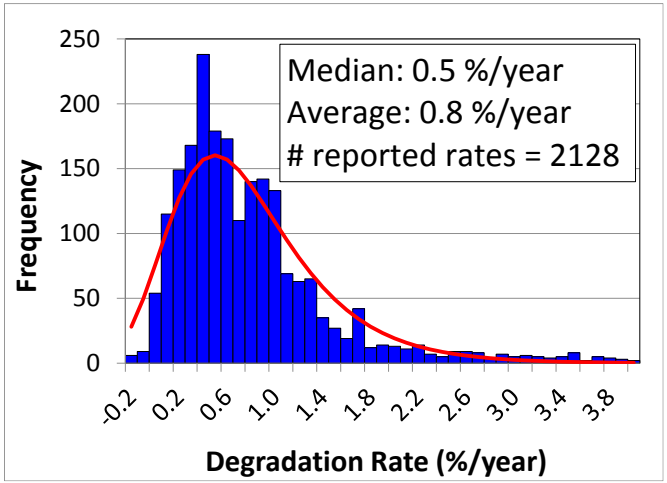
Outline

- Introduction
- Evaluation of field data
- Round-robin study
- Temperature & mounting
- High efficiency modules HIT & PERC
- Conclusion

Ageing is a reality of life!

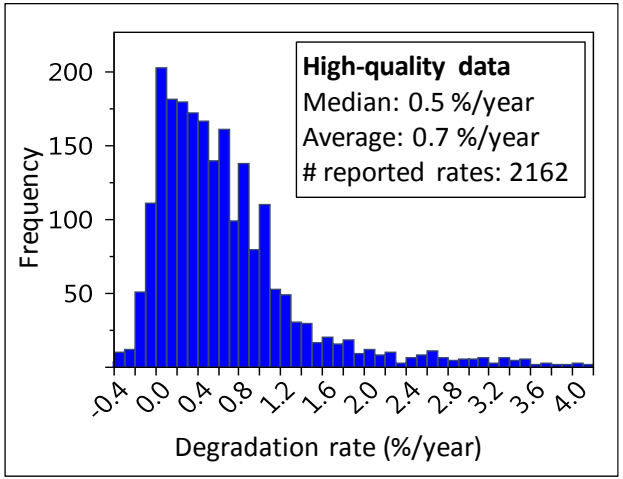
PV Degradation rates (R_d)

2011 – all data



D. Jordan et al., "Degradation Rates – An Analytical Review", Progress in PV, 2011

2016 – high quality data



D. Jordan et al., "Compendium of photovoltaic degradation rates", Progress in PV, 2016

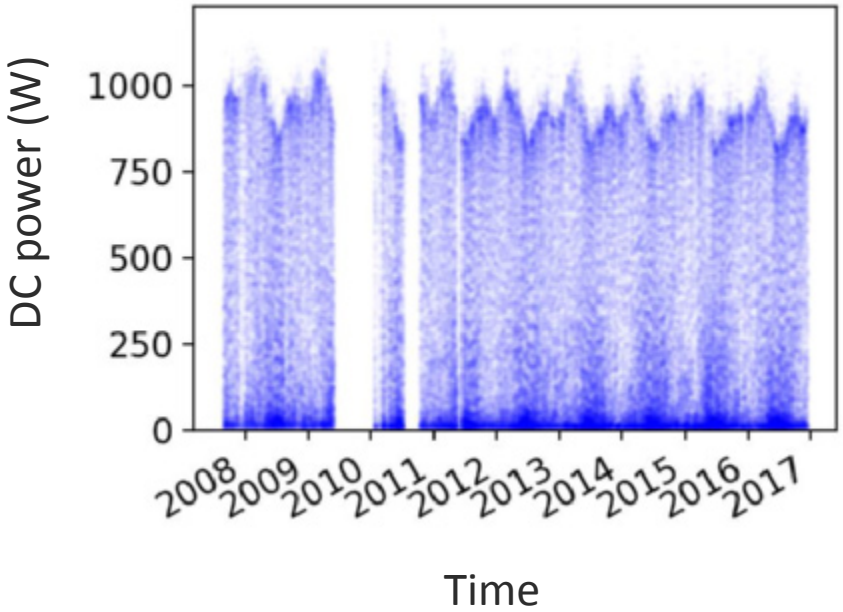
2016 contains > 11,000 data but a lot of data use questionable methods.

Natural gas turbines
0.3 – 0.6 %/year
(regular maintenance)
0.75 – 2 %/year
(unmaintained)*

*F. Brooks, GE report, 2000

R_d depends on factors such technology, module/installation quality, mounting, climate etc.

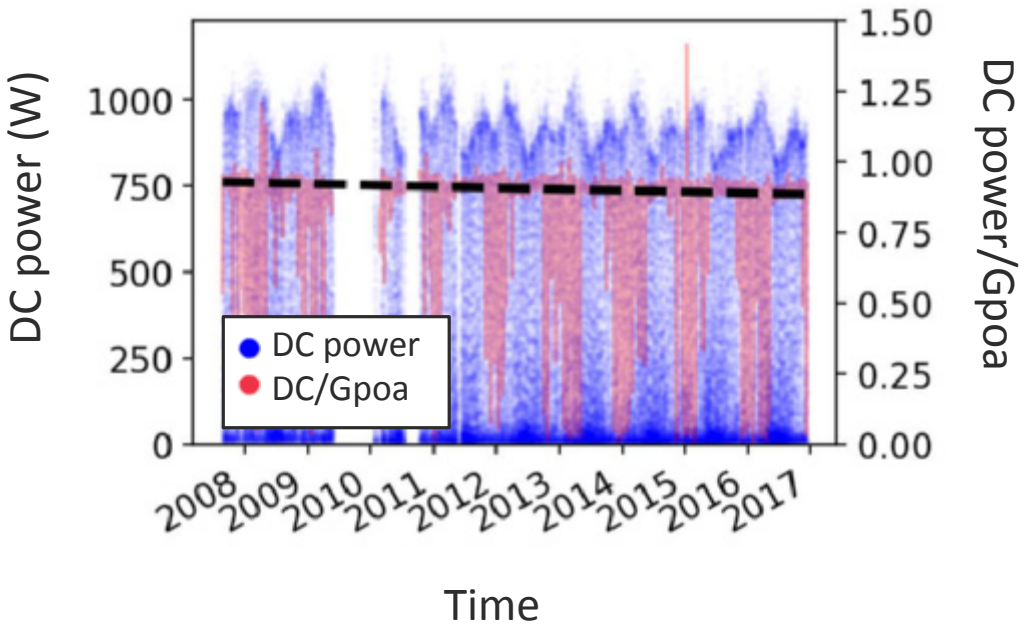
Evaluation of field data



x ± y %/year

(assuming linearity)

Evaluation of field data



x ± y %/year

(assuming linearity)

How do we do this?

Decision in evaluating field data

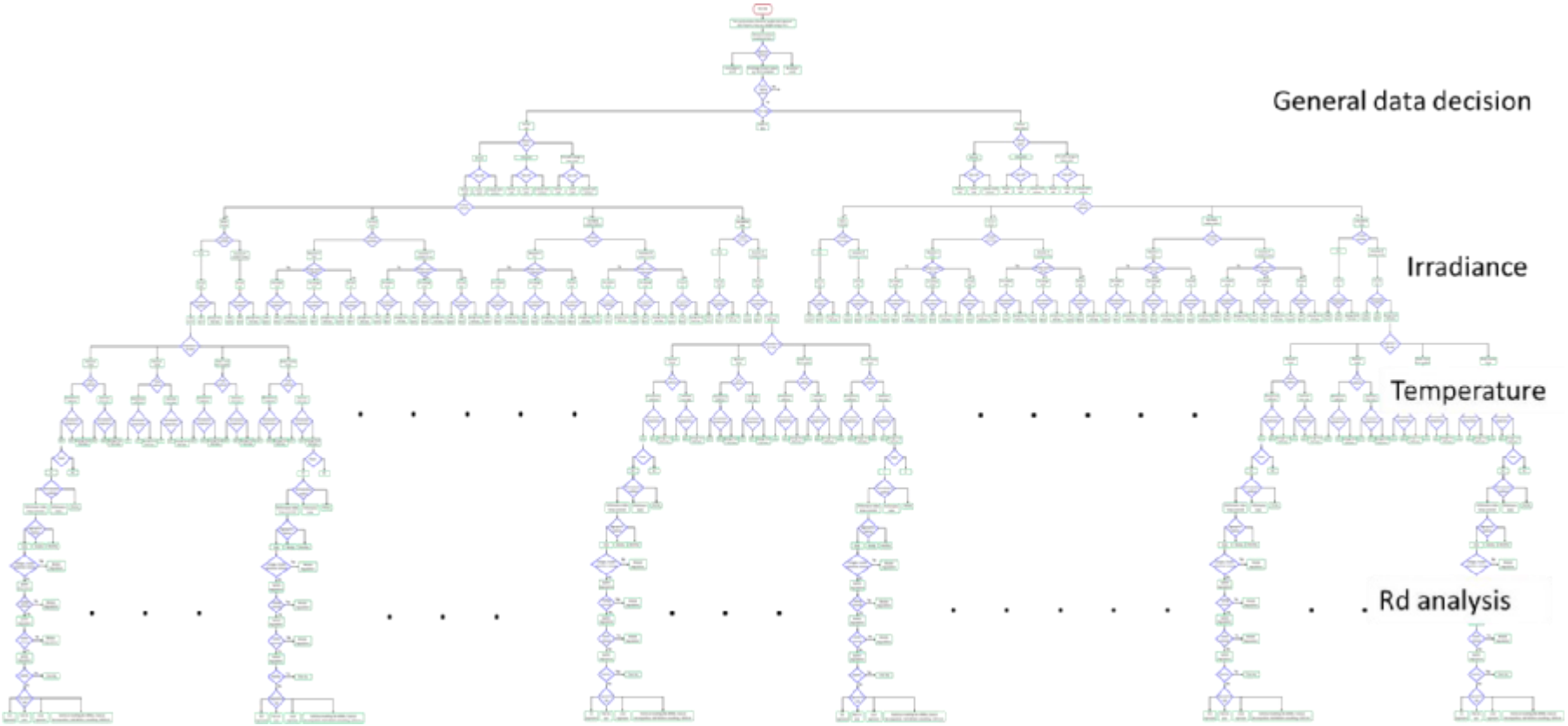
Data
Synchronization
Daylight savings
Alignment
Nighttime data
Full data set/subset
Inverter clipping
Missing data
Data shifts

Irradiance
Type of sensor
Calibration
Modeled/measured
Local weather station
Satellite data
Orientations POA/GHI
Multiple weather station
Normalization value (1000, 900..)

Temperature
Tamb/Tmod
Measured/modeled
Clearsky modeled
Temperature coefficient
Multiple weather station
Normalization value (25, 45..)

R_d method
Normalization
Aggregation interval
Outages/downtime
Soiling
Outliers
Stability
Regression/YOY
Machine learning

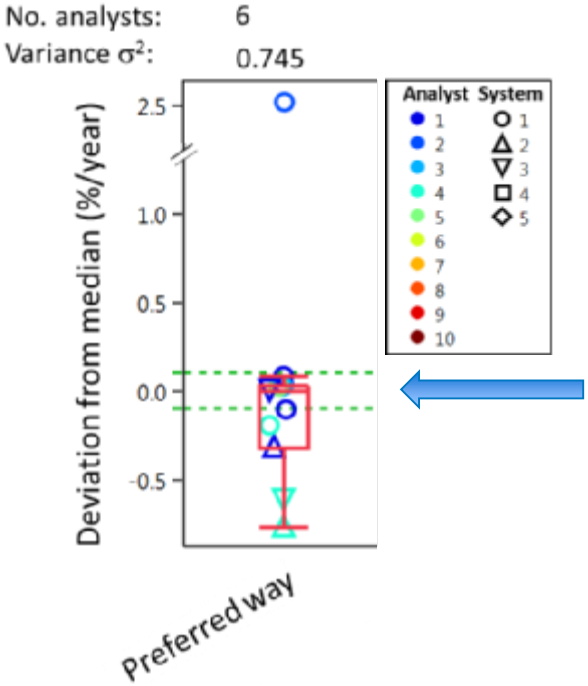
Why do 2 analysts come to different conclusions (same data)?



International round-robin study

Different analysts evaluated the same data

5 different systems,
15min increments (1 NREL system changed from 15min to 1min during fielded period)
Irradiance: Gpoa or GHI, some photodiodes, some pyranometers → possible sensor drift, translation to POA
Weather data: Tamb, Tmod, wind speed → contained issues
Soiling: some high soiling, some low soiling environment



Preferred way: different normalization, data filtering, sensors drift, soiling, temp. coefficients used by analysts. Based on linear regression!

"holy grail" of degradation rates, ±0.1 %/year

International round-robin study

Different analysts evaluated the same data

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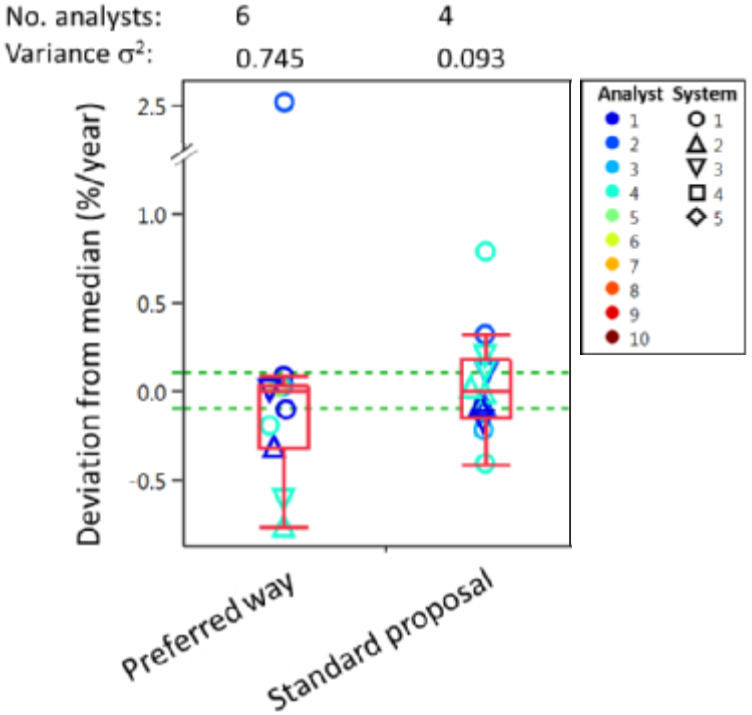

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Standard proposal: Relied on outlier & stability filter. Insufficient for sensor drift, soiling. Instructions had to be implemented by analyst. Based on linear regression!

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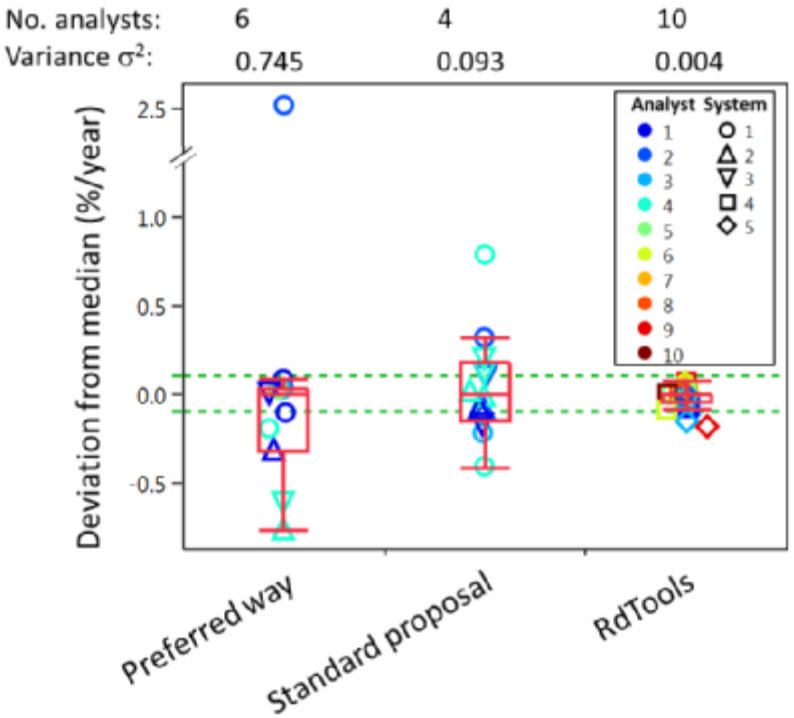


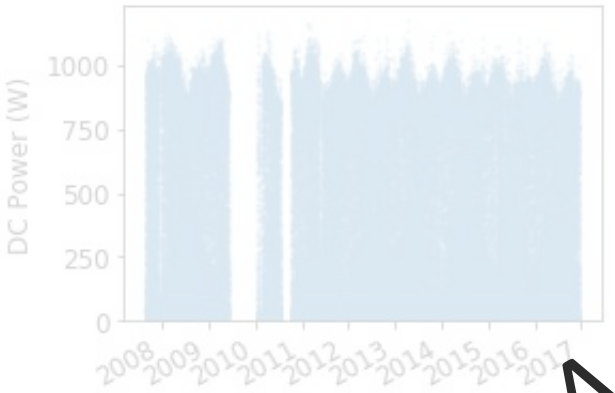
Preferred way: different normalization, data filtering, sensors drift, soiling, temp. coefficients used by analysts. Based on linear regression!

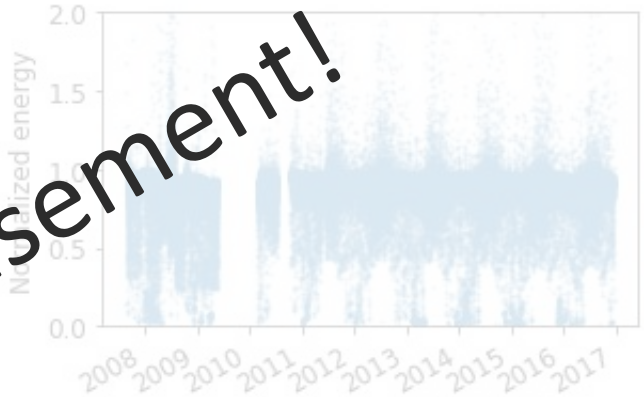
Standard proposal: Relied on outlier & stability filter. Insufficient for sensor drift, soiling. Instructions had to be implemented by analyst. Based on linear regression!

RdTools: Software provided, provides guidance, robust to sensor drift, seasonal soiling,
Based on year-on-year approach!

Reduced variations between analysts by 2+ orders of magnitude

RdTools





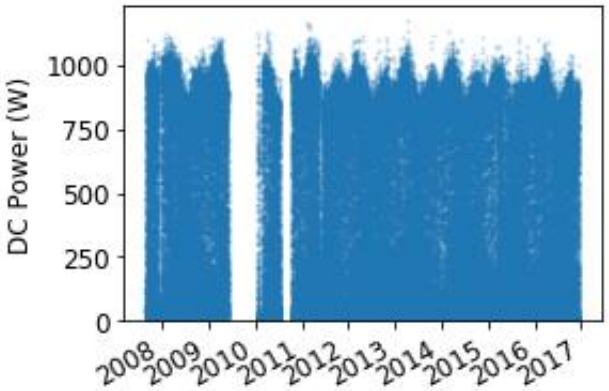
$$P = P_0 \frac{G_{POA}}{G_0} (1 + \gamma(T_{cell} - T_0))$$

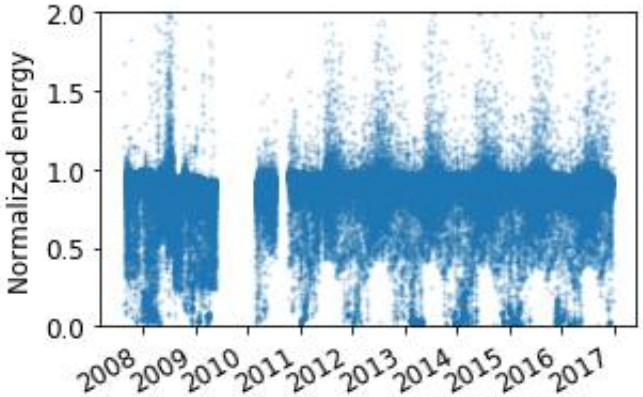
- Input: PV energy, irradiance, cell temperature (modeled or measured)
- Use a simple irradiance and temperature model to calculate normalized high-frequency performance index
- Frequency mismatch between weather and energy is automatically handled by RdTools

Dobos, NREL, Tech. Rep., 2014

Warning: Advertisement!

1. Normalization - sensor





$$P = P_0 \frac{G_{POA}}{G_0} \left(1 + \gamma(T_{cell} - T_0)\right)$$

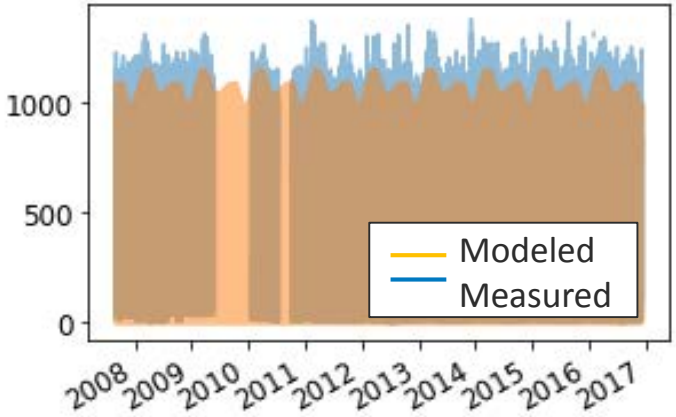
- Input: PV energy, Irradiance, cell temperature (modeled or measured)
- Use a simple irradiance and temperature model to calculate normalized high-frequency performance index
- Frequency mismatch between weather and energy is automatically handled by RdTools

Dobos, NREL, Tech. Rep., 2014

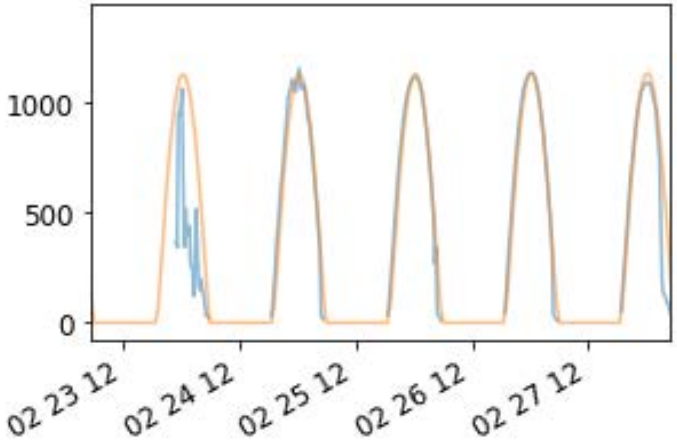
1. Normalization - clearsky

Plane of array irradiance (Gpoa)

Seasonality pattern



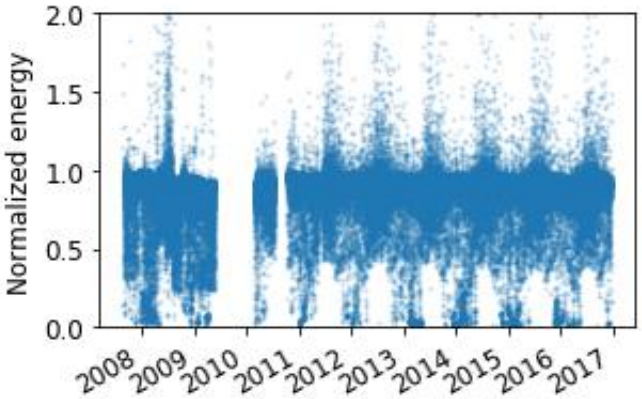
Good fit between measured & modeled Gpoa

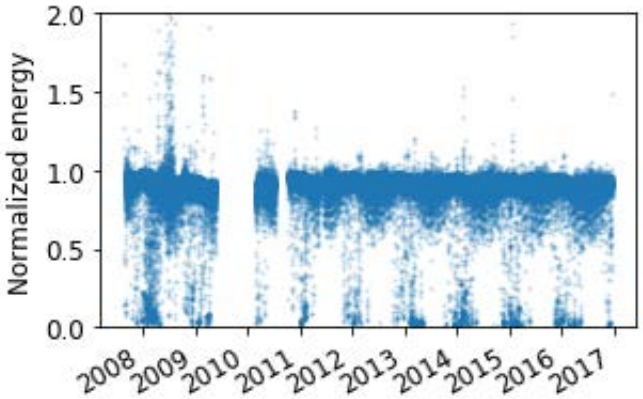


Use modeled irradiance to normalize, not the measured irradiance

Holmgren et al., PVSC, 2015.
Jordan et al., JPV, 2017

2. Filter





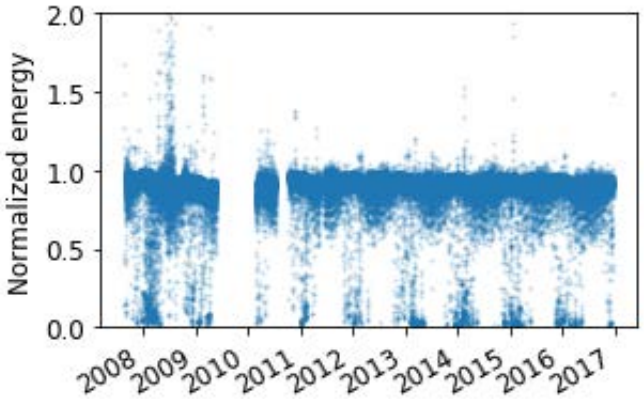
Minimally filter out data:

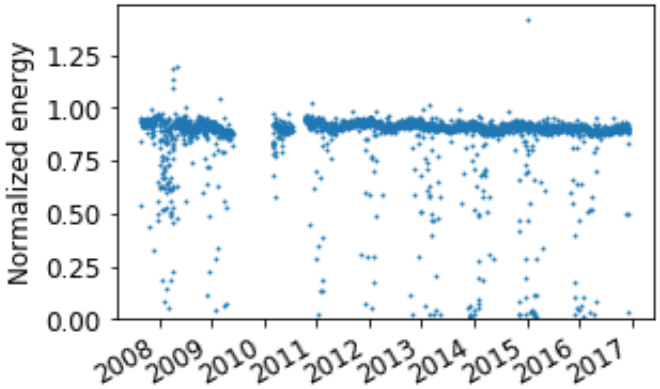
1. Power ≤ 0
2. Irradiance <1200 and >200 W/m2
3. $T_{cell} < -50°C$ and $T_{cell} > 110°C$
4. Power is <99% of capacity

For clearsky method:

Clearness index (measured/modeled Gpoa) > 0.85 and < 1.15

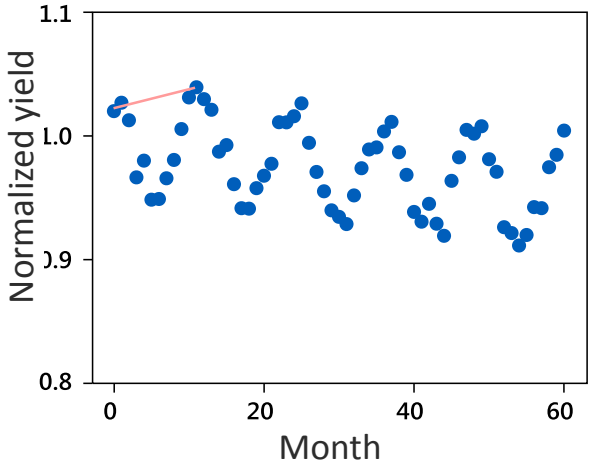
3. Aggregate





Typically use daily irradiance-weighted performance index

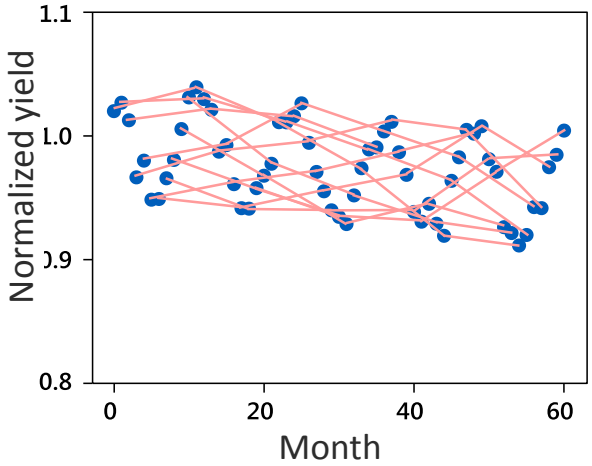
4. Year-on-year

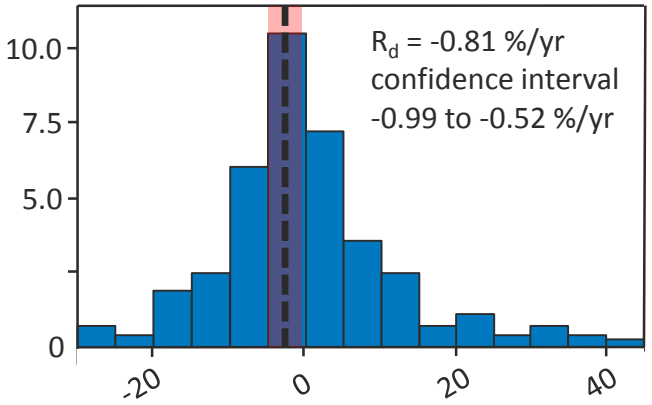


- Year-on-year is robust to seasonality, outliers, soiling, sensor drift
- Steps:
  - Compare each day (or week, month, etc.) to its corresponding day (week, month) a year later

Hasselbrink et al., PVSC, 2013
Jordan et al., PVSC, 2016

4. Year-on-year





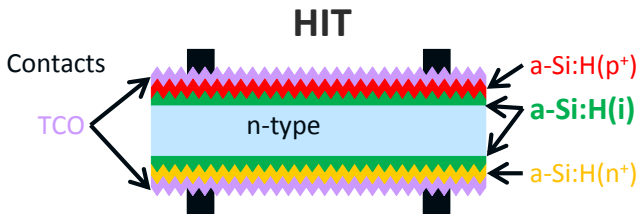
- Year-on-year is robust to seasonality, outliers, soiling, sensor drift
- Steps:
  - Compare each day (or week, month, etc.) to its corresponding day (week, month) a year later
  - Calculate the median of all year-on-year slopes
- Confidence interval from bootstrap method

Hasselbrink et al., PVSC, 2013
Jordan et al., PVSC, 2016

Case study 1: HIT degradation in V_{oc}

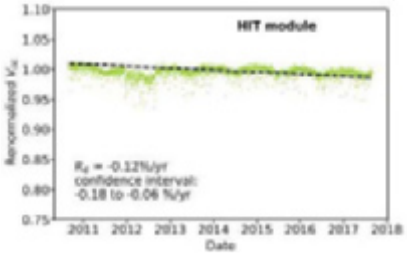
Mono-Si cell with a-Si layer

HIT (heterojunction with intrinsic thin layer)



Japan

Singapore



Historically: x-Si degradation is split between I_{sc} (short-circuit current) and FF (fill factor)

Typically no or minimal loss in V_{oc} (open-circuit voltage) → indicative that cells are changing

Jordan et al. JPV, 2018.

Ishii et al., *Prog. in PV* 2017

Luo et al. JPV, 2018.

HIT installations

Dessert Knowledge Center, Australia

Location: **Australia**
Climate: **desert**
Mounting: **rack**
Size: 6.3 kW
Mar-2010

California

Location: **California**
Climate: **moderate**
Mounting: **roof**
Size: 450 kW
Dec-2010

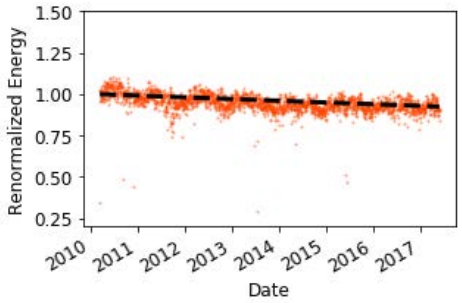
NREL, OTF

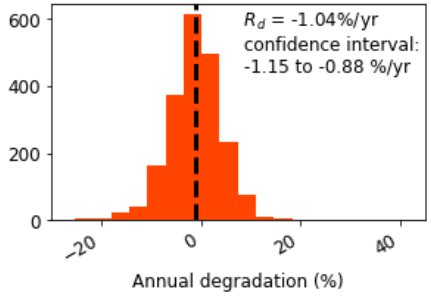
Location: **NREL**
Climate: **moderate**
Mounting: **rack**
Size: 1.0 kW
Sep-2007

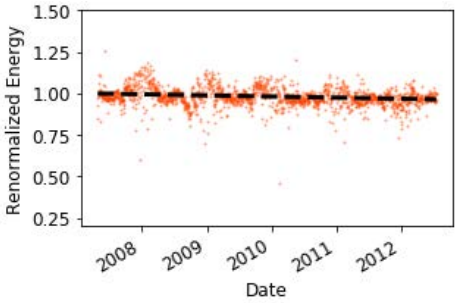
NREL, Mesa site

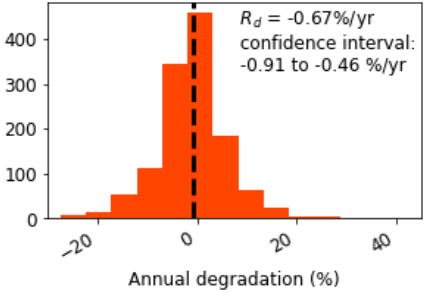
Location: **NREL - Mesa**
Climate: **moderate**
Mounting: **1-axis**
Size: 720.7 kW
Installation date: Dec-2008

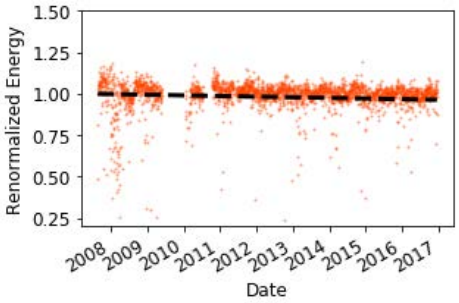
Clearsky analysis results

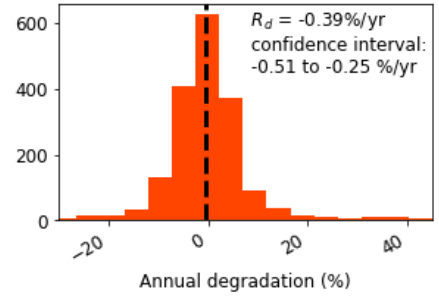


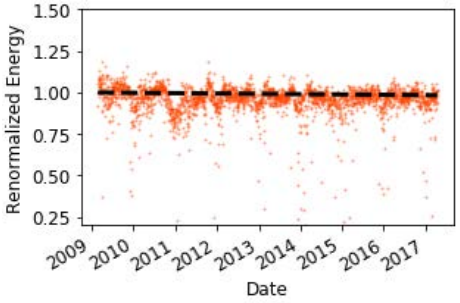


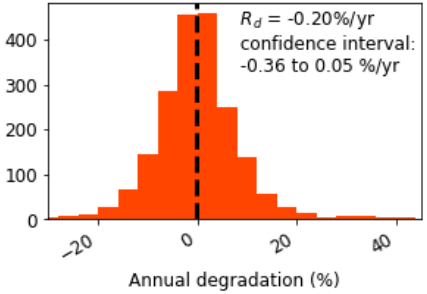












Location: **Australia**
Climate: **desert**
Mounting: **rack**
Size: 6.3 kW
Mar-2010

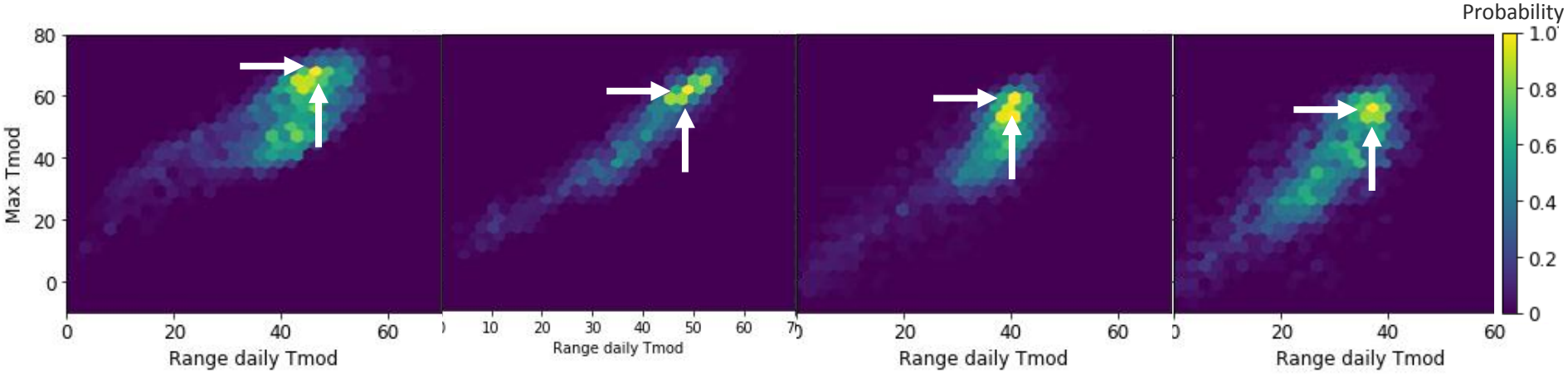
Location: **California**
Climate: **moderate**
Mounting: **roof**
Size: 450 kW
Dec-2010

Location: **NREL**
Climate: **moderate**
Mounting: **rack**
Size: 1.0 kW
Sep-2007

Location: **NREL - mesa**
Climate: **moderate**
Mounting: **1-axis**
Size: 720.7 kW
Installation date: Dec-2008

Comparing temperature from 4 different systems

Daily ΔTmod vs. Tmod,max



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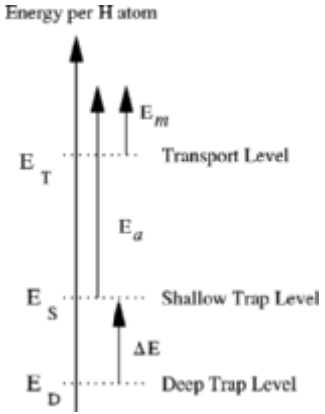
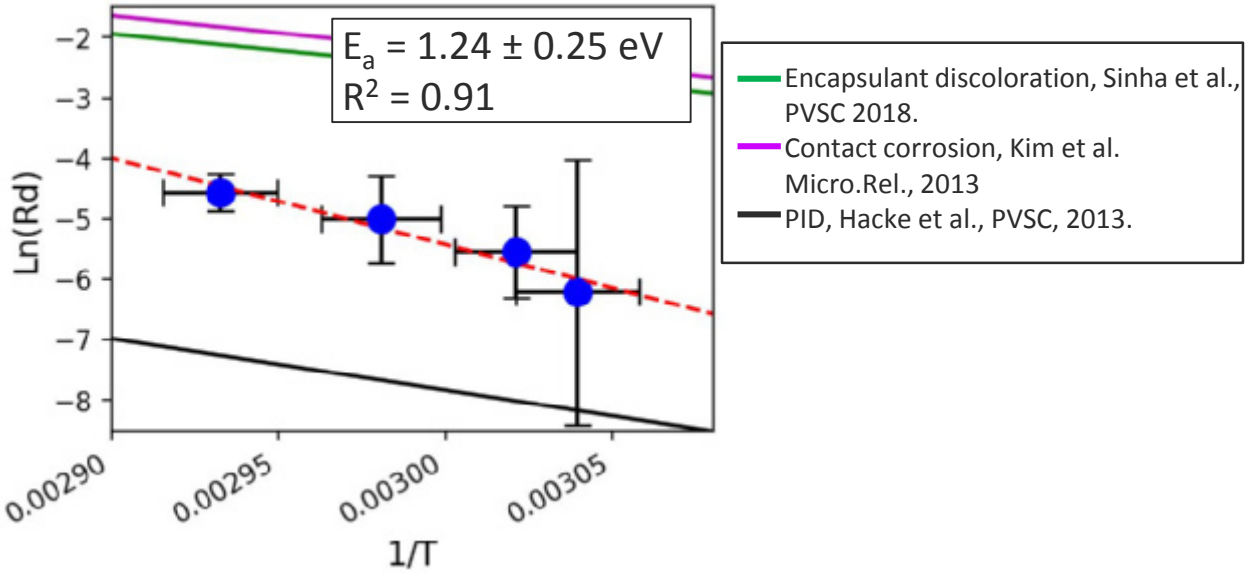
Activation energy of degradation mechanism

Long-range H diffusion in a-Si



(Stretched Si-Si bonds)

(Dangling Si bonds)



Ea=**1.54 eV**, ab initio calculations, Tuttle et al., Phys.Rev.B, 1998
Ea=**1.4-1.6 eV**, experimental, Kakalios, 1991
Ea is lower for p-doped a-Si, De Wolf, J.Appl.Phys, 2009

The extracted activation energy points towards passivation degradation

Activation energy of degradation mechanism

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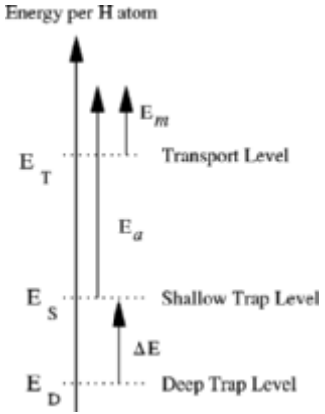

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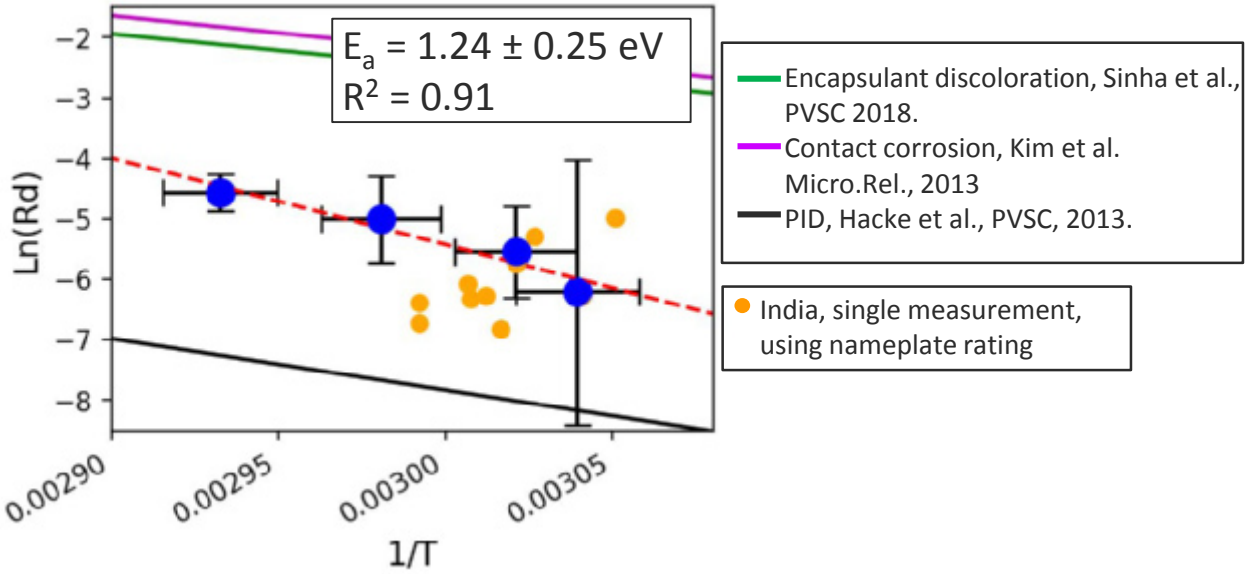

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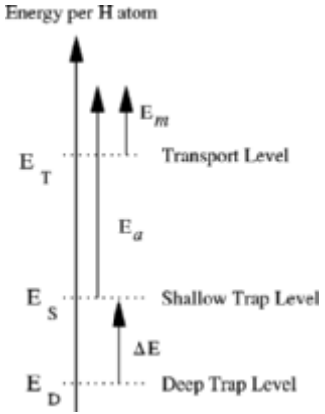

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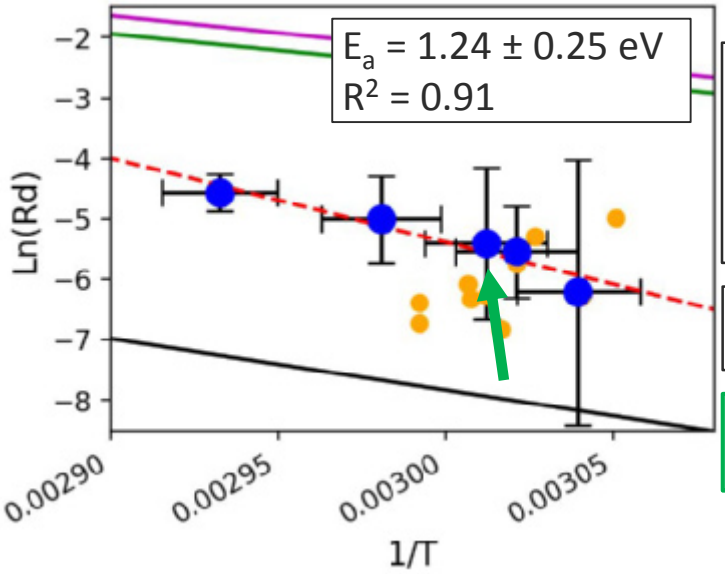


Encapsulant discoloration, Sinha et al., PVSC 2018.

Contact corrosion, Kim et al. Micro.Rel., 2013

PID, Hacke et al., PVSC, 2013.

India, single measurement, using nameplate rating

Single module: roof-mounted, hot & humid climate

Ea=**1.54 eV**, ab initio calculations, Tuttle et al., Phys.Rev.B, 1998

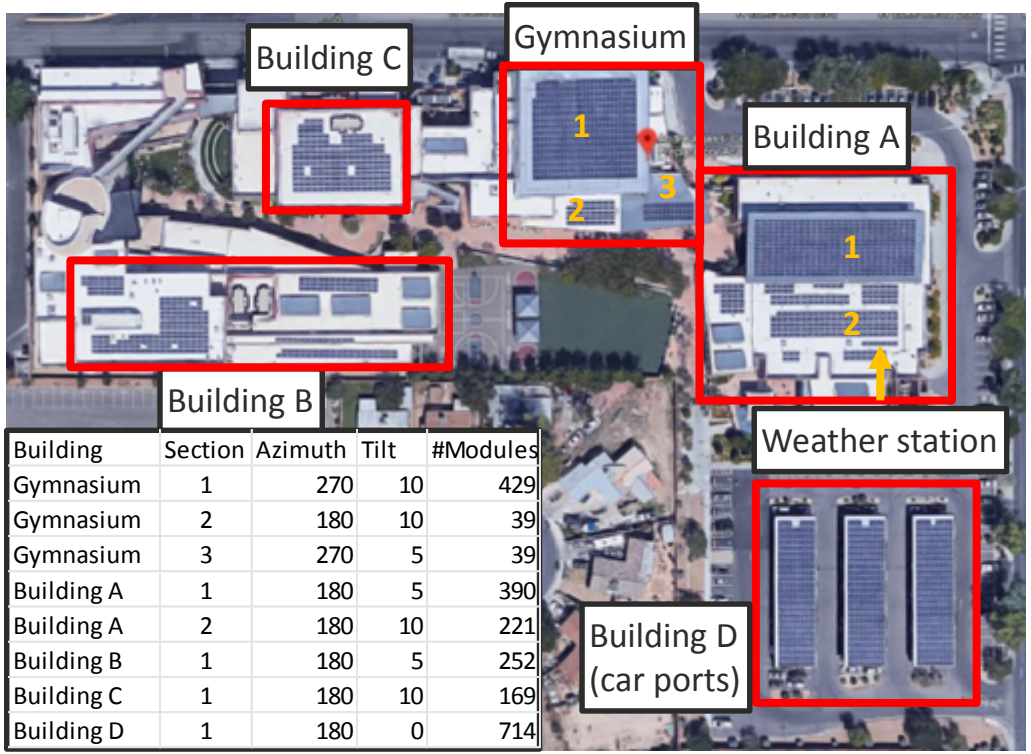
Ea=**1.4-1.6 eV**, experimental, Kakalios, 1991

Ea is lower for p-doped a-Si, De Wolf, J.Appl.Phys, 2009

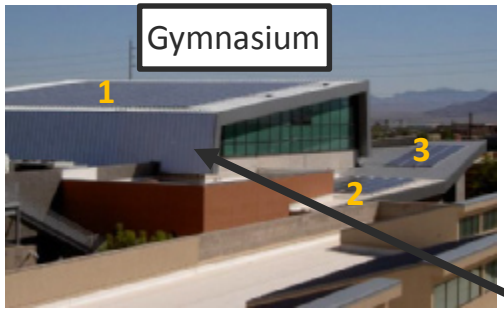
The extracted activation energy points towards passivation degradation

Case study 2: Andre Agassi Preparatory Academy, Las Vegas

Same modules different mounting → different degradation



Building	Section	Azimuth	Tilt	#Modules
Gymnasium	1	270	10	429
Gymnasium	2	180	10	39
Gymnasium	3	270	5	39
Building A	1	180	5	390
Building A	2	180	10	221
Building B	1	180	5	252
Building C	1	180	10	169
Building D	1	180	0	714



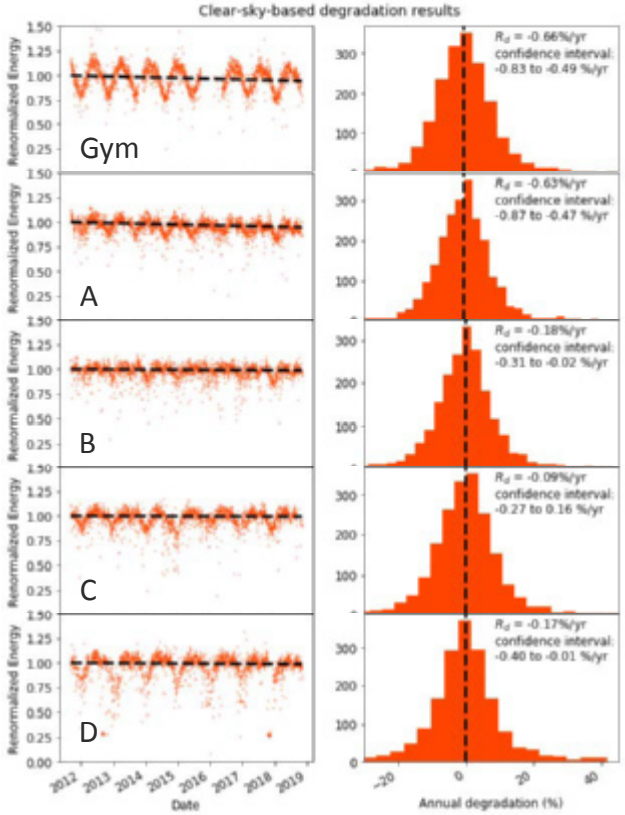
Metal roof

Thermoplastic polyolefin coated roof

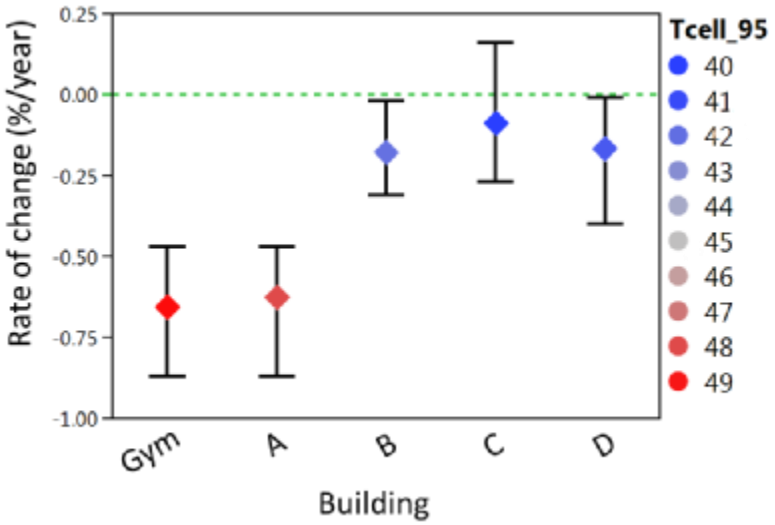
- Same modules, mono-Si (Al-BSF), different mounting configurations
- Desert location
- 8 years of continuous data

Hotter mounting configurations show higher degradation

Irradiance sensor is uncalibrated photodiode & drifting → need to use clearsky approach



Overall degradation fairly moderate given the desert location & mounting
2 buildings with large metal roof sections show higher degradation



(1) $ECT = 25C + \frac{1}{\beta}\left[\frac{V_{mp,2}}{V_{mp,STC}} - 1 - a \cdot ln\left(\frac{G_2}{1000}\right)\right]$ IEC 60904-5

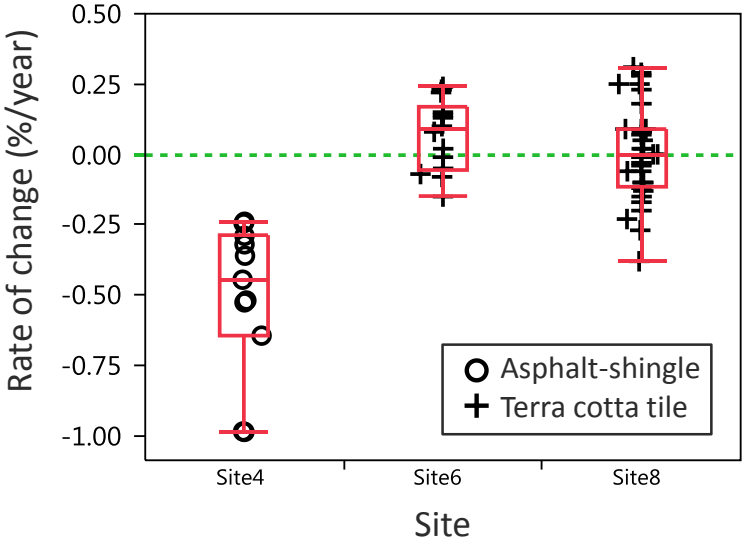
(2) $T_{cell} = T_{amb}(time) + c \cdot G_{poa}(time) \cdot [1 - PR(time)]$

Have to filter for thermal stability, clear days, middle of the day →
Max daily temperature for building A is ca. 4° higher than building C.

Degradation rates in line with historical values, especially considering desert location

Case study 3: Microinverter degradation data

Same location Phoenix, AZ
Same modules from the same manufacturer
Same field exposure, ca. 4 years
Similar roof stand-off distance

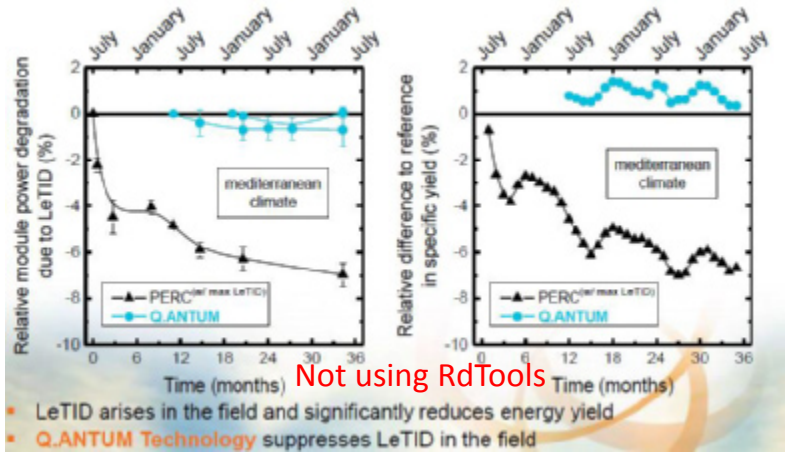


Climate & mounting (rack vs. roof) may not be sufficient to understand field performance
Need more details on mounting & temperature

Case study 4: PERC field performance

Passivated emitter & rear cell (PERC)

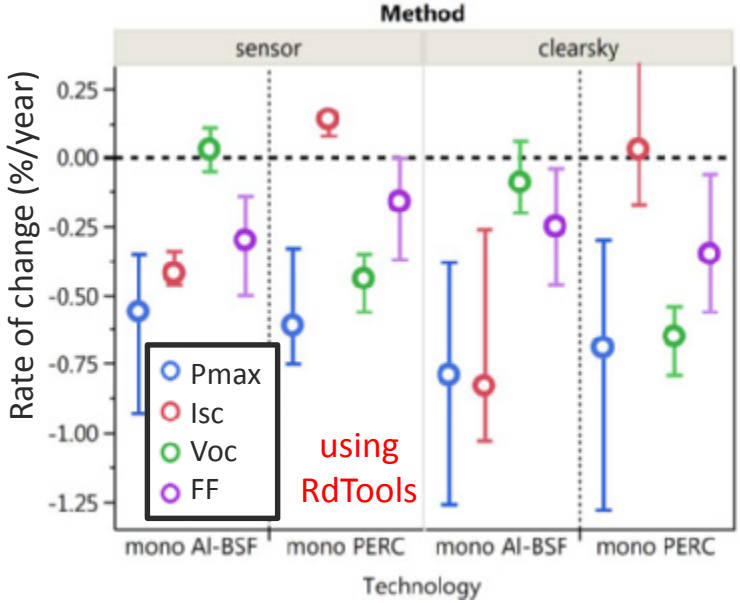
LeTID can have significant impact on energy yield
(light & elevated temperature induced degradation)



Slide from Fertig et al., Hanwha Qcells, Si workshop, 2016.

Some products may be more susceptible to LeTID than others

mono Al-BSF vs. mono PERC at NREL



Sensor & clearsky are 2 different methods in RdTools

Side-by-side comparison, same manufacturer (not Hanwha Qcells)
Used "RdTools" open-source software to analyze, 2 years of data
Similar degradation rates in the 0.5 -0.8 %/year
Al-BSF degradation is dominated by Isc & FF losses, no Voc loss
PERC degradation dominated by Voc

Side-by-side comparison PERC, Al-BSF shows similar behavior but indicating different mechanisms

Summary

- Open-source software RdTools helped to improve consistency in evaluating field data by 2 orders of magnitude.
- Evaluations of HIT module type installations are consistent with indoor characterization and passivation layer degradation.
- PERC module from 1 manufacturer shows similar R_d as Al-BSF module but indicates different degradation mechanism.
- Exact mounting configuration appears to play a large role in degradation. We need more detailed description, such as stand-off distance, roof type etc.

Acknowledgments

Thank you

Reliability group, Greg Kimball, Adam Shinn,
Ambarish Nag, Jim John, Jim John, Aaesha Alnuaimi, Ammar Elnosh, Wei Luo, Anubhav Jain, Mashad U. Saleh, Heidi von Korff, Yang Hu, Jean-Nicolas Jaubert, Sylvia Gao, Fotis Mavromatakis, Sarah Kurtz, Robert Flottenmesh, Didier Thevenard, Jeff Newmiller, Frank Vignola, Roger French

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NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Photovoltaic & Advanced Materials

February 26, 2019

Material Degradation Impacting Performance of PV Modules in the Field

Kaushik Roy Choudhury & DuPont PV Reliability

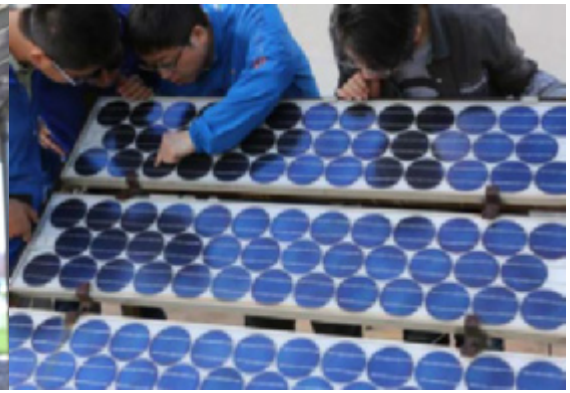
2019 PV Reliability Workshops, Lakewood, CO

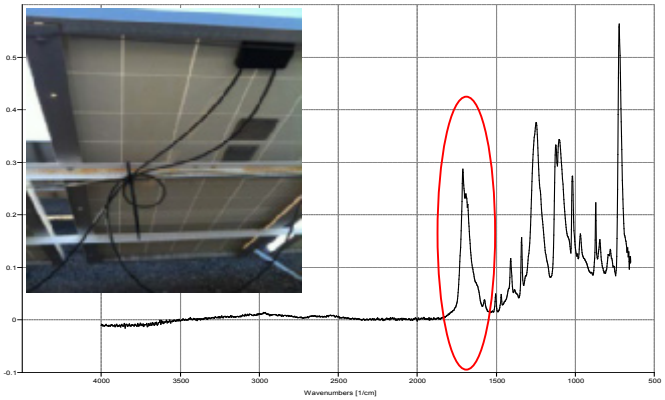
Will PV modules perform for ~~25~~ 30+ years?

Expectation: All PV modules need to meet claims for degradation and performance over lifetime

- Industry focused on **nominal degradation rates** and **initial capital expenses** (CAPEX) as key metrics
- **Unanticipated Operational Expense** (OPEX) can have greater financial impact than degradation rates
  - Studies have shown modules having performance issues related to field
- Reluctance to acknowledge, learn from and act upon field failures
- "design & build" to "operate & maintain"
  - Improved understanding of system performance as a result of OPEX is required to obtain reliable economic assessments
  - **Understanding of durability issues through field analysis** will lead to more accurate LCOE models and deeper understanding of system economics

DuPont Global Field Reliability Program



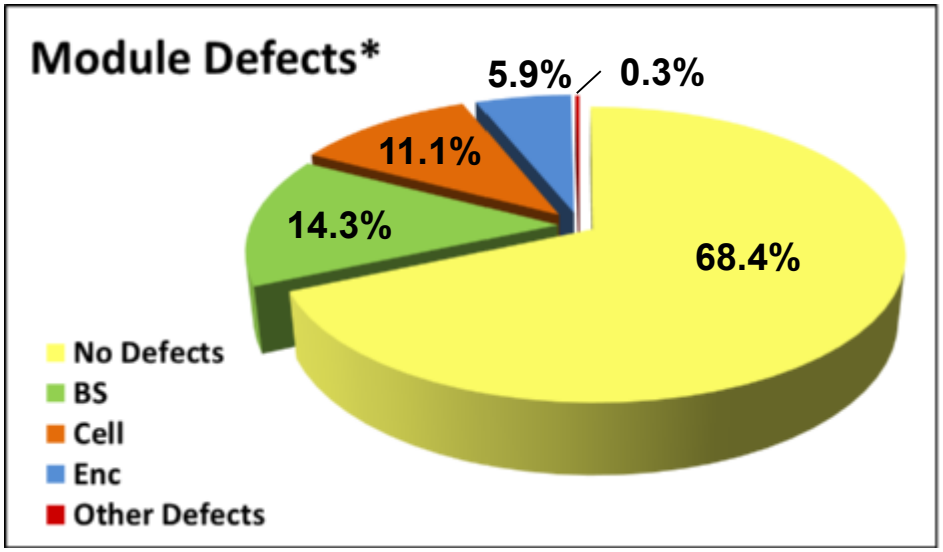


Run since 2011 to **inspect, assess, gather data and understand the performance and material degradation of fielded PV modules** of different ages, having a variety of Bill Of Materials, and from different geographies and climates over North America, Europe, Asia and Middle East

- Comprehensive survey of module and component degradation
- Multi-step inspection protocol
- Statistical analysis of data by climate, component, material, mounting, age
- Modules selected for extensive post-inspection analytical characterization
- Collaboration with field partners, customers, downstream developers

2019 Global Field Data Analysis Summary

Highlights	2019
North America, Europe, Middle East, Asia/Pacific	
Installations	322
# of panels (million)	6.1
# of module makers	102
Age range (yrs)	1 to 33
Average age (yrs)	3.7
GW	1.8



* Actual module defects can be higher due to defects not picked up by inspection protocol (eg. cell cracking evidenced by EL, PID)

Defect types

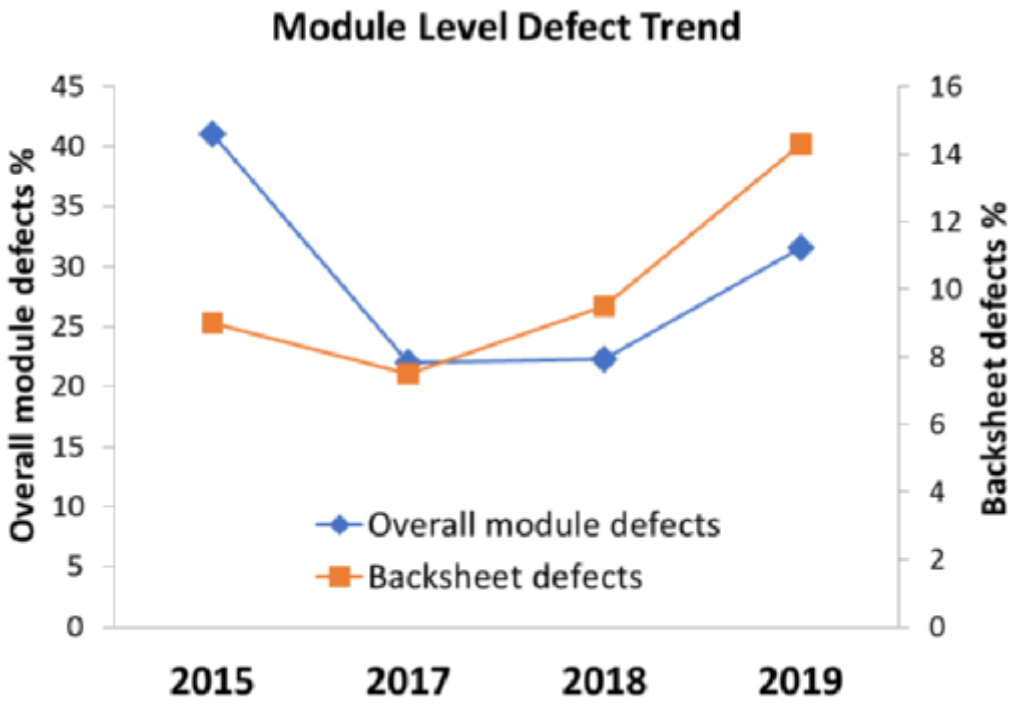
Cell/interconnect: corrosion, hot spot, snail trails, broken interconnect, cracks, burn marks

Backsheet: cracking, delamination, yellowing, inner layer cracking

Encapsulant: discoloration, browning, delamination

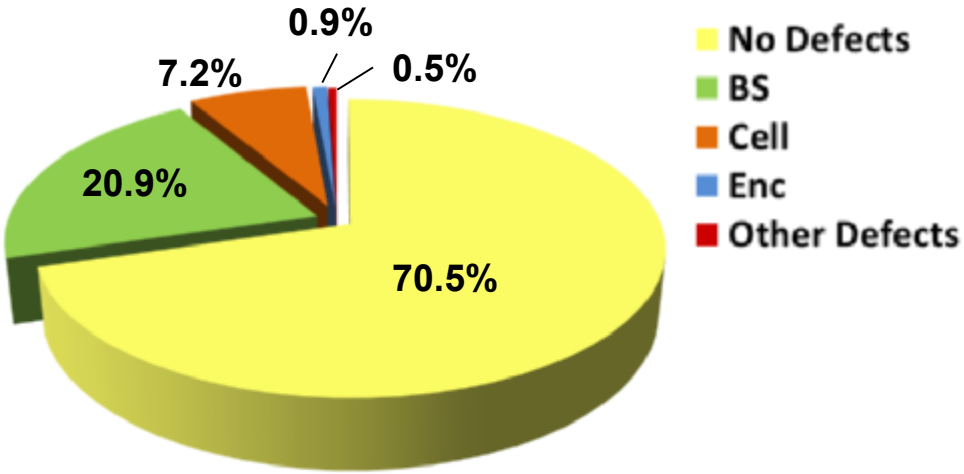
Others: glass defects, loss of AR coating, junction box

Defect Trends



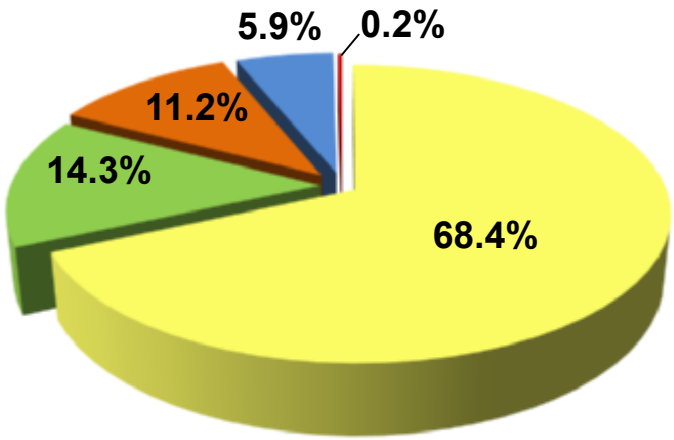
- Total module defects 31.6%; backsheet defects 14.3%
- YOY: Total module defects increased by 41.7%; backsheet defects increased by 48%
- Polymer defects: hot > tropical > temperate climate

Effect of Mounting Systems



Roof Mounted Installations*(21 MW)

*limited data from 70+ installations



Ground Mounted Installations (1739 MW)

Overall similar defect rates for Roof vs Ground installations

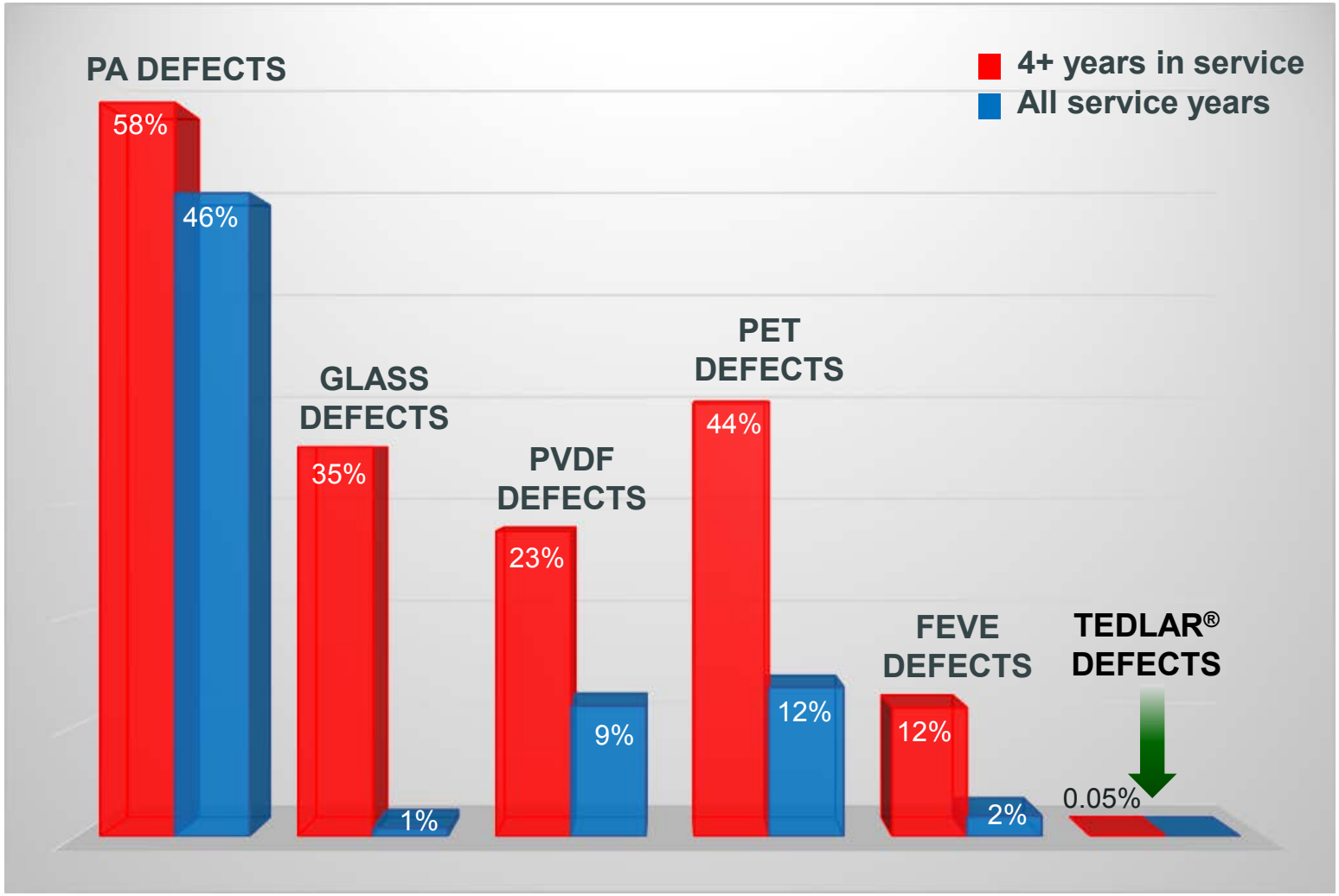
- Backsheet defects rates are 50% higher on Roof systems
- Cell defects are similar for Roof and Ground

Differences are likely due to higher temperatures for roof systems

- Roof Systems are typically 15°C higher than Ground Mounted[1]
- This trend with temperature is similar to the effect seen in climates

1 Creep in Photovoltaic Modules: Examining the Stability of Polymeric Materials and Components (2010) 35th IEEE Photovoltaic Specialists Conference (PVSC '10) Honolulu, David C. Miller, Michael Kempe

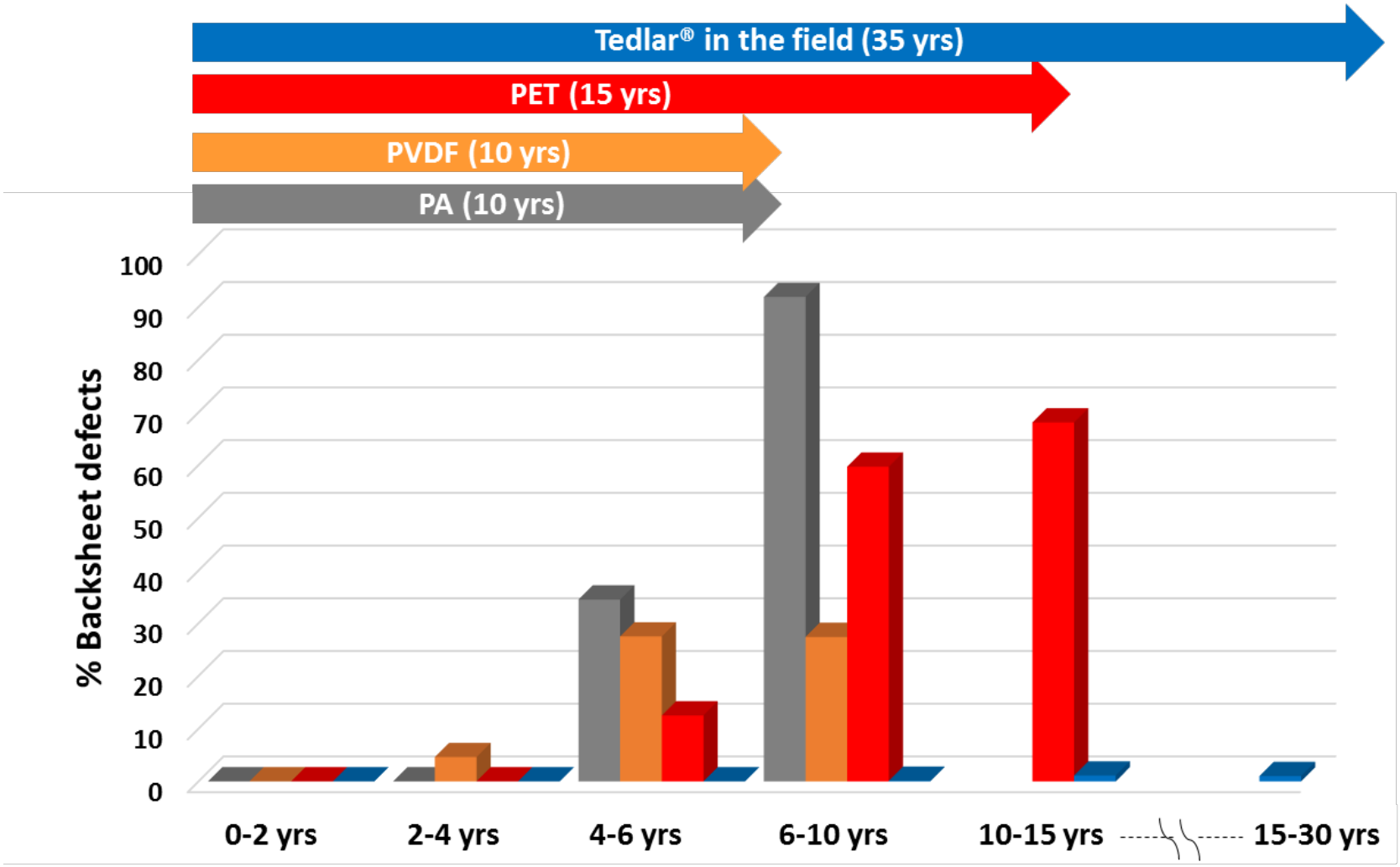
Defect Rates of Backsheets after 4 Years in Field



PA = Polyamide
PVDF = Polyvinylidene Difluoride
PET = Polyethylene Terephthalate
FEVE = Fluoroethylene Vinylether

* Data includes installations with minimum of 4 years of service life

Total Defect Rates vs Age of Backsheet in the Field



- Defect rates in all backsheets increasing with age in the field
- Rate of increase in PVDF, PET and PA significantly higher than in Tedlar

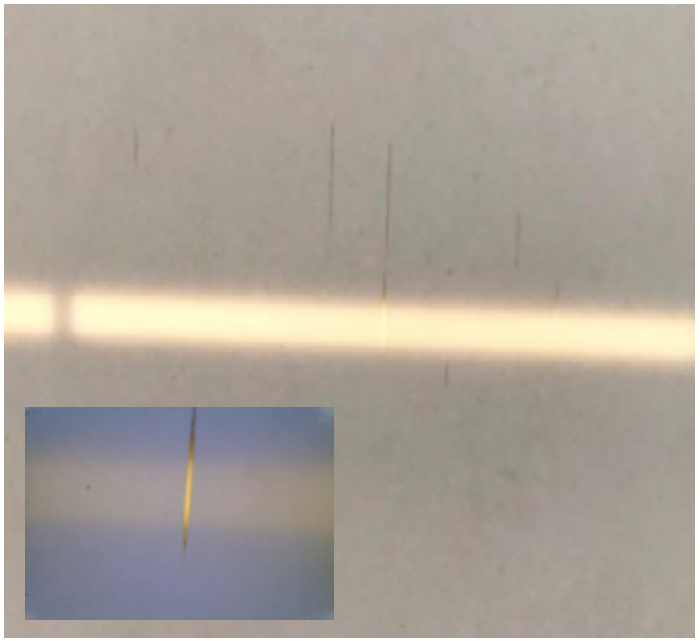
Recent Case Studies on Backsheet Defects from the Field

PVDF backsheets: cracking and delaminaiton

Arizona, USA, 6 years

- 6 MW installation
- 100 % modules with cracked backsheets
- All modules being replaced

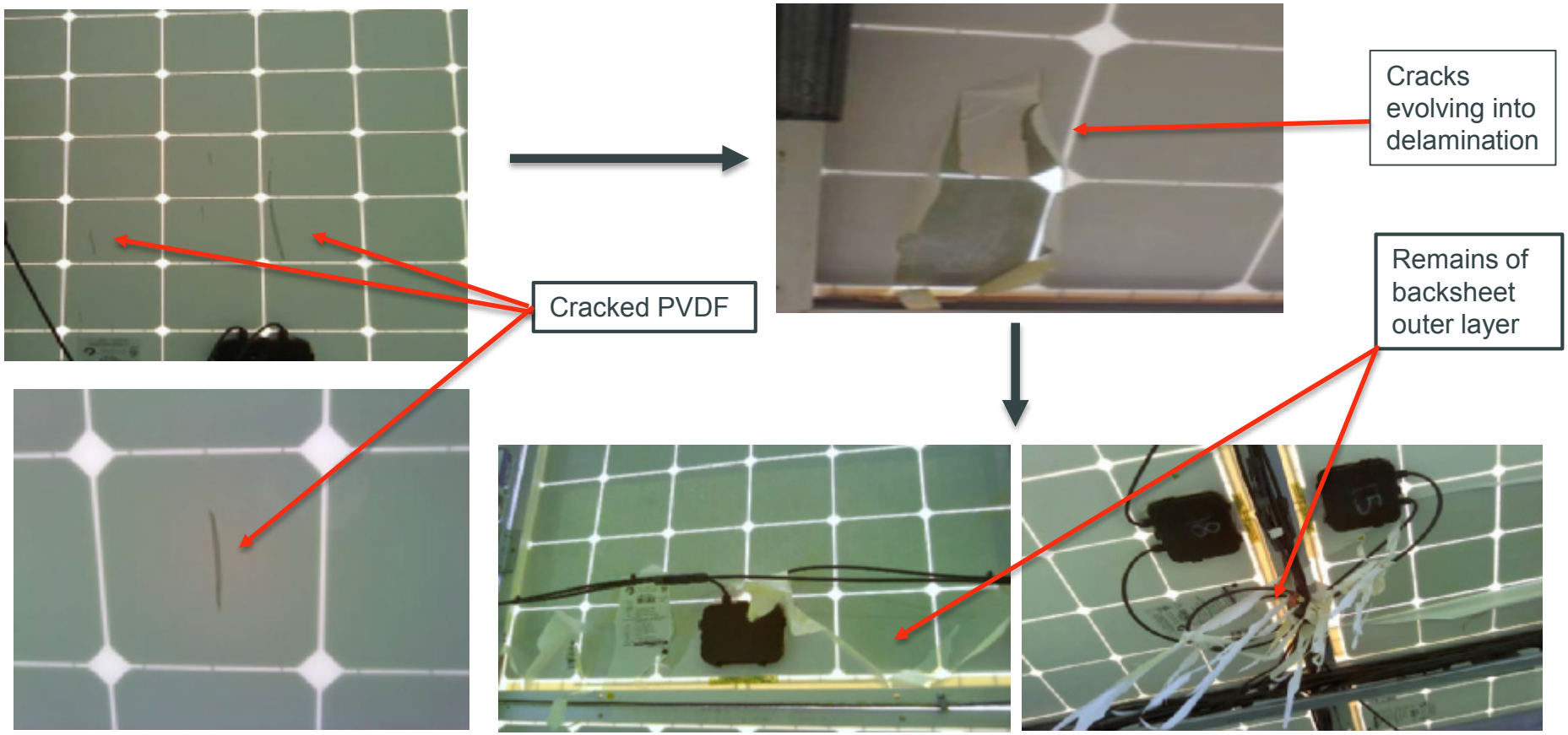
Qinghai, China, 6 years



- Rooftop installation
- Significant cracking in 80% backsheets along the machine direction

PVDF backsheets: cracking and delamination

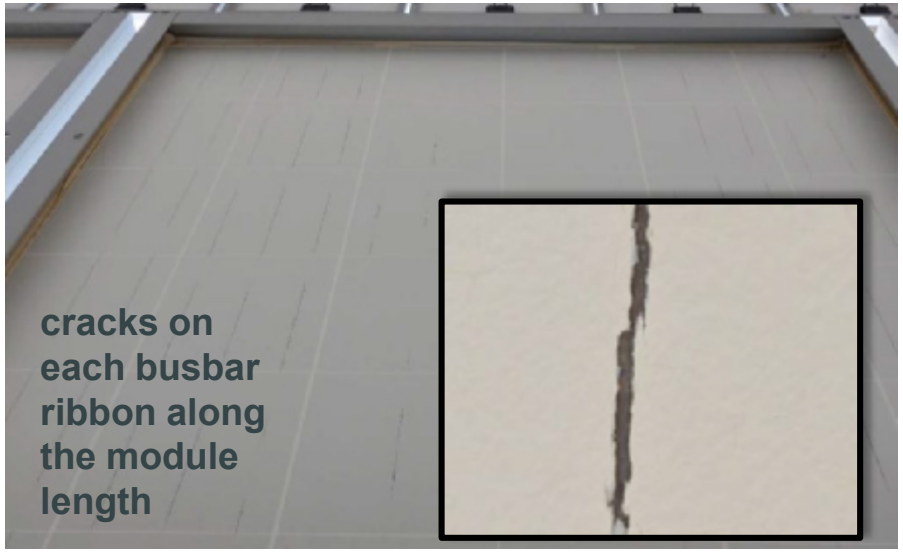
North America, 5 years



- 69 microfit sites
- Over 40 % modules with cracked backsheets
- All modules being replaced

PA backsheets: large-scale cracking

Nevada, USA, 6 years



- ~6 MW of modules affected
- 100% backsheets cracked along busbar ribbon over the entire module
- Some cracks extending through backsheet

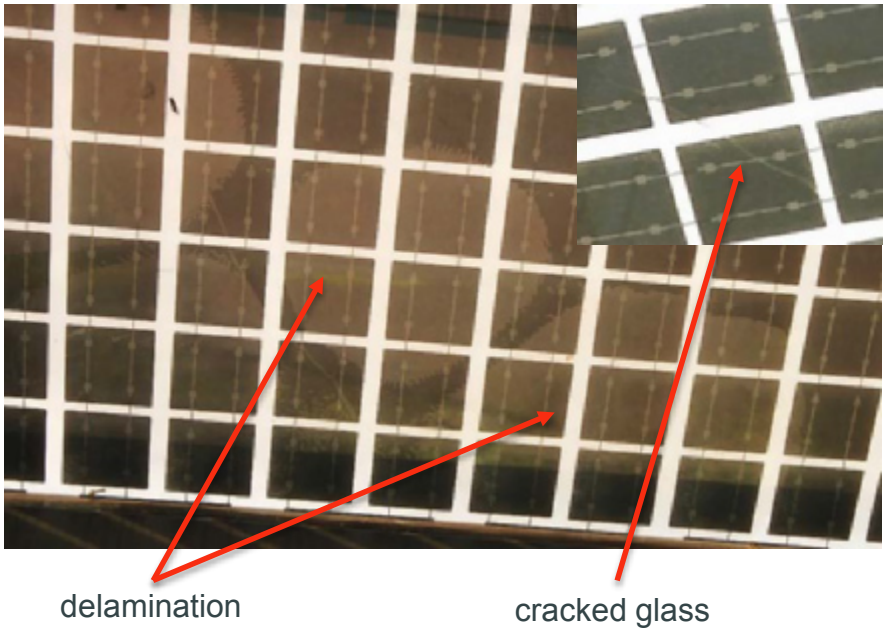
Arizona, USA, 6 years

- **3 different PV plants** totaling 22 MW
- 100% backsheets cracked
- Ground faults, inverter tripping, power loss
- All modules being replaced

>12GW total globally

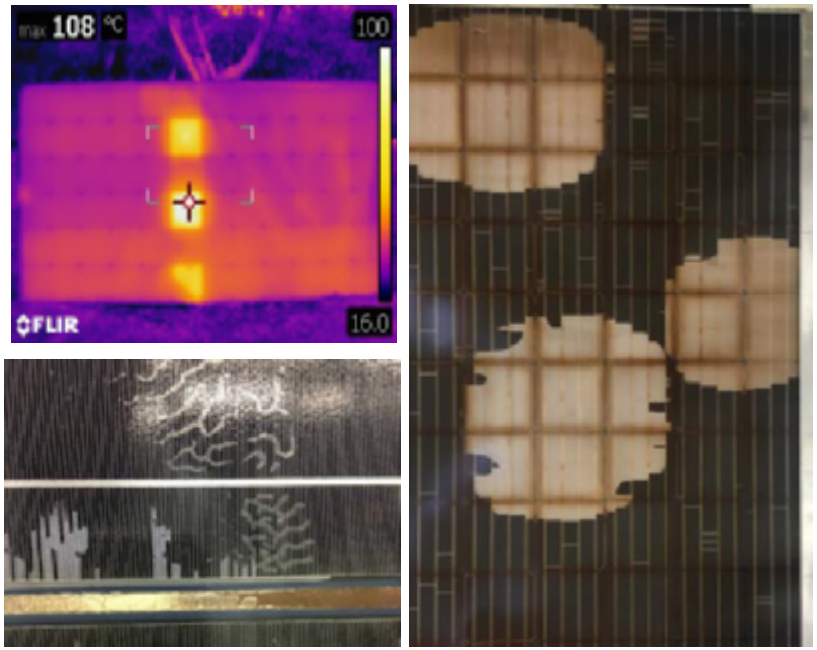
Glass-Glass delamination and hot spots

Arizona, USA, 10 years



- Building integrated installation
- 100% modules having extensive encapsulant delamination
- Cracks in the rear glass in 80% modules

Western China, 1 year



- Bifacial modules
- Significant encapsulant (POE and EVA) delamination and browning
- Hot spots

Glass-Glass Frameless Bending in Early Life

Guangdong, China, 1 year

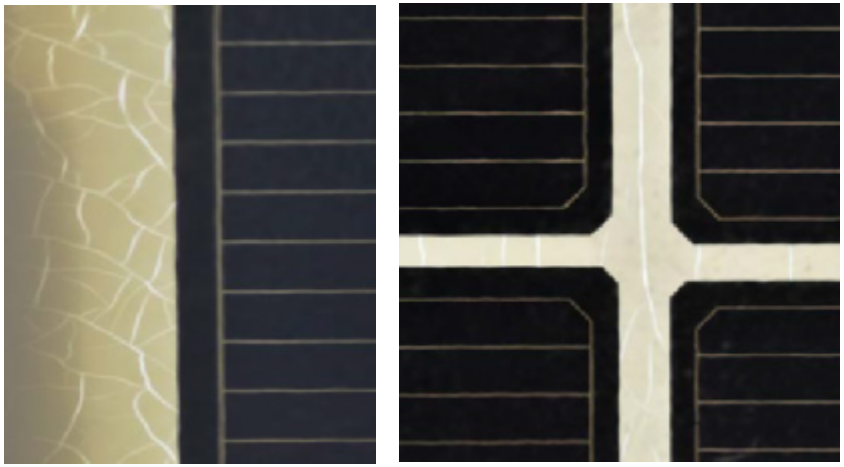
- Around 10-20% G/G modules show apparent bending
- Bending distance is > 1cm
- Installation: back clips
- **Frameless module**

East China, 1 year

- > 30% G/G modules show apparent bending
- Installation: side clips
- **Frameless module** with corner protection

PET backsheets: inner layer cracking

Texas, USA, 6 years



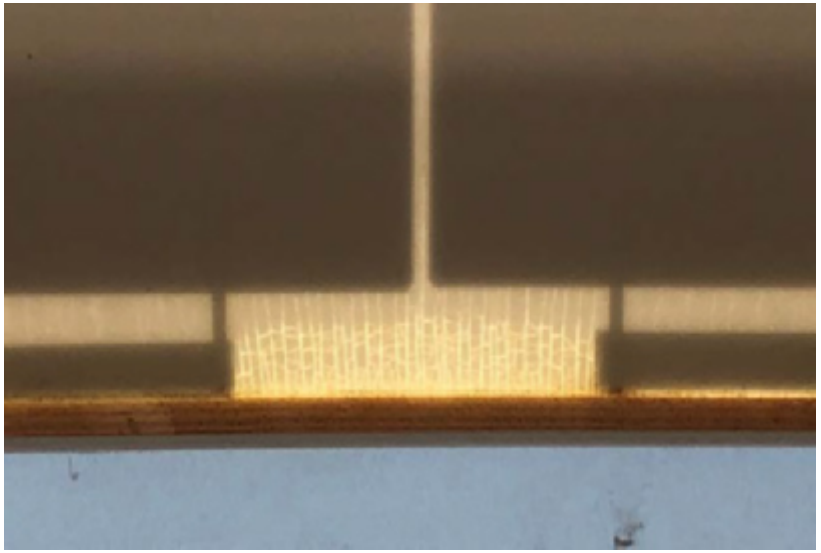
- 35 MW installation
- 100% modules affected
- Inner layer cracked between cells and around edges
- Inverter tripping and ground faults
- All modules replaced

Nevada, USA, 6 years

- ~ 80% of 6 MW modules affected
- Cracked inner layer promotes moisture ingress and retention
- Corrosion of string interconnect and busbars
- Inverter tripping and ground faults

PET backsheets: inner layer cracking

Arizona, USA, 7 years



- 8 MW installation
- 50% modules affected
- Inner layer cracked between cells and around edges
- Inverter tripping and ground faults

Arizona, USA, 7 years

- ~ 3 MW modules affected
- Inner layer cracked between cells and around edges
- Inverter tripping and ground faults
- Ground faults leading to fire
- All modules being replaced

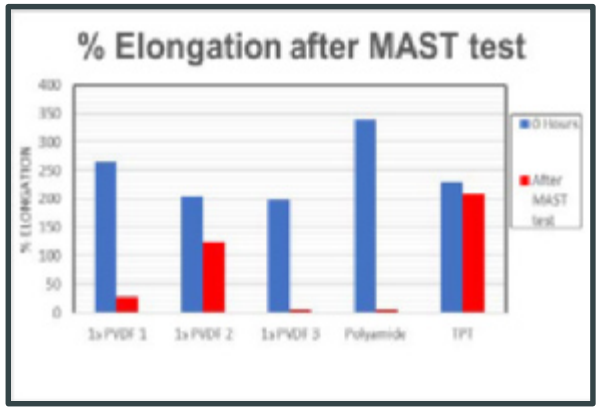
Summary

Failures in the field threaten long-term performance, durability and ROI

- **High frequency of visible defects are pervasive in early years, but typically not addressed due to the high cost of module replacement**
  - Unproven BOM can lead to high levels of defect
- **Increase replacement costs and system LCOE**
- **Learn from the defects seen in the field to choose more robust and durable components through <u>materials design</u> and <u>appropriate testing</u>**

Inner layer cracking

Front side UV exposure in xenon weatherometer + water front spray, 3500h (~5y outdoor equivalent)



Materials Matter™
The use of field-proven materials is critical to long- term performance and ROI

Thank You

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DuraMAT
Durable Module Materials Consortium

DuraMAT Overview

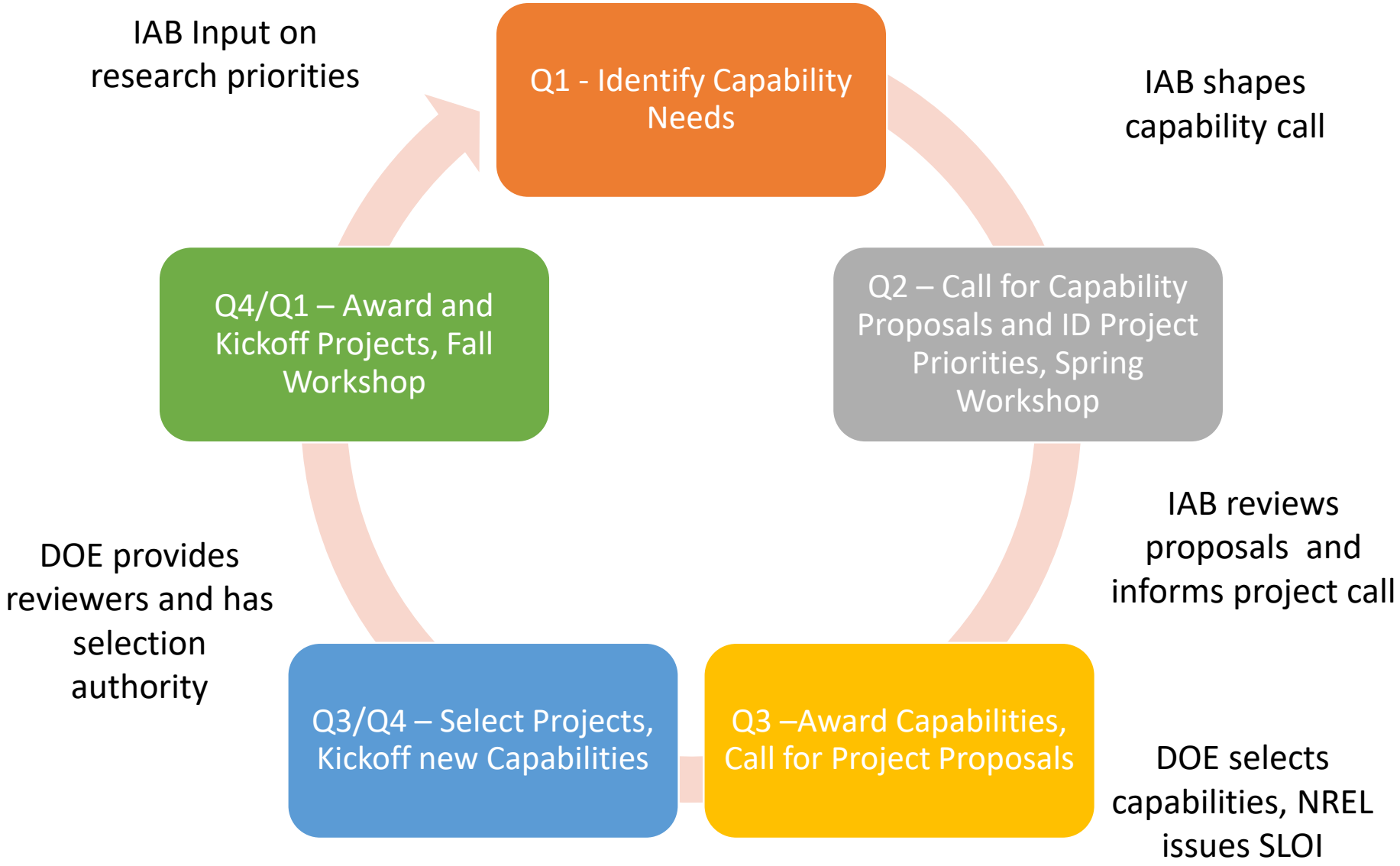
Teresa M. Barnes, Margaret Gordon, Laura Schelhas, and Mike Woodhouse

PVRW Feb 26, 2019

What Is DuraMAT?

- An Energy Materials Network research consortium focused on precompetitive research needs in module packaging
- Five Year Program
- Four National Laboratories develop capabilities
- Industry and academic projects using capabilities to develop materials solutions
- 14-20 member Industrial Advisory Board
- Integrated national lab capabilities, industry led projects, and university research in module durability
- www.duramat.org

The DuraMAT Year of Funding



DuraMAT Goal

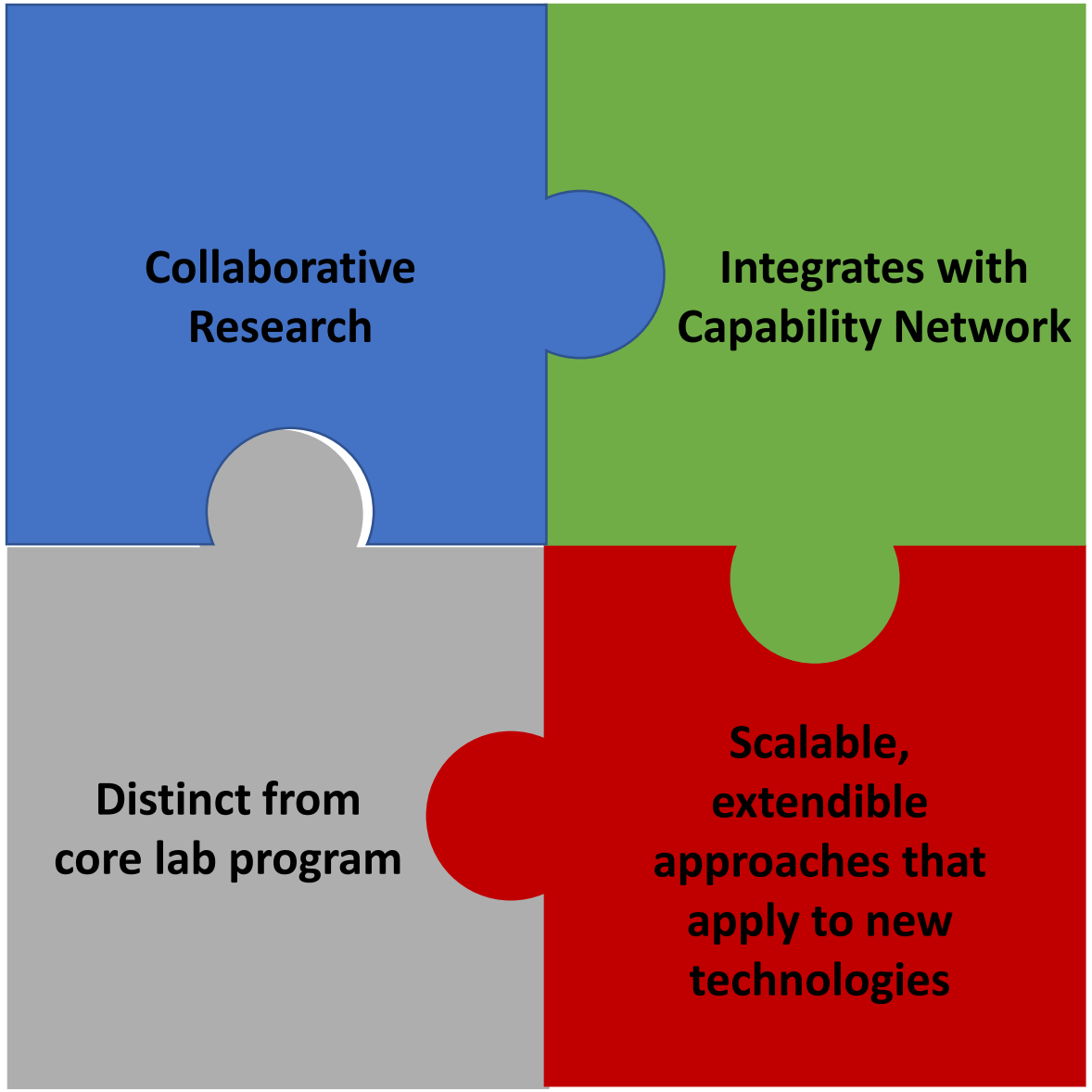
"The overarching goal of DuraMat is to discover, develop, de-risk, and enable the rapid commercialization of new materials, designs, predictive tests and models for photovoltaic modules that increase performance, extend lifetime, and enable new markets."

Capability Network

DuraMAT Projects	Data Management & Analysis	Predictive Simulation	Materials Forensics	Module Prototyping & Test	Outdoor Testing	Techno-economic Analysis
	DataHub	Multi-scale Module Simulation	Material Properties and Aging	Accelerated Testing	Non-Destructive Testing	Quantify LCOE
	Software Development and Machine Learning	Materials Modeling	Correlating Accelerated Testing and Field Data	UV Ionization Damage	Field Aged Module Library	Decision Support
	PVDAQ Upgrade	Flexible Modules	Barrier and Encapsulants	ECA and Contacts	Wind Loading and Structural Materials	Financial Modeling
	Data Visualization	Materials Selection	Cell Cracking	Module Design and Fabrication		Circular Economy
			Front Coating			

Research Priorities

- Use technoeconomic analysis to identify opportunities
- Work with Industry Advisory Board to prioritize needs
- Work with SETO to achieve programmatic balance
- Enable industry to leverage capabilities
- Build a capability network that is more than the sum of its parts

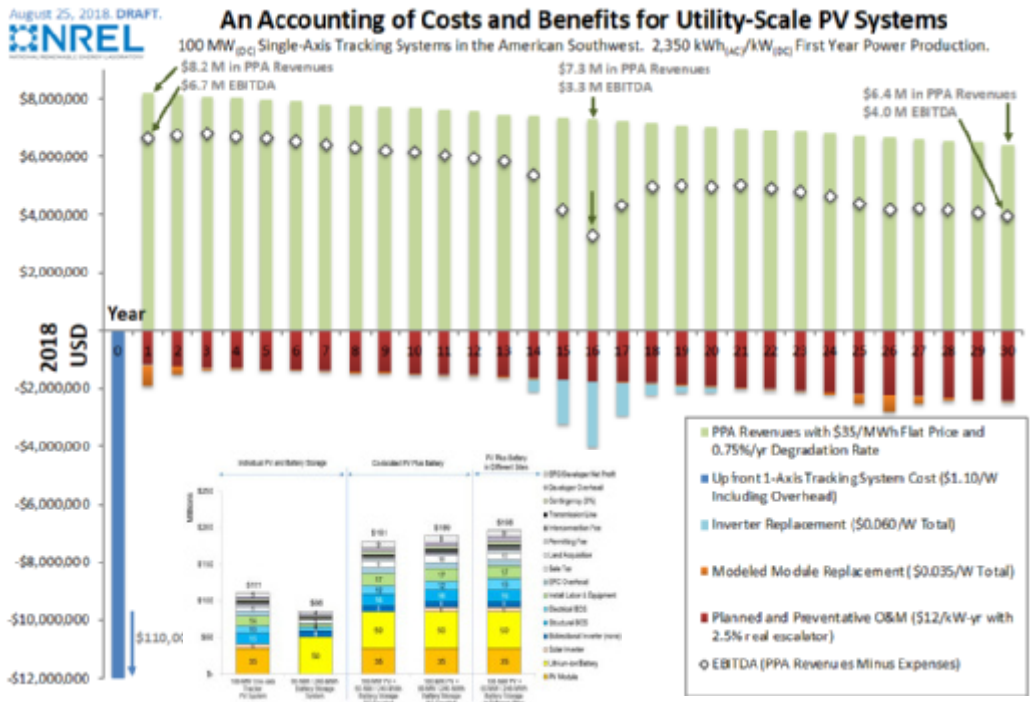


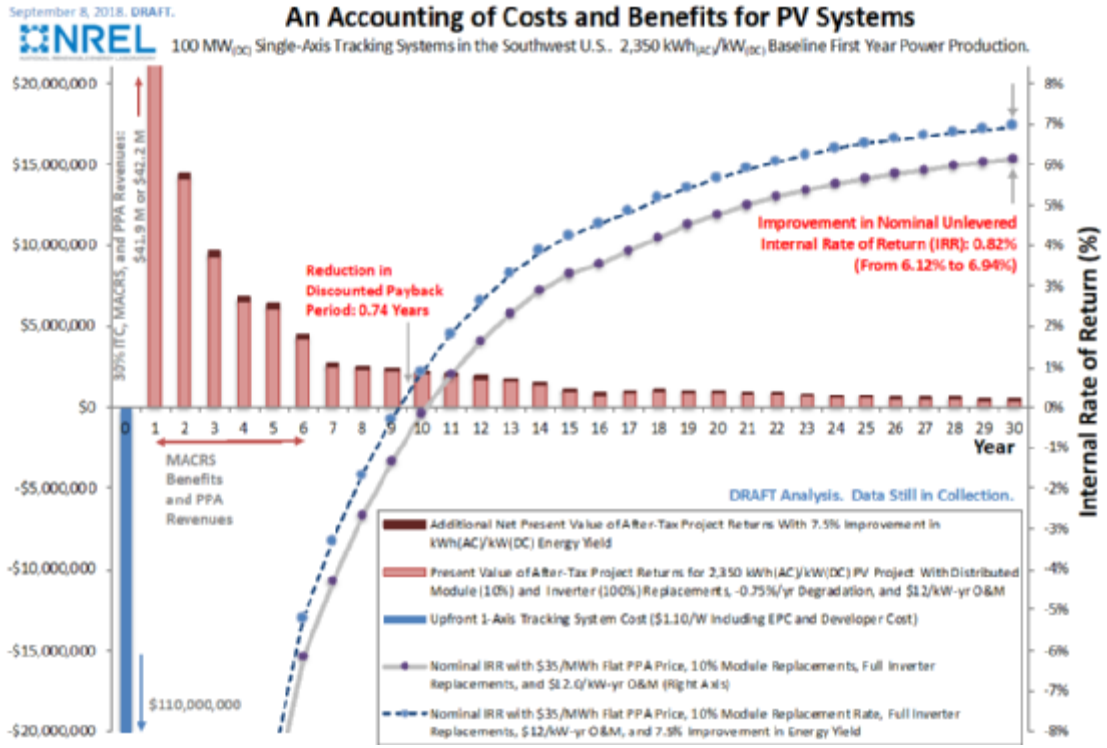
Bottom-Up Module O&M Costs Analysis and Repowering Economics

Bottom-Up Module O&M Costs Analysis and Repowering Economics

- Quantify the value of longer component lifetimes and replacement frequency
- Approach: PV project financial modeling to quantify the lifecycle cash flows for module replacement issues and costs.

Accomplishments and Highlights: DuraMAT-Relevant LCOE and IRR Model Development

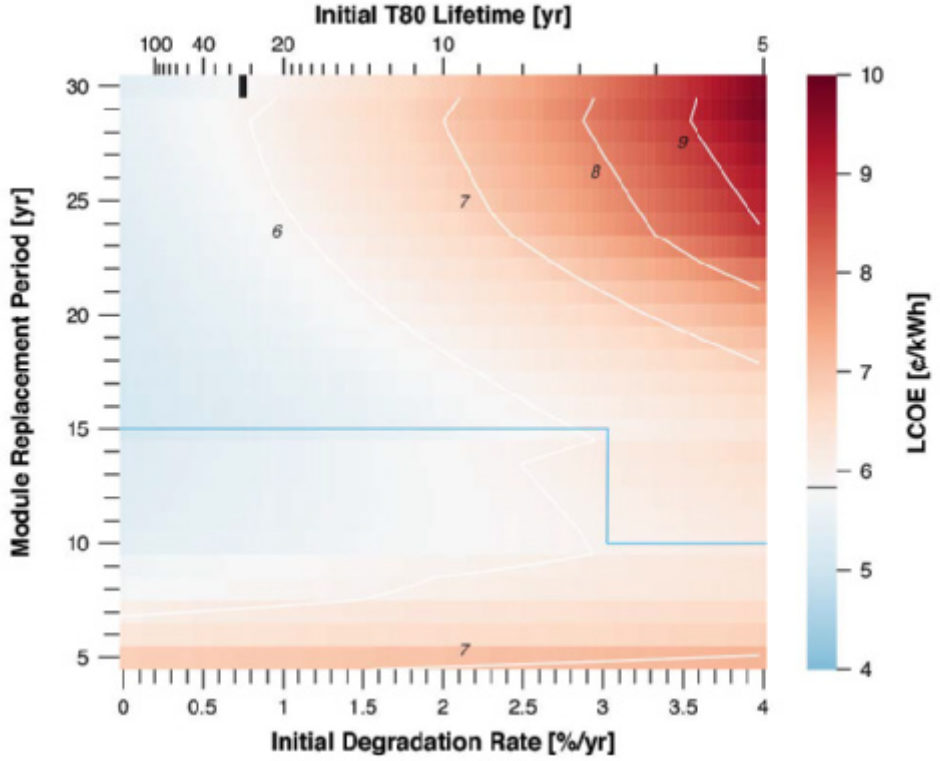


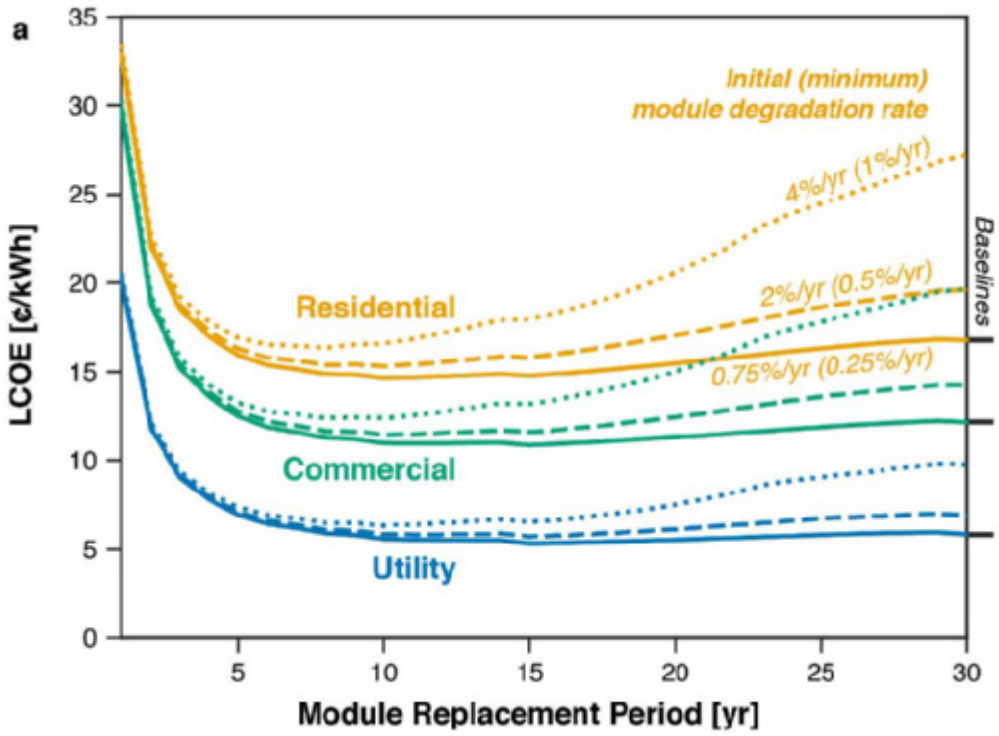


- PV project cash flows (left) and IRR implications (right) for changing module replacement rates and distributions
- Analysis in preparation for publication and always available to DuraMAT researchers at any time

LCOE Depends on Degradation Rate

Initial Degradation Rate vs. Module Replacement Period



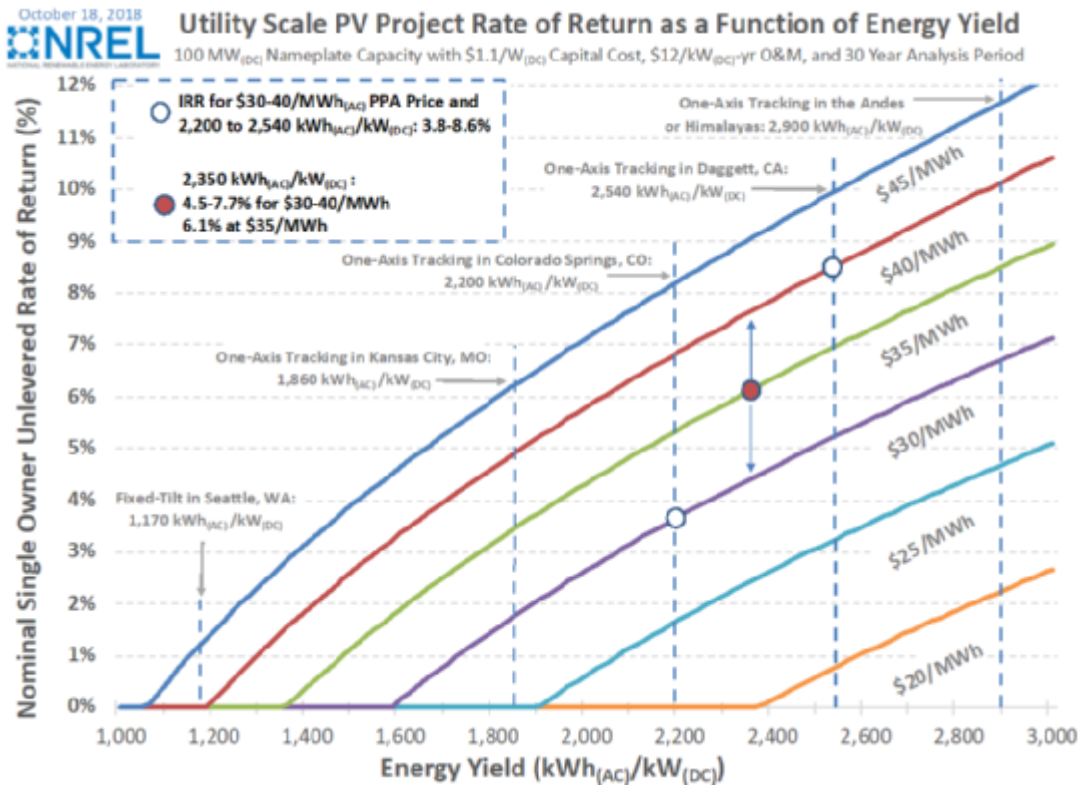


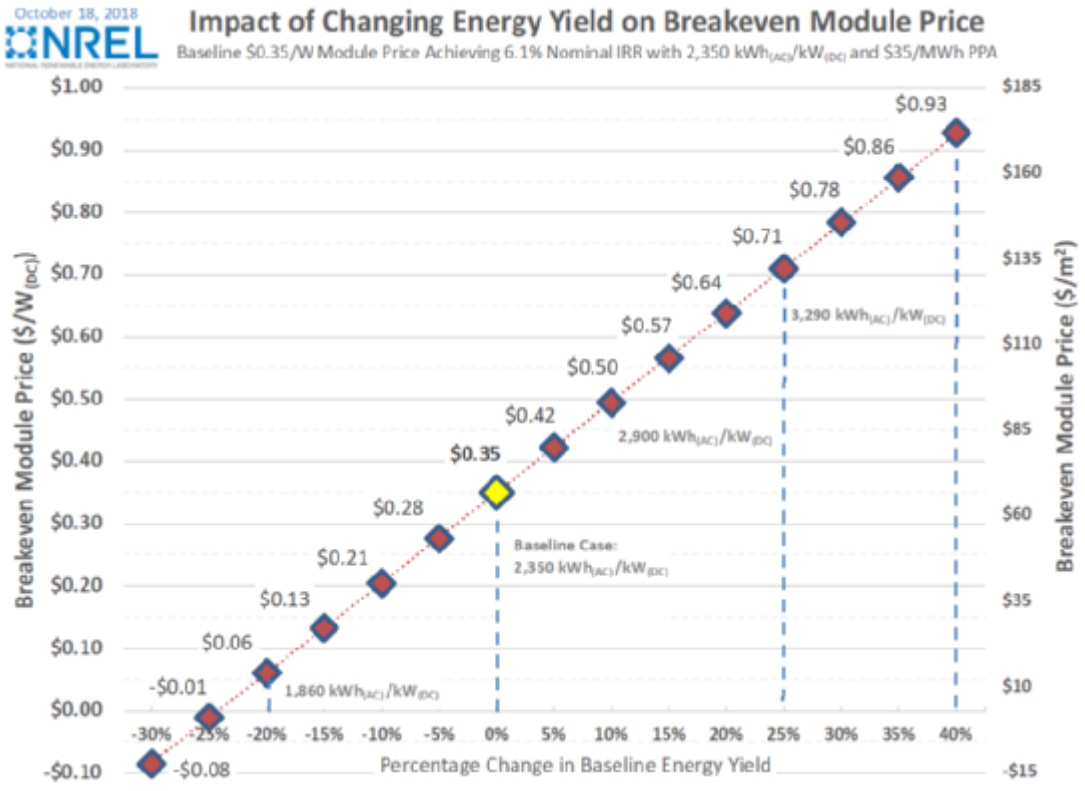
- LCOE as a function of module replacement period and degradation rates
- Demonstrates the value of reducing uncertainty in degradation rates over time

- Source of figure: "J Jean, M Woodhouse, and V Bulovic, "Lower the cost of solar energy with periodic module replacements", submitted to *Nature Energy*

Anti-soiling Coatings for Improved Energy Yield

What is the upfront value of increased energy yield (and reduced cleaning frequency_





- Breakeven analysis completed for module price premium leading to higher energy yield.
- Internal Rate of Return for different climates, irradiance, and tracking vs. fixed

DuraMAT Material Focus Areas

Leverage capabilities to design, de-risk, develop materials, tests, and approaches

Primarily industry and academic led efforts

Capability demonstrations

Goal: Develop materials solutions to well-known and emerging reliability challenges

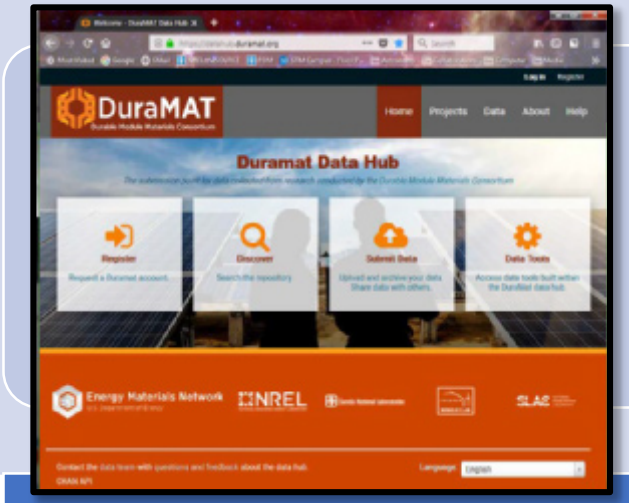
Capability Proposals Lab Call Open Now

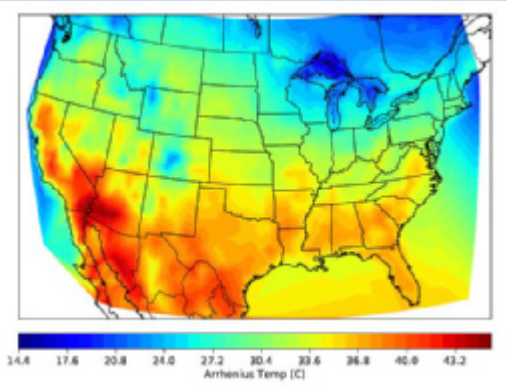
Find the call at: www.duramat.org

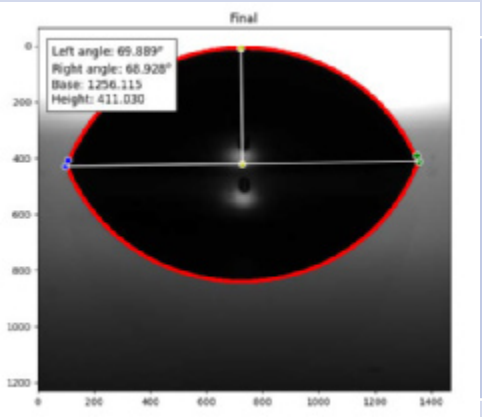
Central Data Resource	Multi-Scale, Multi-Physics Model	Disruptive Acceleration Science	Fielded Module Forensics
• Heterogeneous data – system performance, materials, etc. • Accessibility • Centrality • Security • Adaptability	• Publicly Accessible • Experimentally Validated • Bulk, Interfaces, Interconnects, and stressors modeled	• Data-Driven • Predictive • Validated by outdoor tests • Materials, modules, and systems	• Identify module failure modes affecting field performance • Multi-scale • Multi-modal • Practical • Validated

Materials Solutions: Leverage the capabilities to design, develop, and de-risk materials that address reliability problems. ECAs, backsheets , anti-soiling coatings, flexible packaging, cell cracking, moisture barriers, etc.

Central Data Resource







Current Portfolio

- Data Hub Deployed
- PVDRDB time series
- Clear sky filter
- PV Specific climate zones
- High throughput characterization

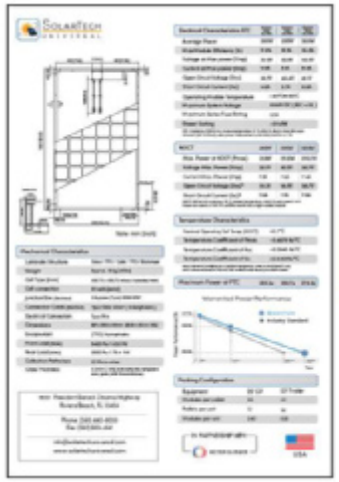
Open Call

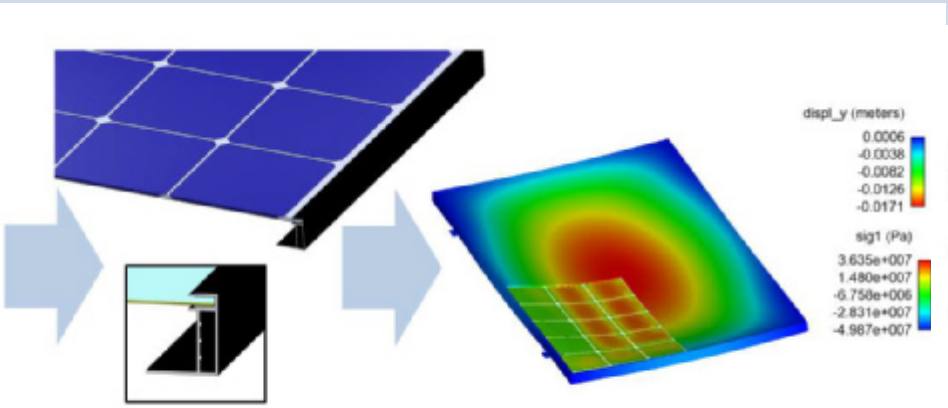
- Analytics
- “Big Data” to overcome sparse data challenge
- Data to knowledge
- Capability integration
- Improve accessibility
- Automate routine materials analysis

5 Year Outcomes

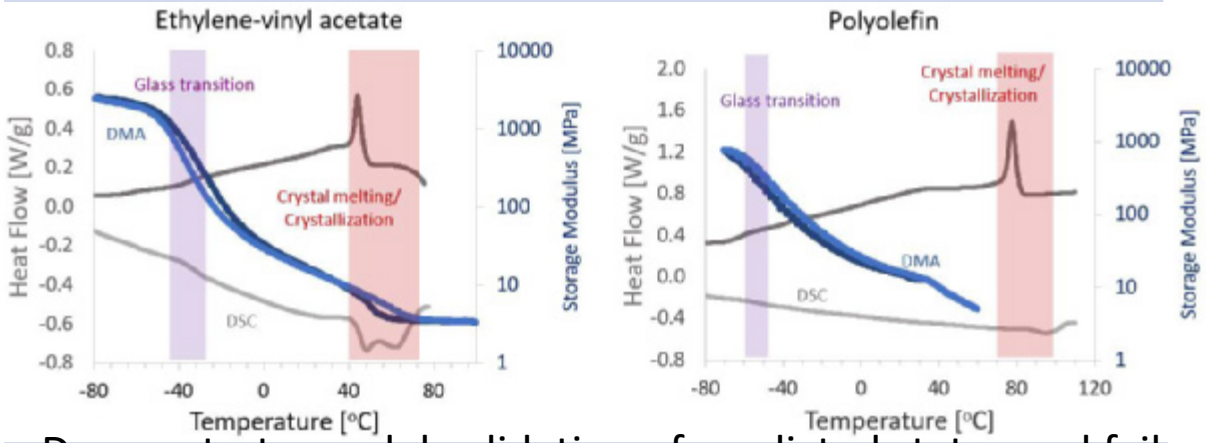
- Link capabilities and heterogeneous data types
- Enable new insights
- Useful queries
- One stop shop for materials, aging, testing, modeling, characterization, and field data

Multi-Scale Modeling





Predict module states under arbitrary environmental input conditions



Demonstrate model validation of predicted states and failure

Current Portfolio

- Thermo-mechanical modeling
- Glass-glass thin film and glass backsheet c-Si
- Cohesive zone model of encapsulant adhesion
- Unified constitutive model of ECA
- Extensive materials characterization to prevent “garbage in”
- Aero-elastic modeling for wind

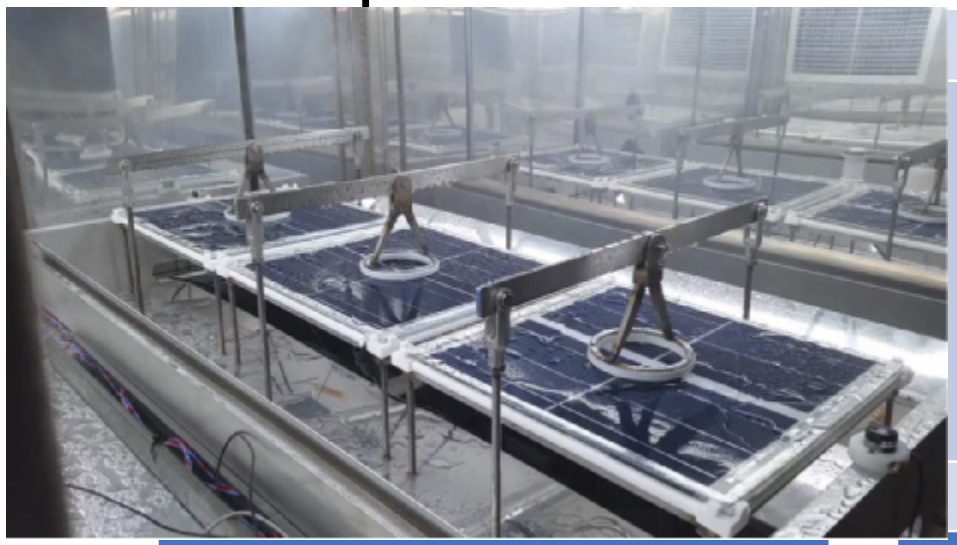
Open Call

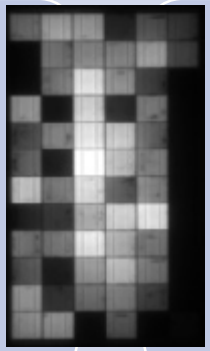
- Incorporate additional physics – electrical, chemistry, bias, UV/light, dynamics, diffusion, reaction
- Integrate scales
- Methods the can be implemented in different software packages
- Improve accessibility
- Materials aging models

5 Year Outcomes

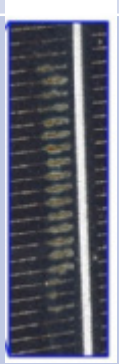
- Truly multi-scale, multi-stress modeling
- Predict module and material behavior over time and under stress
- Link accelerated testing and field performance
- Expandable, modular model that can accommodate new geometries, stresses, designs, materials, etc.

Disruptive Acceleration Science



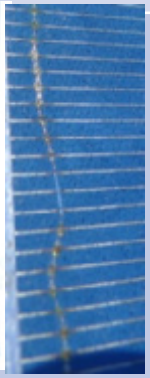


PID

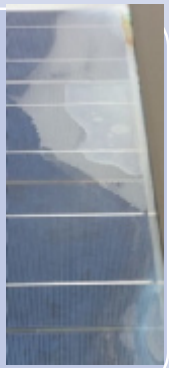


Corrosion

Edge seal failure



Snail trails



Delam.

Current Portfolio

- Combinatorial Accelerated Testing
- Field- predictive backsheet demonstration and cracking mechanism study
- Climate specific acceleration
- UV ionization effects
- Rate constants
- Outdoor fielded module library
- Outdoor accelerated testing

Open Call

- Integration with modeling and forensics
- Degradation rate studies
- Comparison with field data
- Studies of interactions between stressors
- Additional test development
- Materials aging models

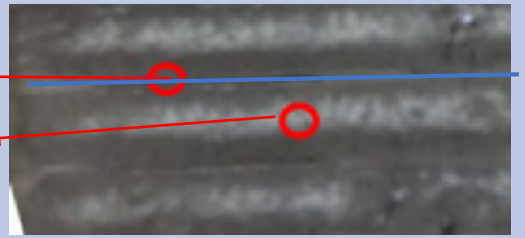
5 Year Outcomes

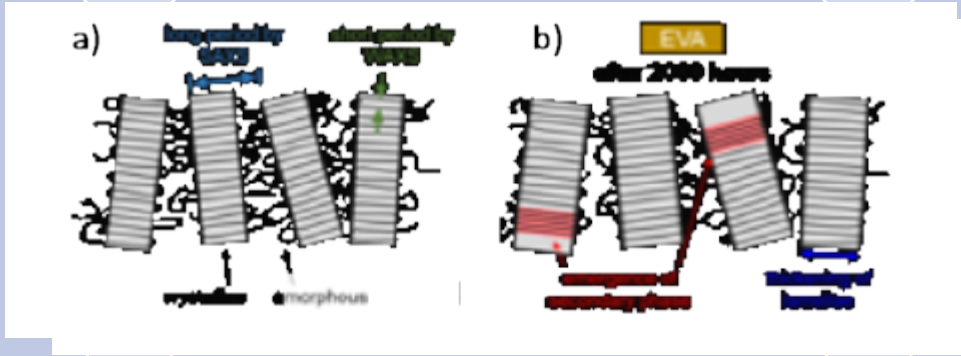
- Field predictive accelerated stress testing
- Quantified degradation rates and mechanisms
- Reduction in time under test or number of tests
- Quickly identify weaknesses in new modules

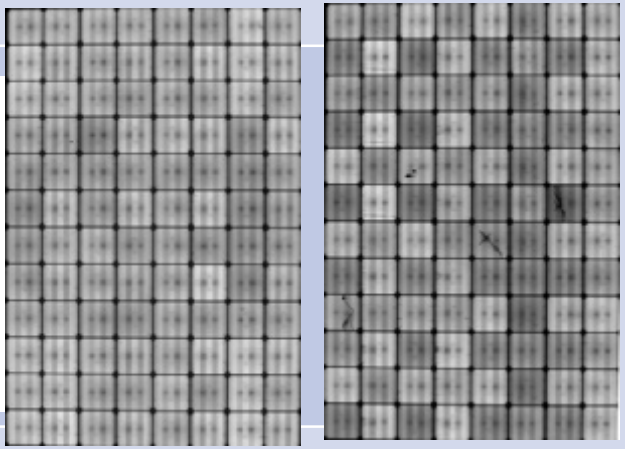
Materials and Module Forensics

Na

No Na







Current Portfolio

- Chemical characterization
- Interfacial characterization
- SAX/WAXS polymer characterization
- Fielded module failure analysis - imaging
- High throughput optical measurements
- Coating characterization
- Backsheet degradation

Open Call

- High throughput, field portable characterization techniques
- Validation of field metrology
- Characterization of emerging materials
- Integration across capabilities
- Materials aging models

5 Year Outcomes

- Field-friendly characterization approaches
- Quantified degradation and reaction rates
- Methods to detect early signs of impending failure
- Techniques to identify materials in fielded modules
- Accessible data and results

DuraMAT at 2.5 Years

- We have great pieces in place
  - Focus on integration and high impact collaborations to solve hard problems
- We have some big successes – talks and posters this afternoon
  - Combined Accelerated Testing
  - DataHUB and Time Series Data Facility
  - Material Property and Aging Studies
  - DuraMAT Early Career Network
- We have a lot of work left to do!

Optimizing PV system asset management using scalable digital models

Nikhil Vadhavkar, CEO

NREL PV Reliability Workshop
Lakewood, CO
February 26, 2019

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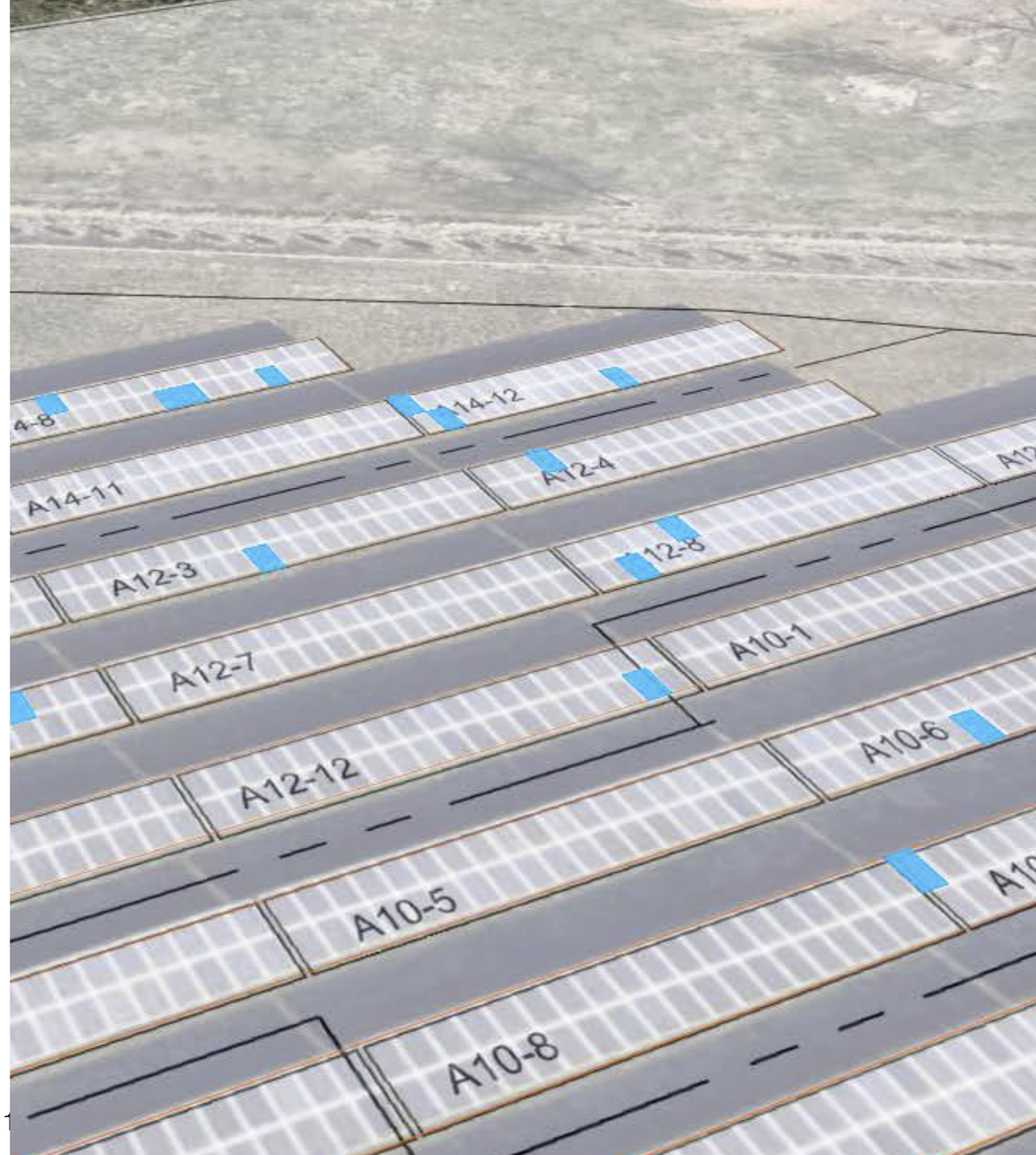

PV System Condition Depends on an Entire Chain of Events

Module BOM And Design — Manufacturing — PV System Design — Construction → **ASSET MANAGEMENT**

Data captured as part of routine asset management practices should both improve existing PV systems and inform future ones.

Engineering Rigor
Directed R&D
Controlled Studies

Scale Up Operations
Squeeze More Production
Faster, Better, Cheaper

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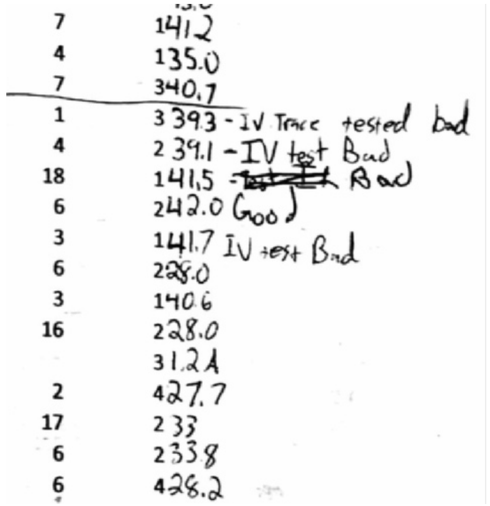
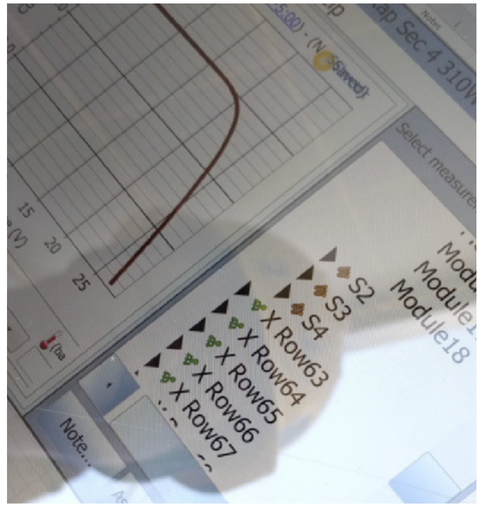
Challenges with Existing Asset Management Data

- Inconsistent practices across portfolios
- Unstructured field data capture
- High temporal resolution, low spatial resolution
- Tradeoff between granularity and coverage
- **Lacking training data with underlying cause**





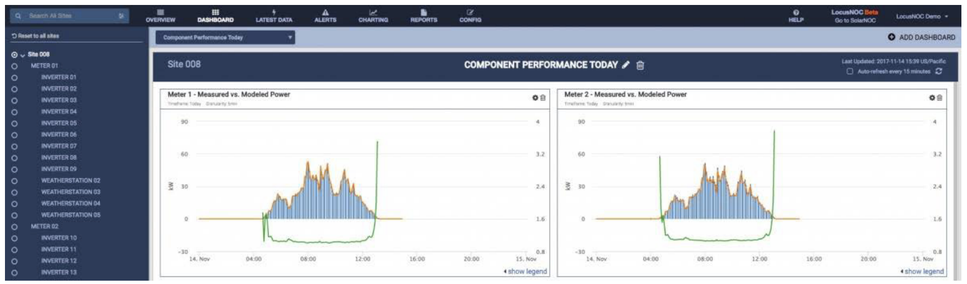


Image source: www.locusenergy.com

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We enable our customers to leverage off-the-shelf drone technology.

- Guidance for internal program
- Validation of contractor procedures and data
- Turnkey solutions

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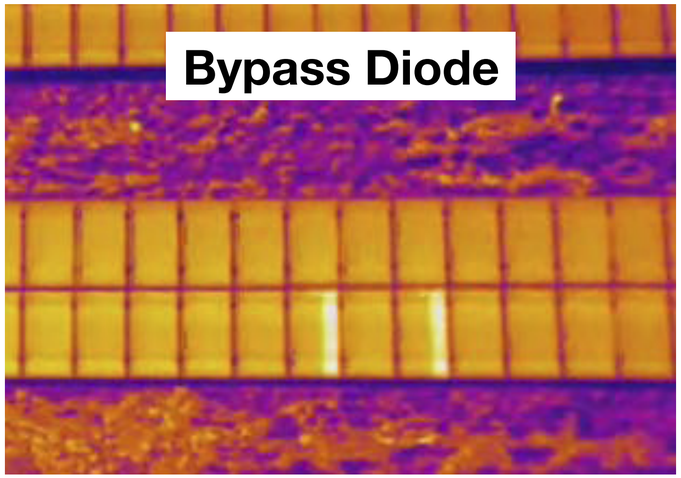
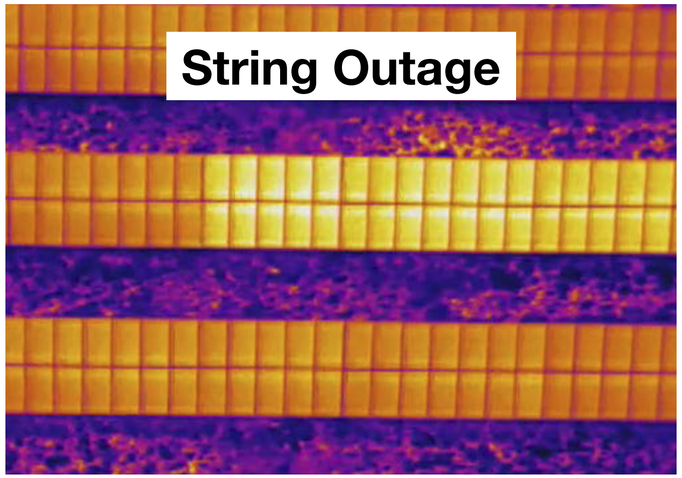
About Raptor Maps

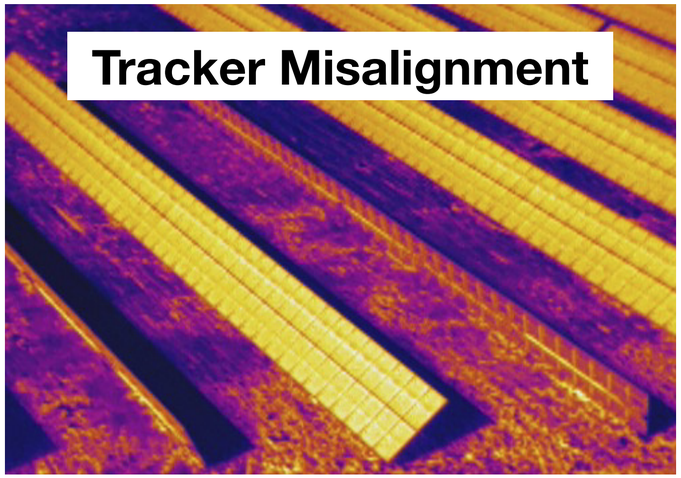
- Software company founded in 2015 by MIT engineers
- Optimize PV system construction and management using ML and digital twins
- Managing aerial thermography for over 4 GW of PV assets in 2018 across 6 continents, and much more in 2019
- Build scalable and enterprise-compatible solutions with both immediate and long-term benefit

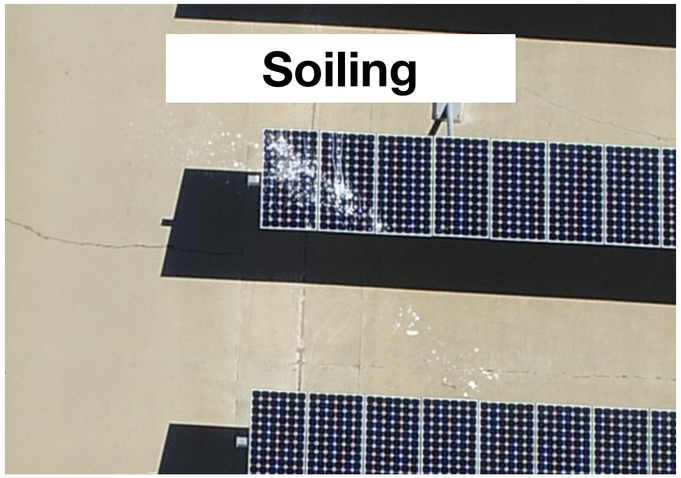
Data Captured With Off-the-Shelf Hardware

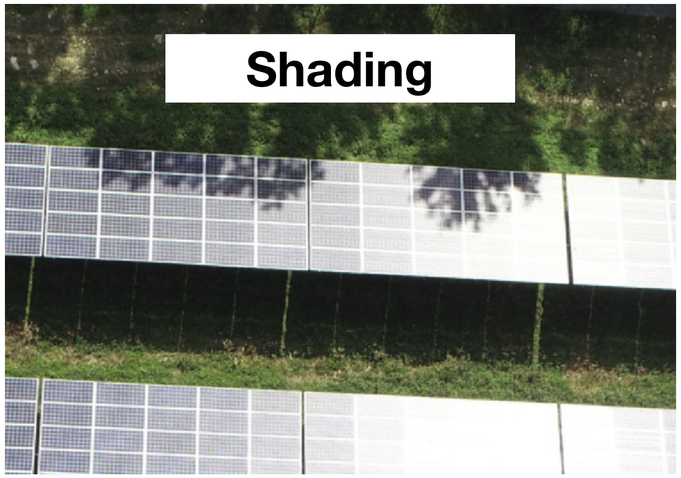
Actual drone images from Raptor Maps customers depicting issues:











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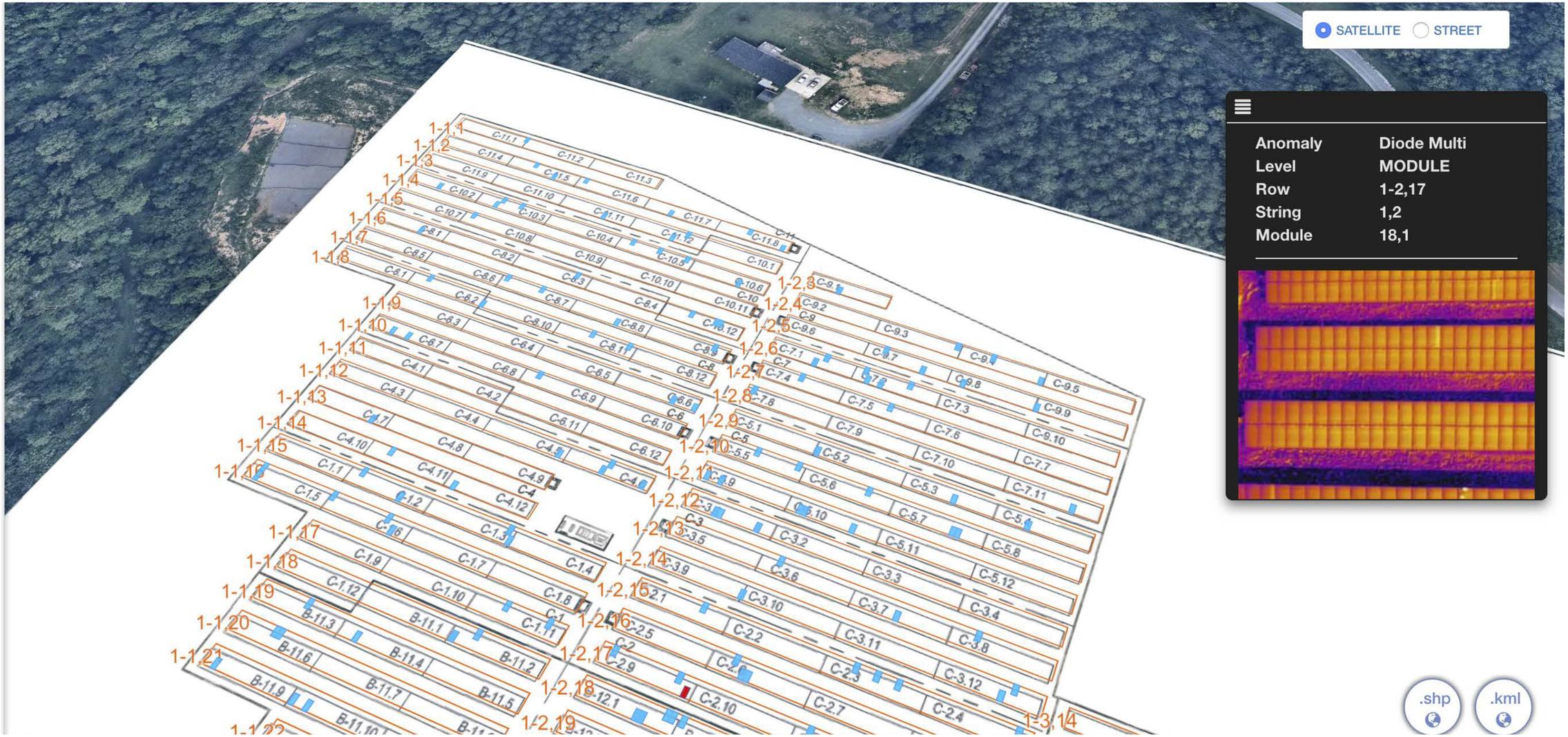
Aerial Thermography Software is an **Opportunity** for the Industry to Build Digital Twins and Increase the Utility of Asset Management Datasets



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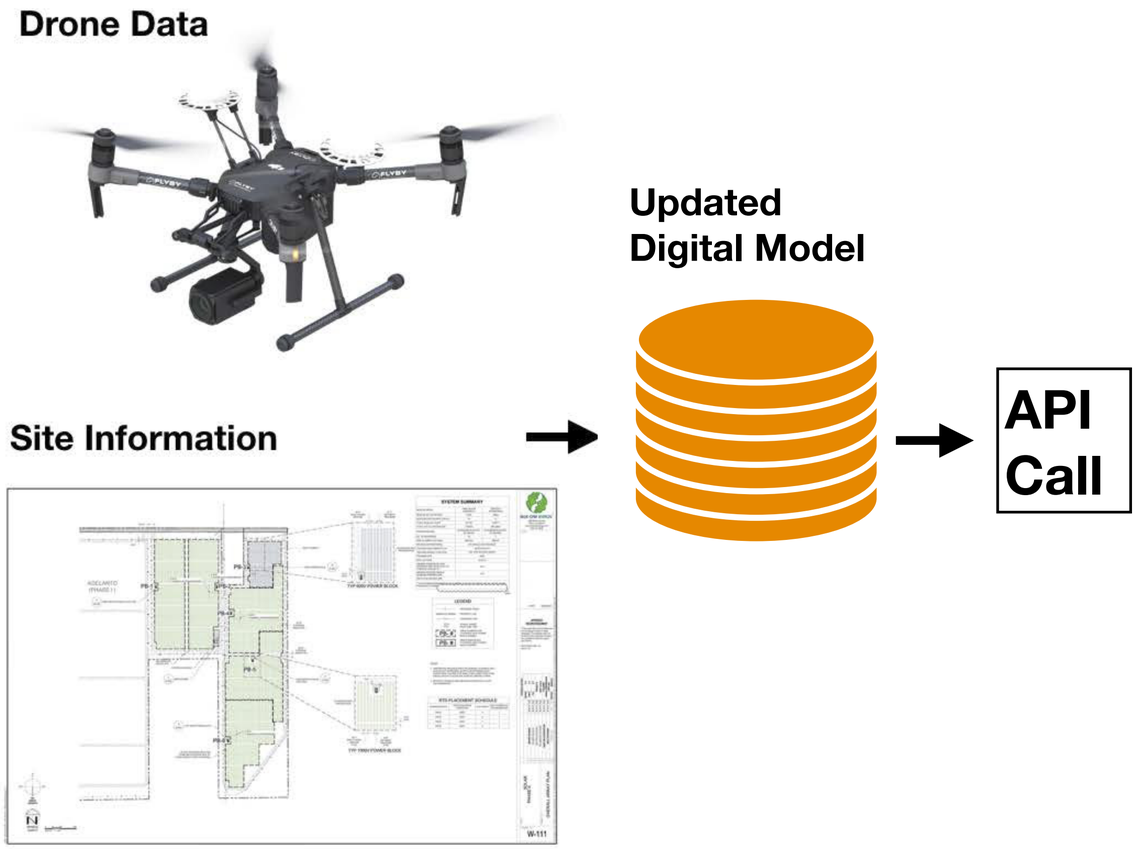
Intuitive Data Model

- Portfolio and digital site model
- Inspection date
- Inverter, combiner, string, module
- Physical and **electrical** location
- Finding/defect condition
- Link back to original data



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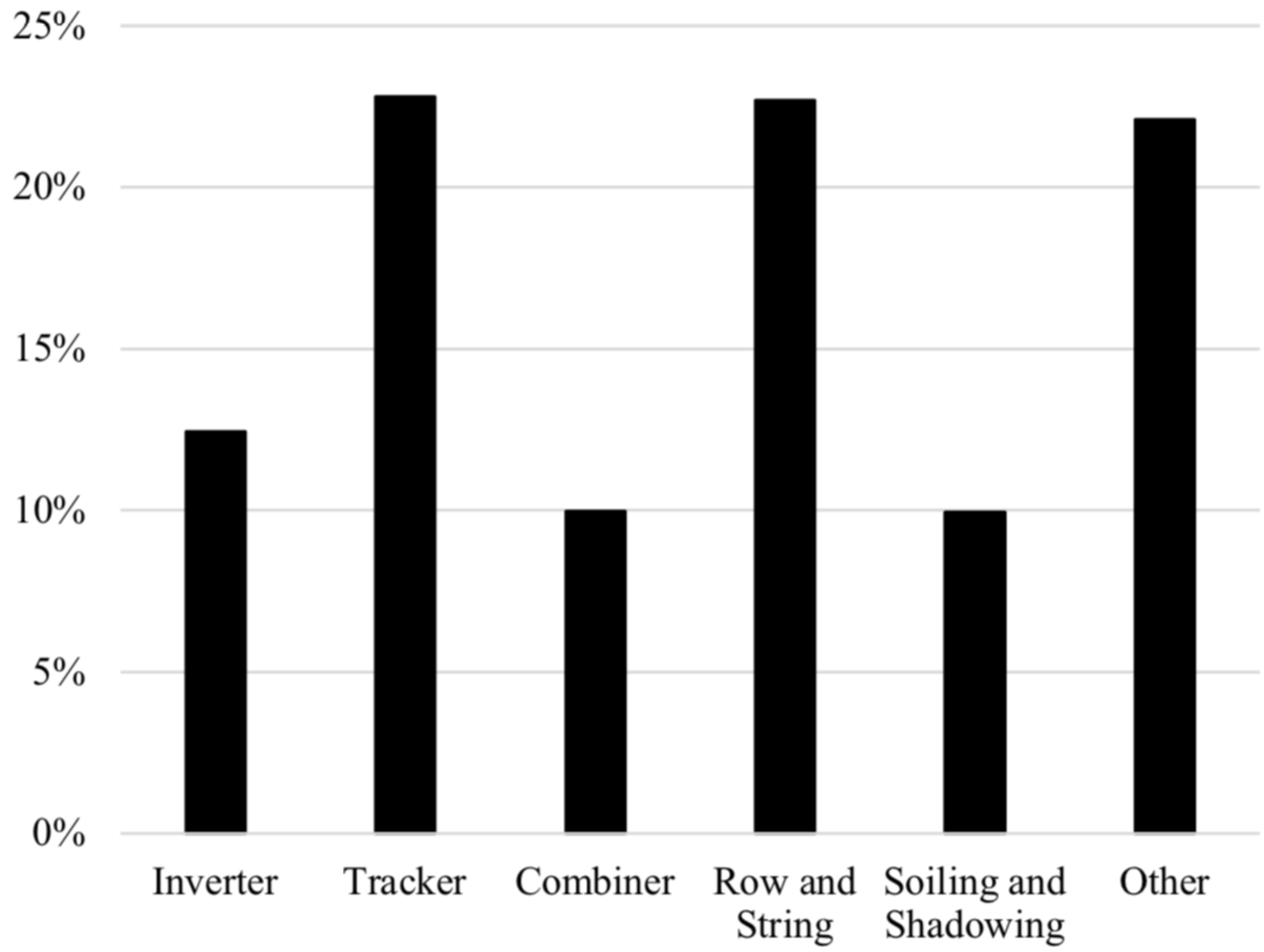
Modules Affected by Category

Modules Analyzed: 12,945,747
Percent of modules affected: 2.1%

Tag	Number of Modules
Inverter	34,460
Combiner	27,621
Tracker	63,192
Row	13,008
String	49,874
Soiling	11,926
Shadowing	15,631
Reverse Polarity	126
Delamination	1,373
Cracking	449
Missing	1,057
Module	12,006
Diode Multi	486
Diode	13,691
Cell Multi	15,250
Cell	16,564
Hot Spot	240
TOTAL	**276,954**

Chart: Relative percentage of modules affected by finding.



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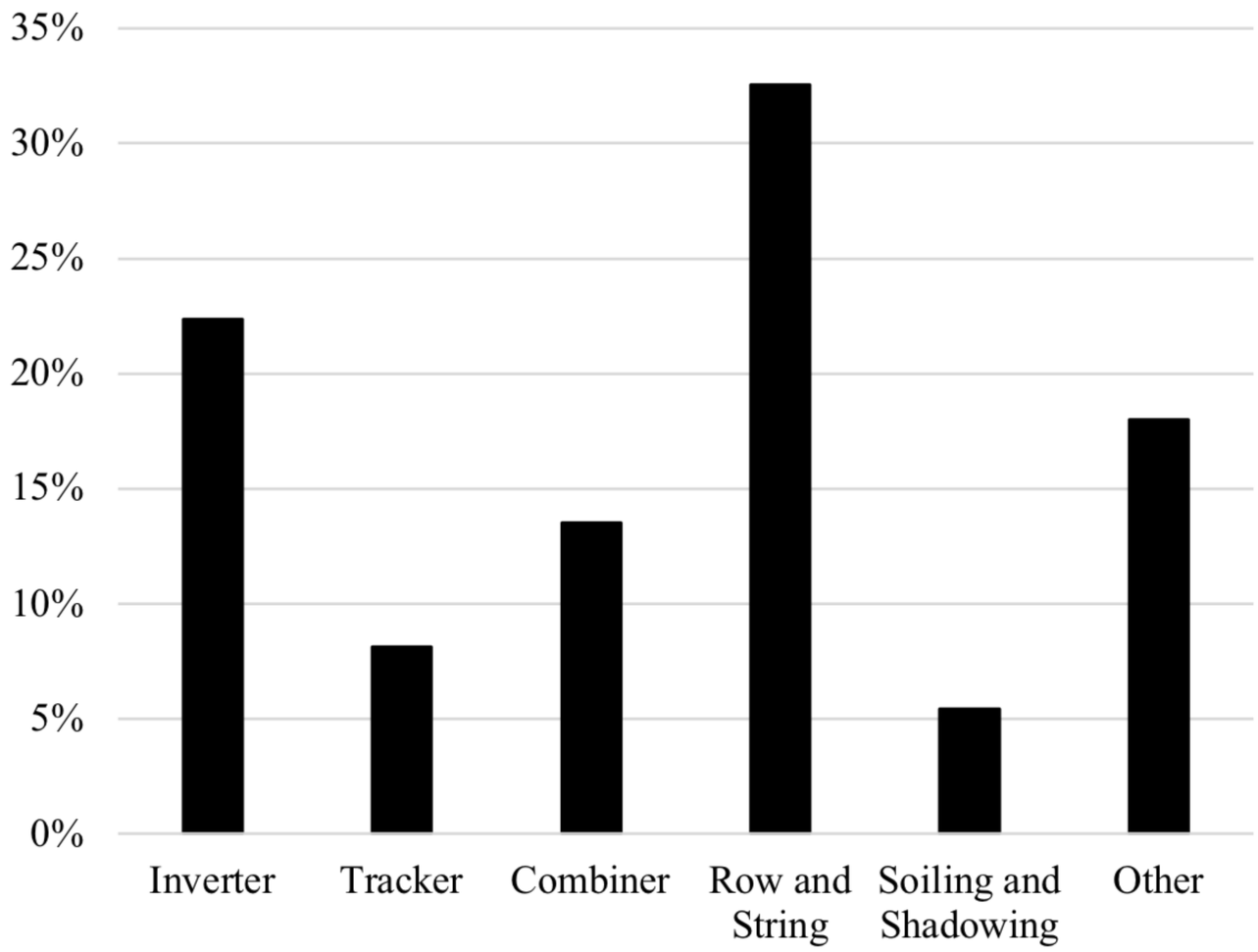
Power Affected by Category

Power in Analysis: 2,882.30 MW
Percent of power affected: 1.7%

Tag	Power (Watts)
Inverter	11,242,180
Combiner	6,792,079
Tracker	4,087,034
Row	2,311,771
String	14,057,220
Soiling	1,103,562
Shadowing	1,621,323
Reverse Polarity	39,690
Delamination	217,095
Cracking	53,740
Missing	295,925
Module	3,015,824
Diode Multi	102,645
Diode	1,498,417
Cell Multi	2,275,178
Cell	1,542,798
Hot Spot	10,167
TOTAL	**50,266,648**

Chart: Relative effect of finding on production.



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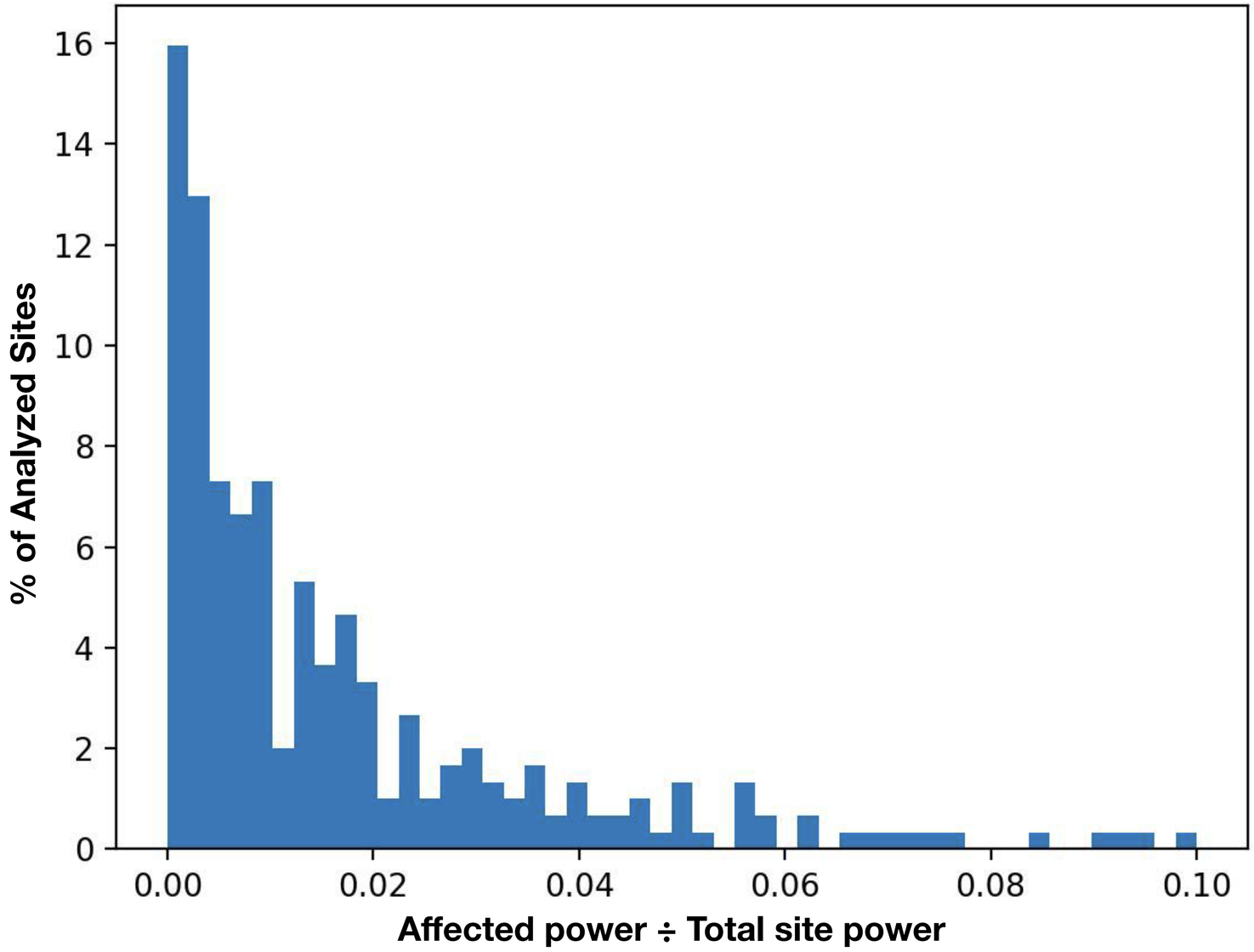
Defect Rate Analysis



- Risk avoidance; long tail is costly
- Financially-driven decisions based on the NPV

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Driving Adoption via Asset Managers and O&M

What does “scalable” mean?

- Compliant with recognized standards (i.e. IEC TS 62446-3:2017)
- Cost-effective, low barrier to entry, fast turnaround
- Scales across global portfolio; accessible COTS hardware
- Compatible with both **existing** and **future** PV systems
- Part of annual processes (better for owners than what was required before)

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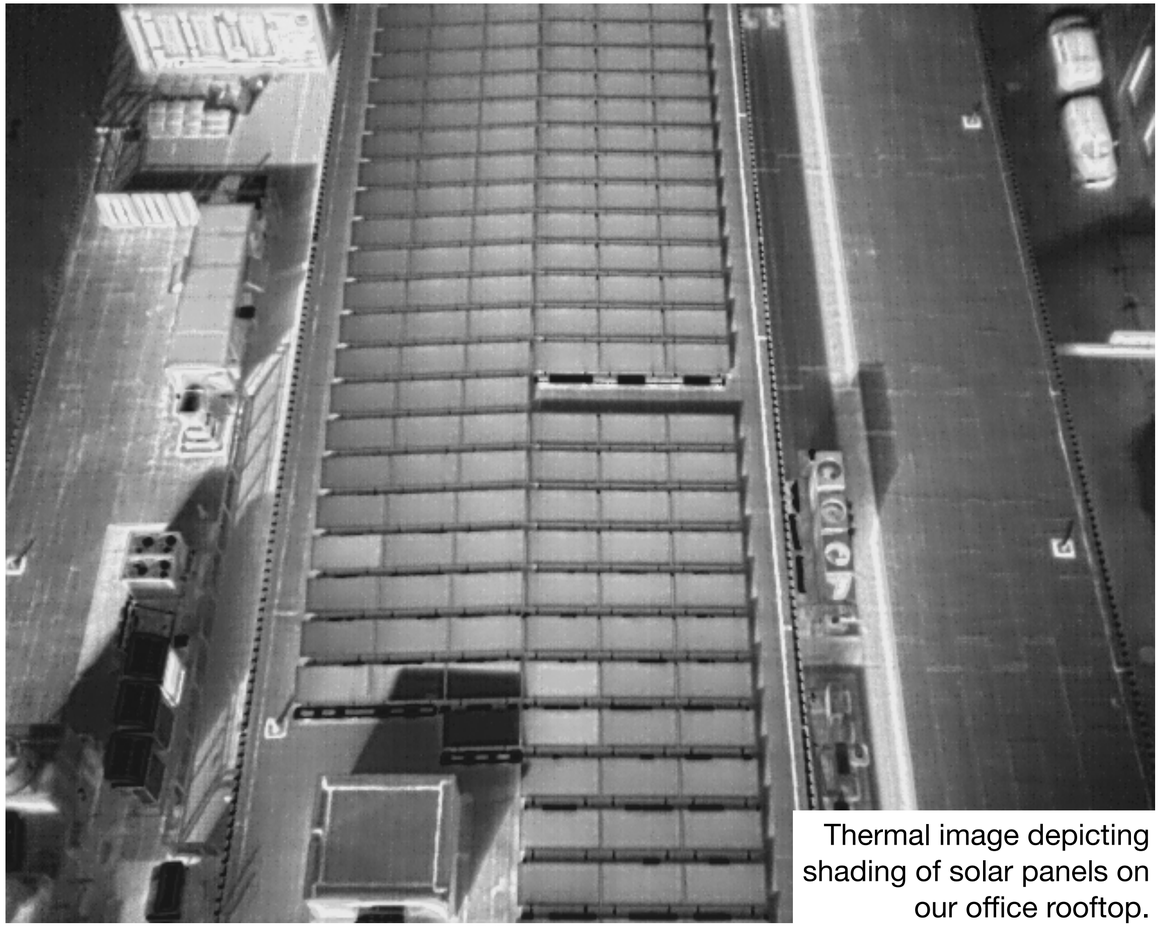
Have a Great PV Reliability Workshop!

Nikhil Vadhavkar, CEO

info@raptormaps.com

Greentown Labs Center for
Global Innovation

444 Somerville Ave.
Somerville, MA 02143



Thermal image depicting shading of solar panels on our office rooftop.

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Large Scale Electroluminescence Inspection: Multi-Sensor Platforms and Automated Evaluation

Andreas Fladung, Jan Schlipf, Aerial PV Inspection GmbH, Germany

NREL, PV Reliability Workshop, 26 - 28 February 2019

About Us

1990 2010 2013 2015 2018 2025

1. **R&D**, development of automated measuring and testing methods, concepts, hard- and software for automation and evaluation
2. **Measurement services** for module manufacturers, EPCs, asset manager, insurances, O&M, testing institutes, universities, end customers
3. **Training** and **qualification**, establishing a network of co-workers
4. **Sales** of Hardware and Software

Requirements for Commercial High-Volume PV Inspections

A. Market requirements / client requests

a. Not fault-specific: Commissioning and inspection, end of warranty check, footprint for lifecycle management, post documentation…

b. Fault-specific: Loss of yield, product defects, damage events (assembly defects, environmental ...)

→ **Costs**

B. Technical requirements

a. Fault specific: cell-/fault types → **choose measurement method(s)**

b. Project specific: plant and inverter/string layout → **choose measurement platform(s)**

C. Content requirements

Normative, scalable, reproducible, root causes, accuracy, forecast ...

Market, Technical and Content Challenges: Solution Approaches

1. **PRIORITY: Fast, reliable, cost effective evaluation of PV power plants → minimize costs**

   → *systematic automation and digitalisation of measurement, evaluation and reporting, selection of suitable measurement methods and sensor platforms*

2. **PRIORITY: Detection of root-causes → maximize significance**

   → *selection of suitable combinations of measurement methods (electrical & imaging) in order to clearly detect the root-causes of faults. Development of intelligent workflow combinations*

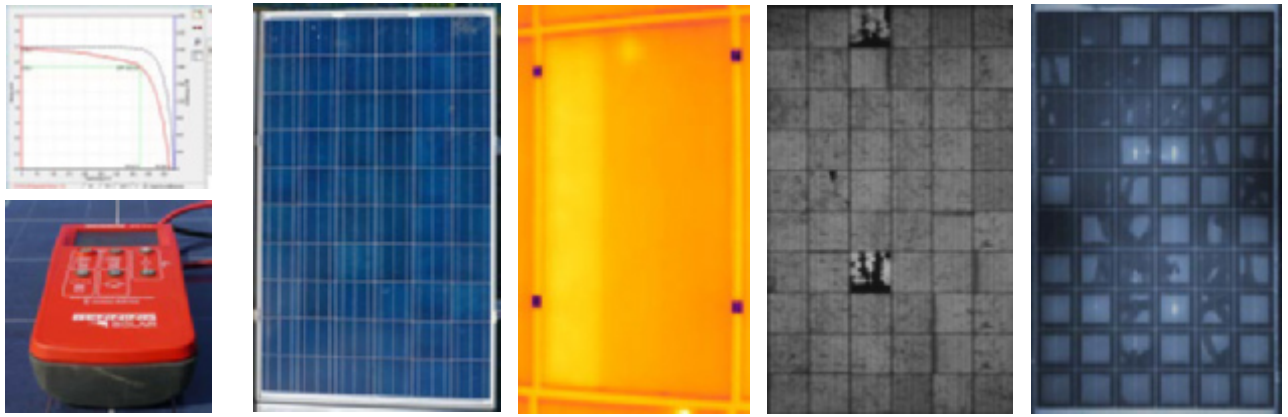
3. **PRIORITY: Comprehensive and detailed analyses → „relativize“ accuracy**

   → *scalable reproducible high-volume comparison measurements instead of high-precision single measurements, preferably normative, AI-supported evaluation enables forecasts*

Analysis of on-site measurement methods and failure types

Method assessment by significance and unambiguity of results

GREEN: currently possible
YELLOW: possible in future
RED: not possible



fault detection / measurement method	EM	VI	IR	EL	UV-FL
glass breakage, shading, and soiling					
delamination and discoloration					
substring, module, and string failure					
cell and finger faults					
PID, also in the initial stages					
LID and LeTID					
cell fractures and isolated areas					
micro cracks					

Analysis of Large Scale PV Plants and Suitable Sensor-Platforms

Existing Monitoring

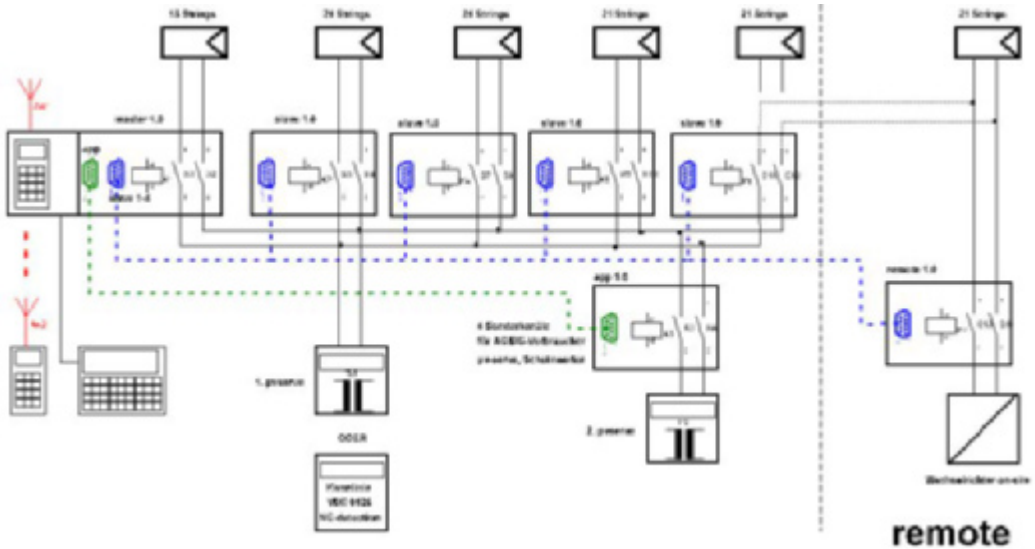
UAV

Tripod Systems

Electrical Measurement & Hub/Switch

Switch Platform – High-Volume Measurement and Energizing

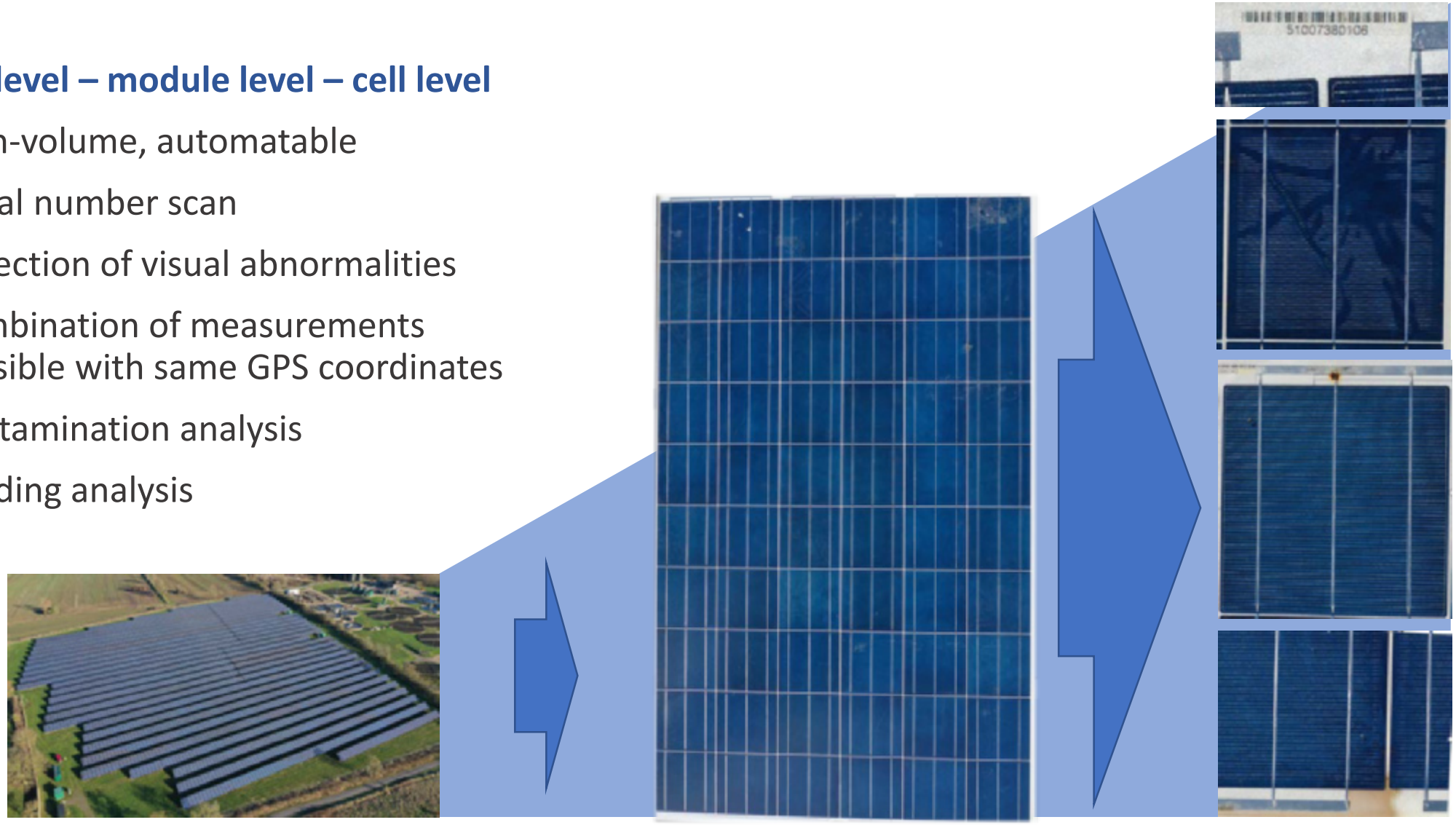
- ✓ 100 channel switch/hub (relay-based or electr.), manual or automated remote control, mobile & modular, emergency shutdown
- ✓ Measurement of Uo, Isc, ISO, IV-curve, Rp, Rs, FF, Vmpp, Impp, dark-IV
- ✓ Power supply DC 0-1500 V/0-15 A per unit, with separat RCD, programmable for simulation of different operating states with EL and IR
- ✓ Automated additional measurements in seamless workflow: cable location, arc-detection, etc.



UAV Platform – Semi-Automated Visual Inspection

Plant level – module level – cell level

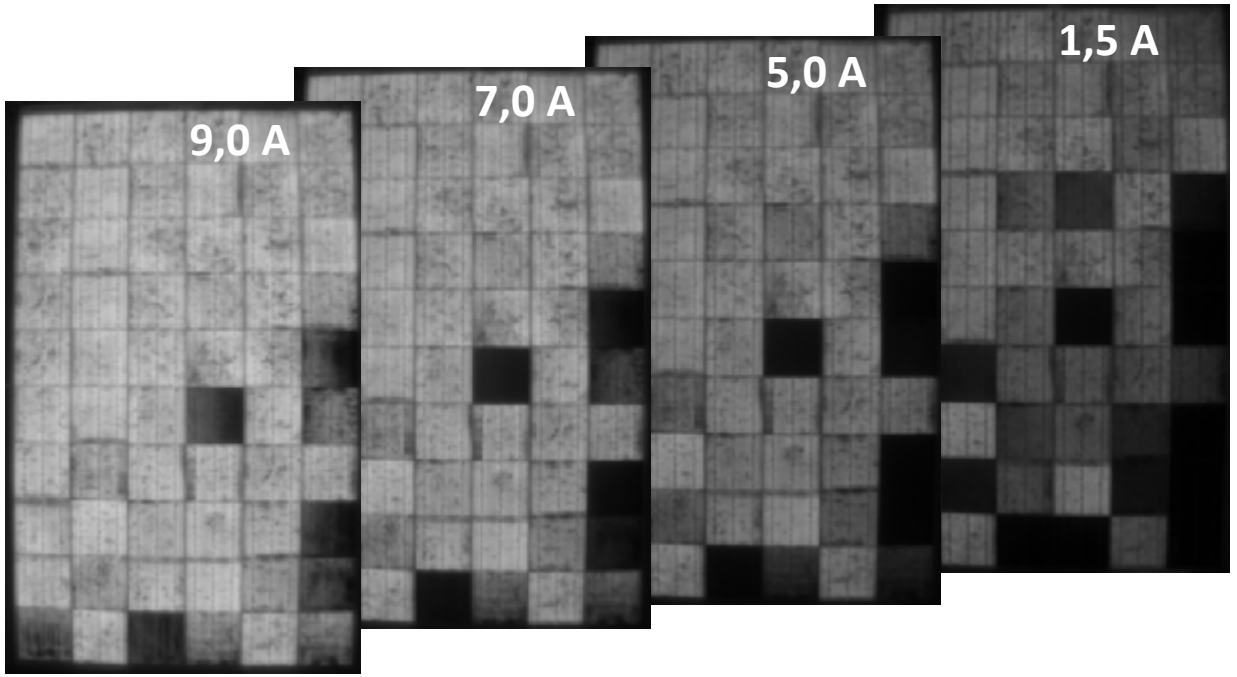
- High-volume, automatable
- Serial number scan
- Detection of visual abnormalities
- Combination of measurements possible with same GPS coordinates
- Contamination analysis
- Shading analysis



UAV Platform – Semi-Automated EL Inspection

Plant level – module level – cell level

- Total and detailed loads can be shown
- Ageing and changes can be depicted
- Cell and finger contact faults
- Cell cracks and fractures, micro-crack analysis
- PID fast-scan, also for initial stage (varying current strength during UAV recording)
- Preventive fire protection



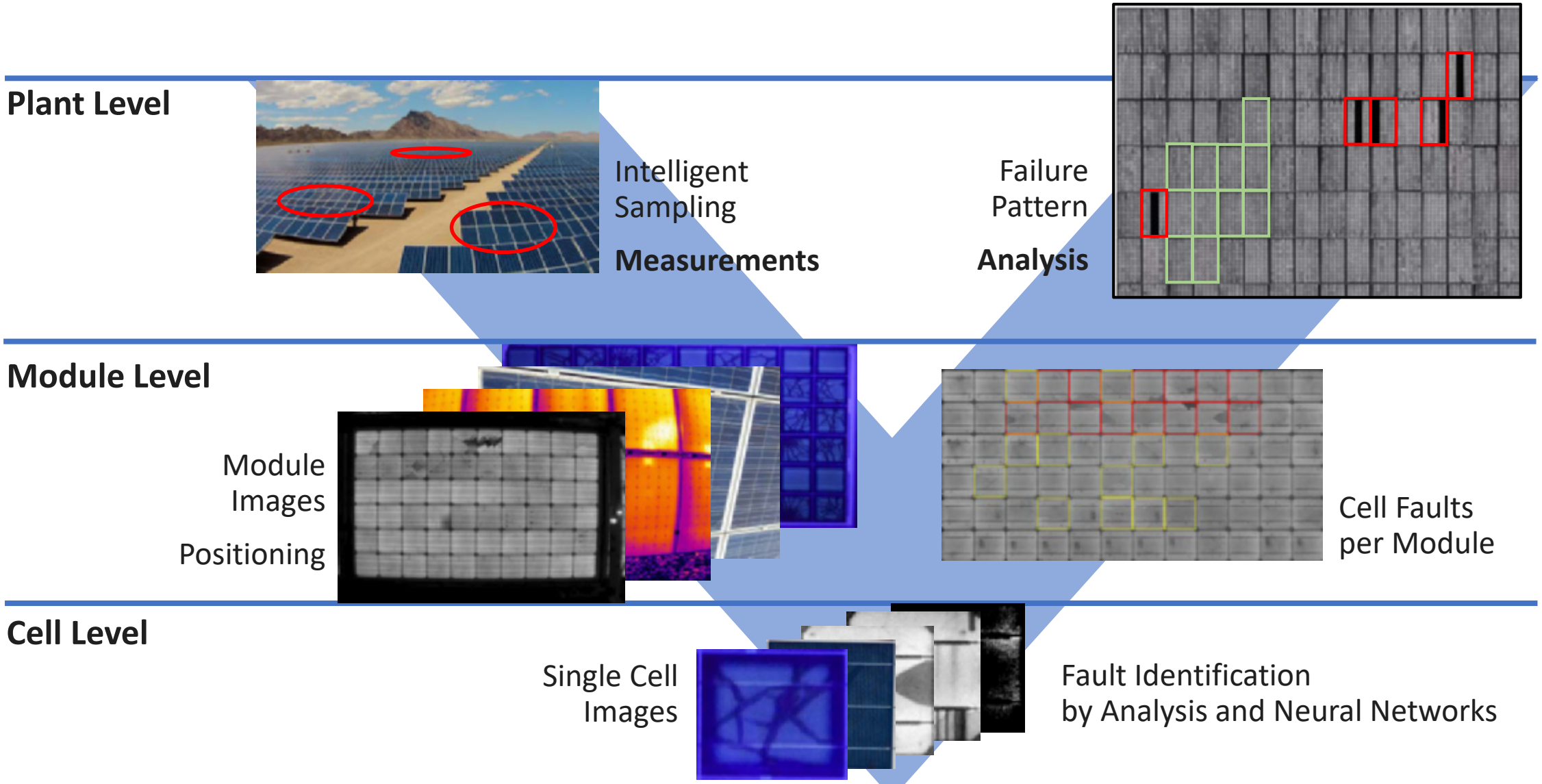
Synopsis of the market, technical and content requirements

Results

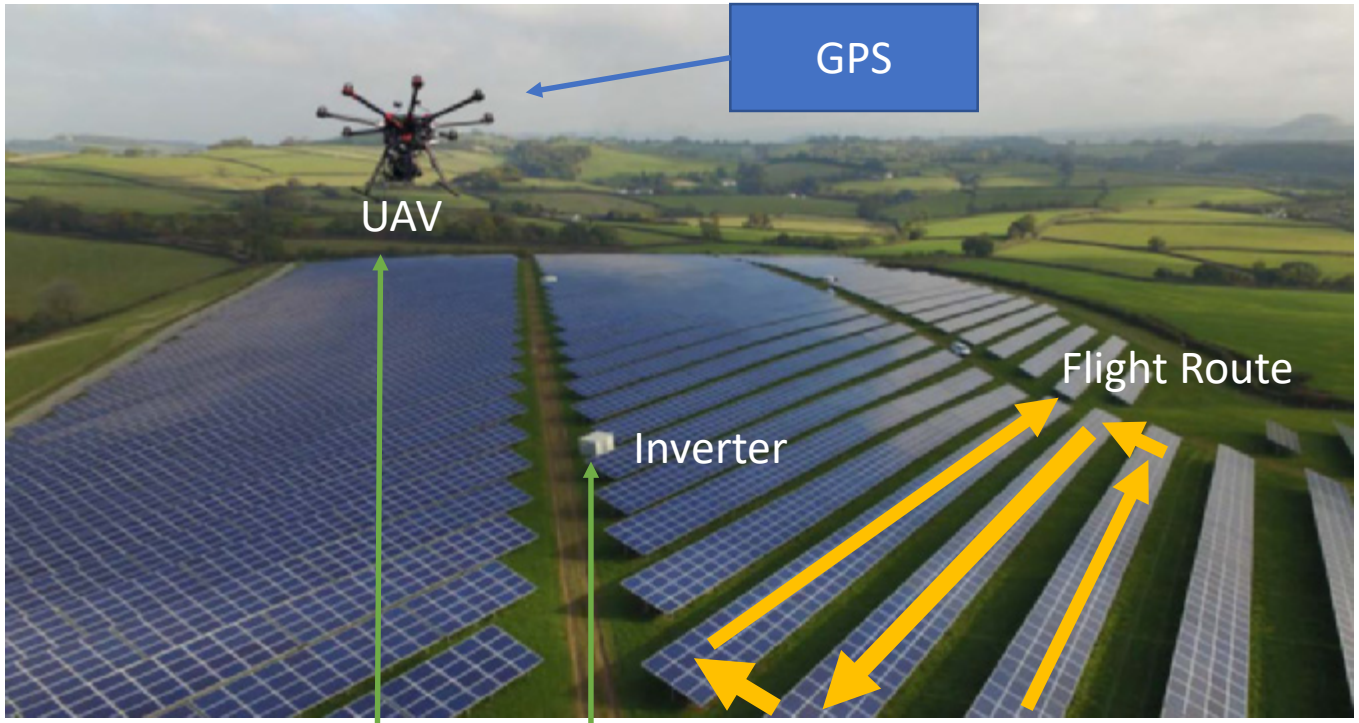
1. **UAV as central/main platform**
2. **EL as central/main method**
3. All test methods suitable for automated measurement and evaluation
4. Reproducible, 100% scalable
5. Combined measurements for 100% fault detection
6. Common workflow to reduce cost
7. Additional analysis are possible: simulate operating status, arc detection, shading and contamination analysis
8. **Integrate monitoring**

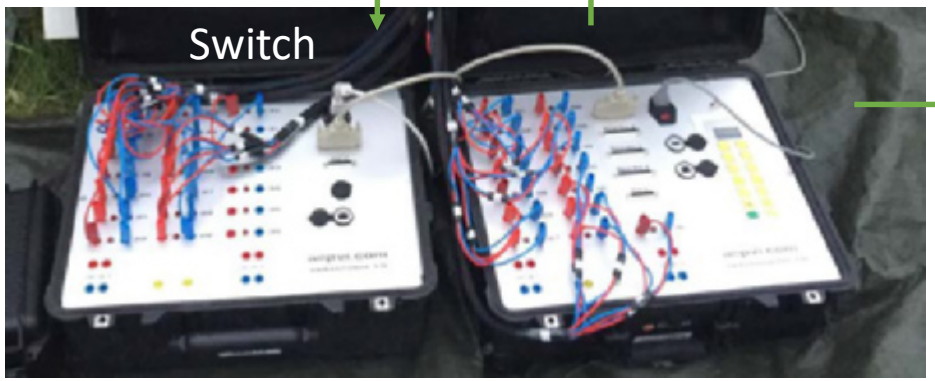
ON-SITE MEASUREMENTS		Monitoring	Electrical		VI		IR		EL		UV-FL	
possible												
possible in future			usual manual	auto	usual UAV	UAV	usual UAV	UAV	usual manual	UAV	usual manual	UAV
not possible		existing										
Measurement	cell level											
	module level											
	string level											
	plant level											
	scalable											
	automatable											
	normative											
operating state	simulatable											
plant layout	independent											
inverter layout	independent											
cell type	independent											
parameters	independent											
cost	low											
effort	low											
Evaluation	cell level											
	module level											
	string level											
	plant level											
fault detection	clear											
	scalable											
	automatable											
cost	low											
effort	low											

Inspection Concept



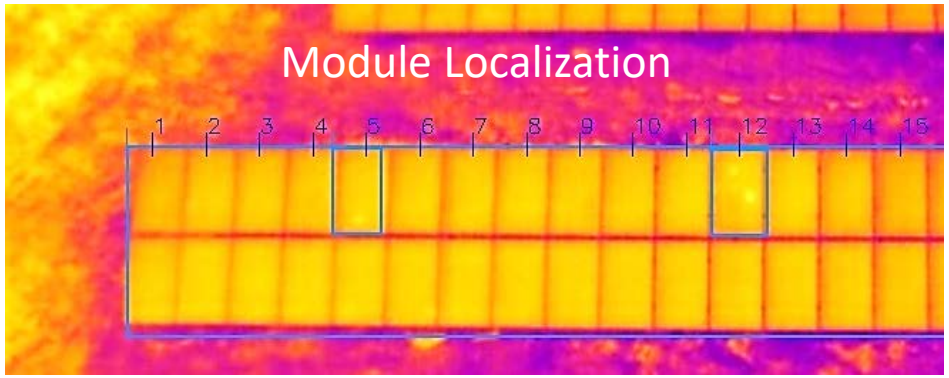
Measurements closely Interlocked with Evaluation





How to inspect large PV plants:

- Central Switch as data and energy hub
- UAV flies along prepared flight route
- UAV keeps track of position by GPS
- Allocate measured data exactly to individual modules
- Automatize step by step:
  - Automatic UAV flight: flight route, communication with Switch, recording
  - Automatic evaluation: module positions, fault classification

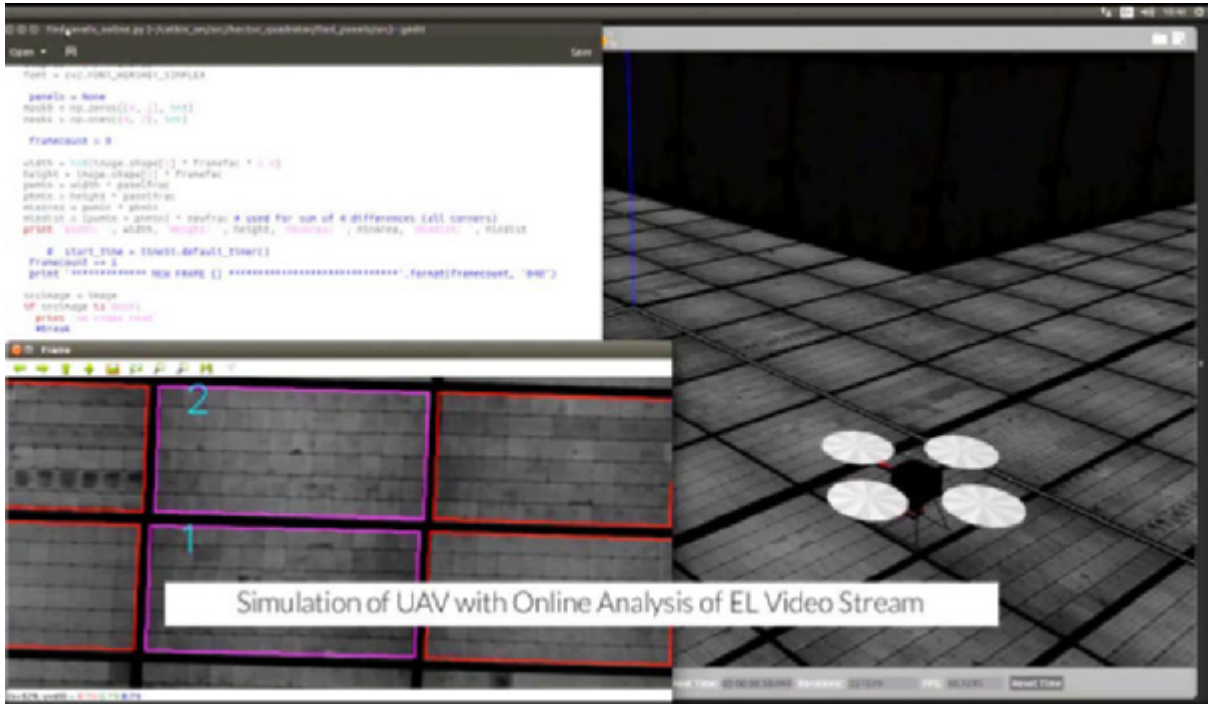


Automated UAVs

- UAVs receive position information by GPS. Improved accuracy is possible with Real-Time-Kinetics. In theroy, the flight route can be planned exactly.

! But: In reality often the installations are not according to the plan, GPS is not reliable enough, and camera view is not straight down.

› So: On-board computer to identify modules in real time and position UAV.



Programming:

- identify modules in view
- follow acutal module positions
- record images and videos

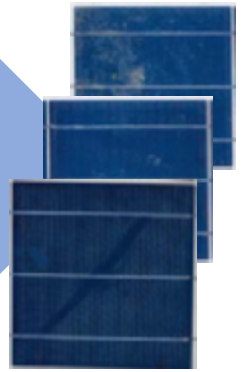
Embedded controller for automated flight

Cell Image Extraction

Visual Video

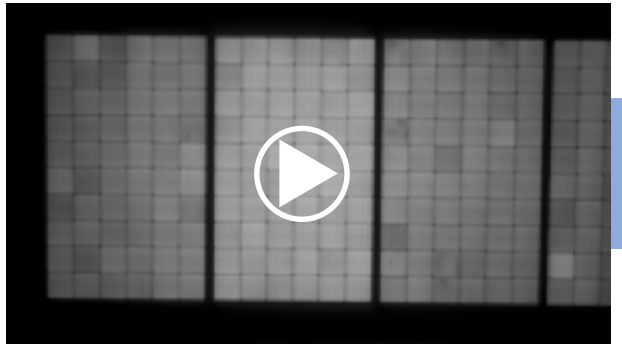
Identify Modules

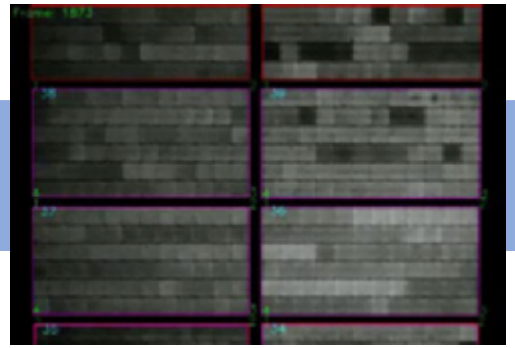
Extract sharpest frame, correct light, cut exactly

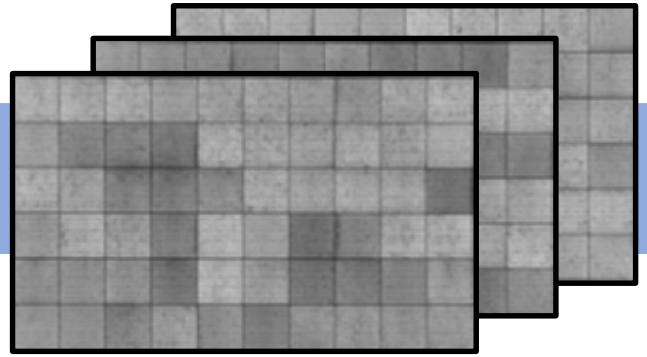


Cut Cells

EL Video



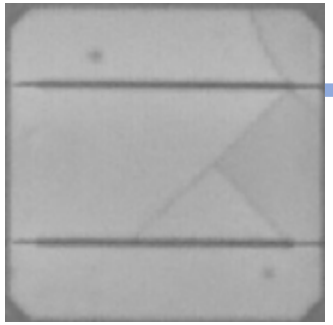




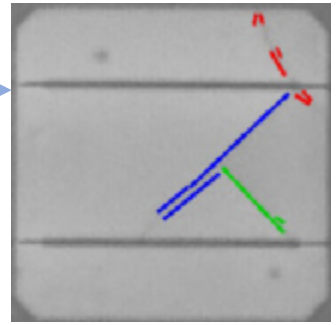
Cell Fault Identification

by **Feature Anlaysis**

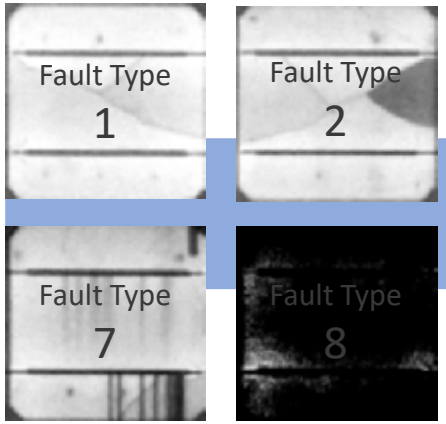
Example: Crack detection
in mono-crystalline cells



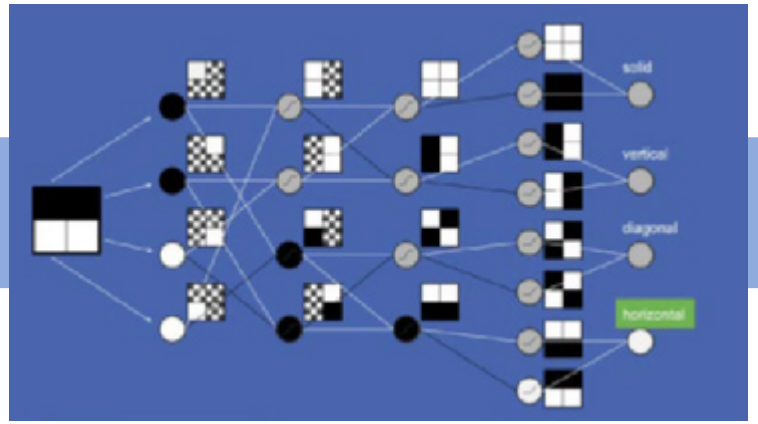
Programming:
- specific feature recognition
- search for local occurences



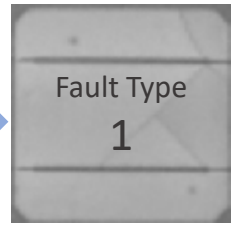
by **Neural Networks**



Training with
evaluated
images

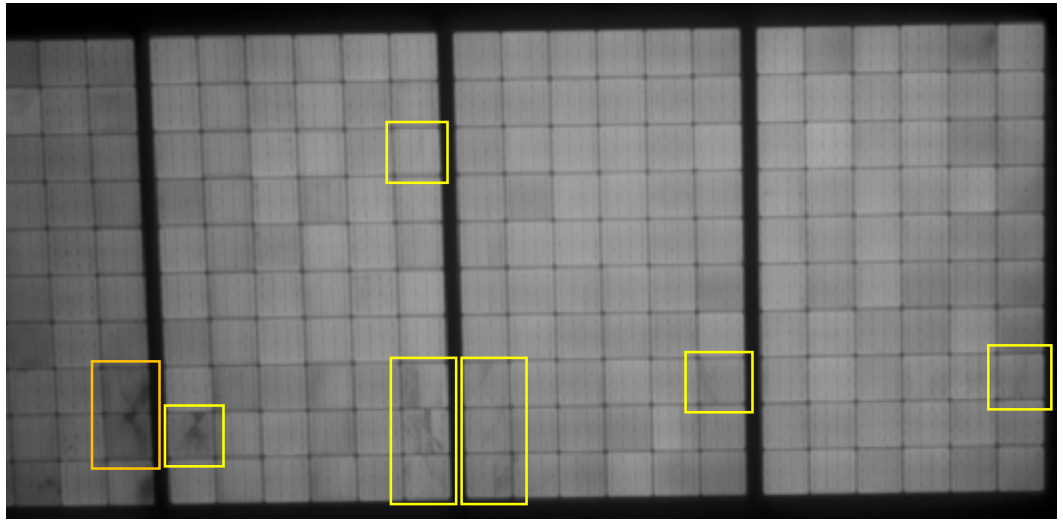


Neural Network
has learned to
distinguish faults



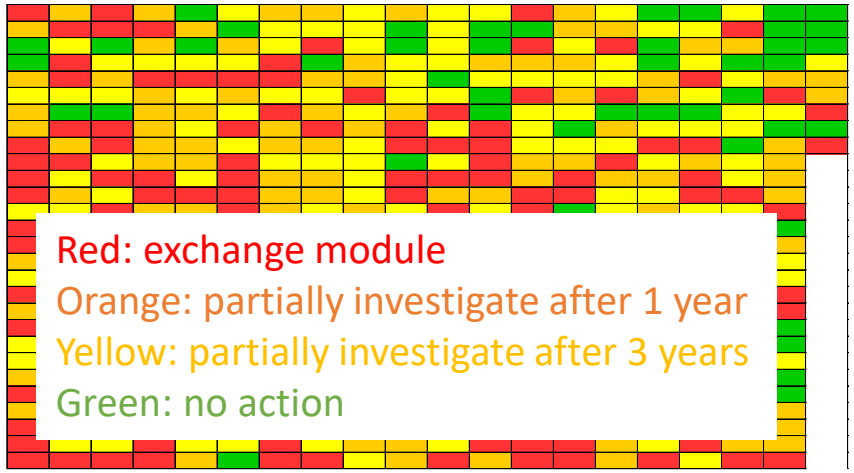
From Cell to Plant Level: Correlations and Causality

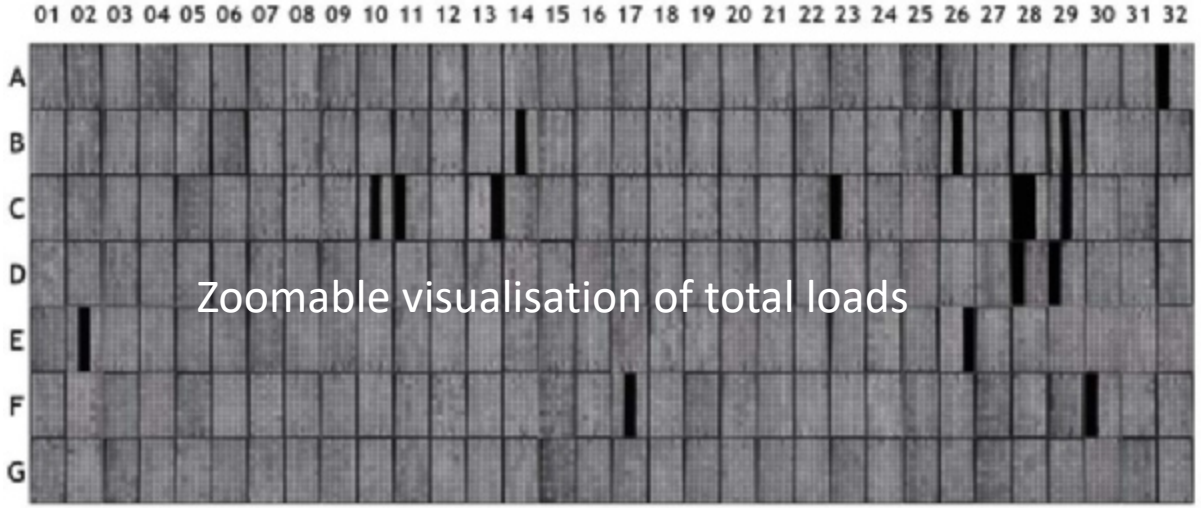
Root cause detection:
Detect installation faults, here: walking or kneeing on modules



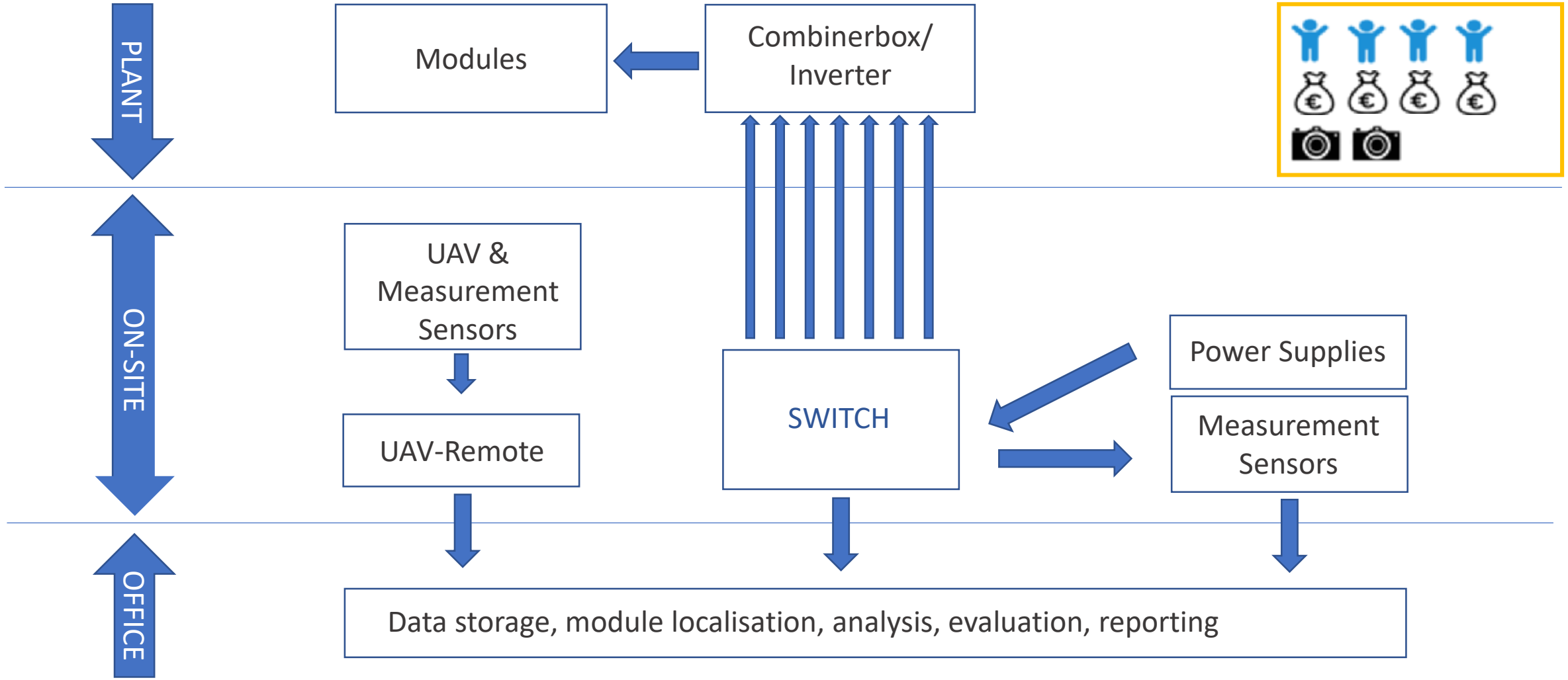
Root cause: mistreatment

Fault localization:
Exact location of faulty modules, recommendation of actions

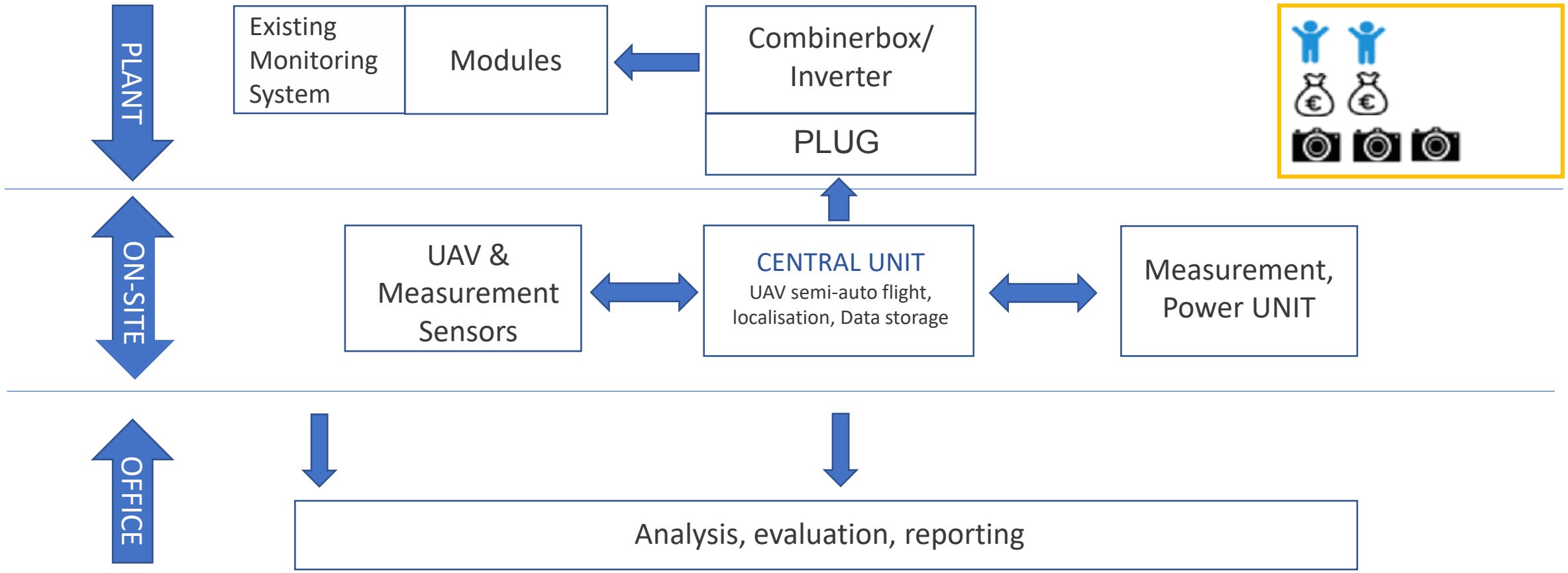




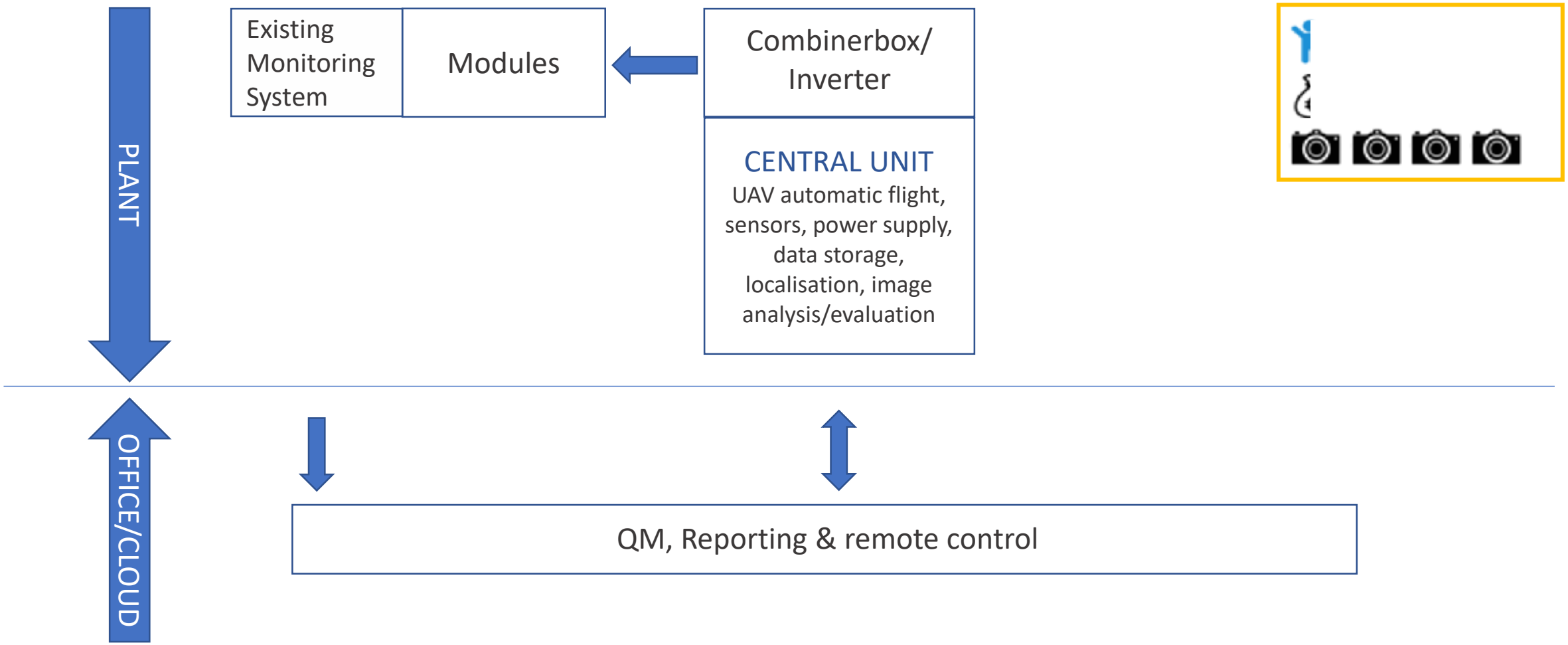
Overview MOBILE System (current state)



Overview PLUG System (2022)



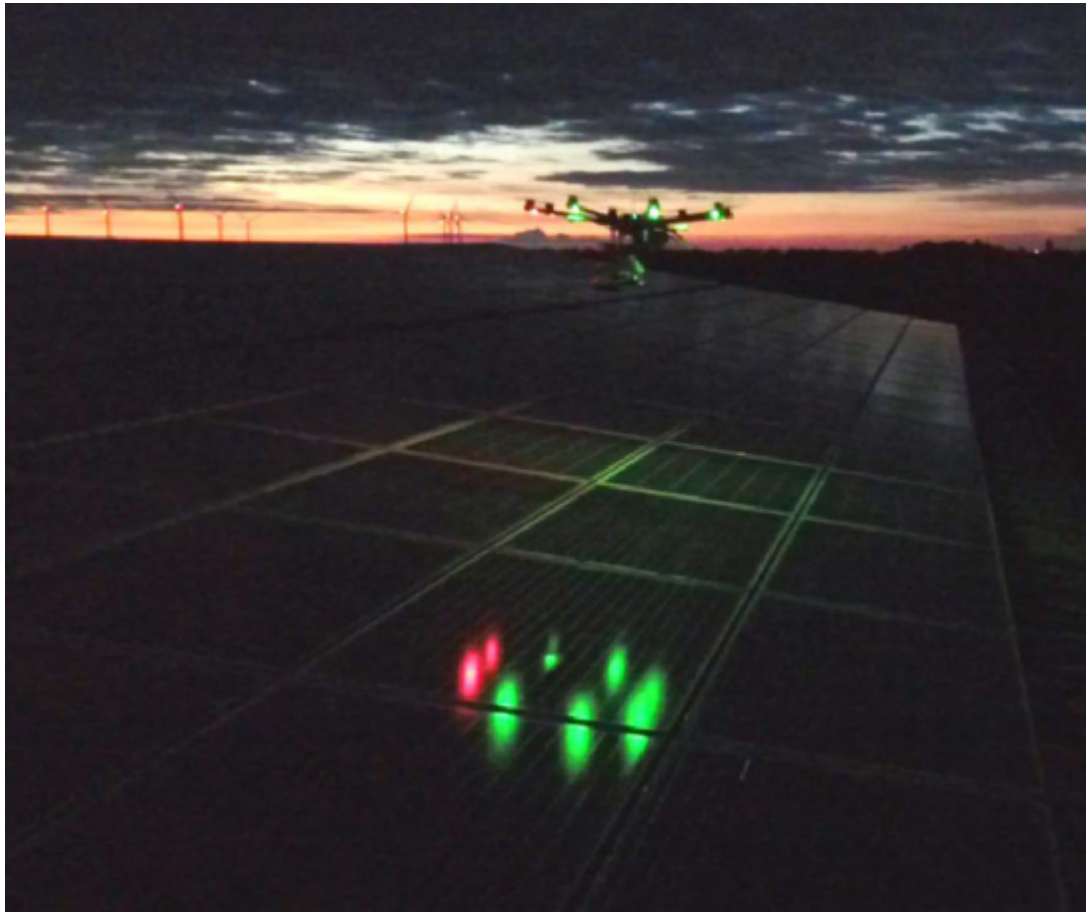
Overview HIVE System (2025)



Large Scale EL - Conclusion

- Quality assurance from cell to plant level
- Scalable sampling up to 100%
- Root-cause detection
- Combination of measurement methods, O&M measures in a common workflow
- Evaluation and reporting automatable
- Footprint and lifecycle data management
- Cost reduction - PLUG/HIVE concept

Low cost inspections by EL are possible



Thank you for your attention

Aerial PV Inspection GmbH
Aachen, Germany
www.aepvi.com

SOLAR ENERGY
TECHNOLOGIES OFFICE
U.S. Department Of Energy

DOE PV Fleet Performance Data Initiative

Inna Kozinsky, Science and Technology Advisor, Contractor
Solar Energy Technologies Office

energy.gov/solar-office

What Problems Will It Address?

- **For PV Fleet Owners and Operators**
  - Lack of accurate knowledge about their system performance, which could help future business decisions.
  - Extracting degradation rate is complex and costly.
- **For PV Research and Analysis Community**
  - Lack of available high-quality data to study degradation, develop standards, accelerated tests, and analysis tools.
- **For PV Financing Community**
  - No US PV fleet annual degradation rate based on actual data to use in financial planning models.

SETO would like to work with you to make sure that the Initiative goals and mechanics address your needs.

DOE PV Fleet Performance Data Initiative

PV fleet owners and operators are invited to contribute:

PV Plant Power Data

CONFIDENTIAL

State-of-the-Art System & Degradation Rate Analysis

Anonymized

Performance Report to PV Data Owner

CONFIDENTIAL

Anonymized and Added to **Aggregate Long-Term PV System Performance Benchmark**

PUBLISHED EVERY YEAR

Open-access Data Sets

PUBLISHED

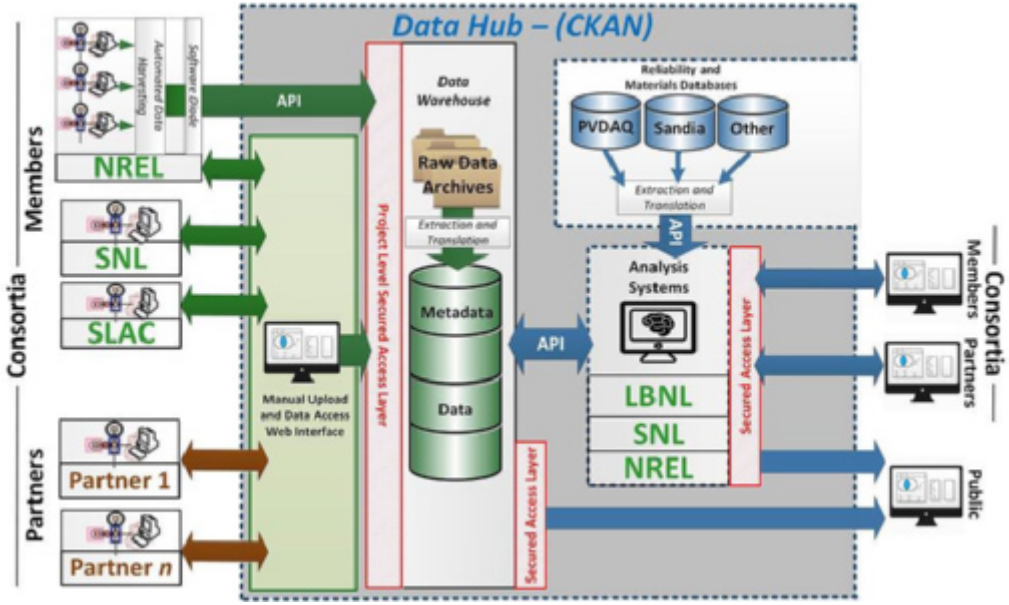
State-of-the-Art System & Degradation Analysis Tools

NREL in collaboration with DuraMAT Data Hub:

Chris Deline (NREL)
Mike Deceglie (NREL)
Dirk Jordan (NREL)
Robert White (DuraMAT/NREL)
Teresa Barnes (DuraMAT/NREL)

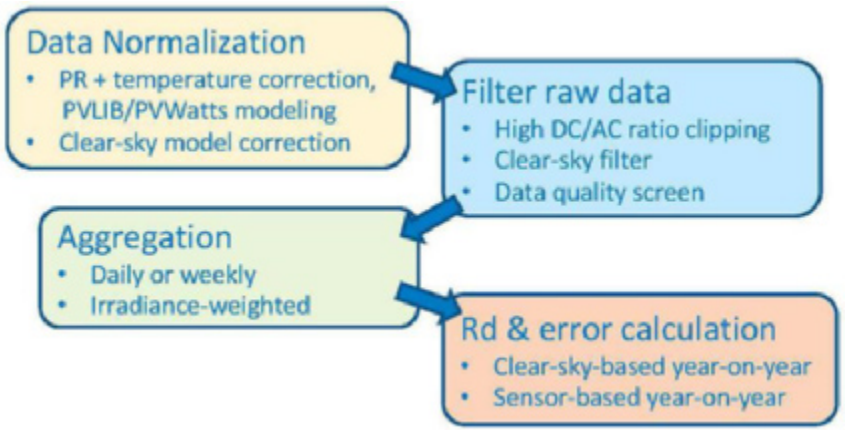
https://datahub.duramat.org

DuraMAT Data Hub will be used to store data and provide secure access to multiple users.

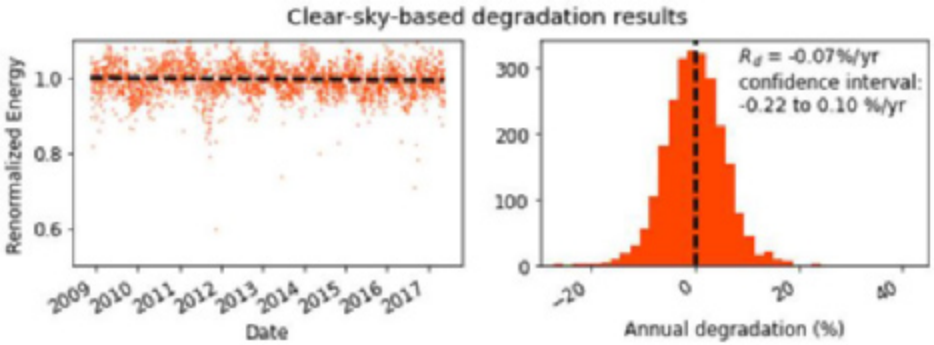


State-of-the-Art System & Degradation Analysis Tools

RdTools will be used to calculate annual degradation rates and confidence intervals from time-series performance data.



https://www.nrel.gov/pv/rdtools.html



"The RdTools method was used to analyze energy generation from 264 PV systems at locations across the globe, revealing that degradation rates were slower than expected," said Greg Kimball, a senior performance engineer at SunPower. "The result prompted improvements to and extension of our warranty coverage to customers." https://phys.org/news/2018-04-solar-pv-tool-accurately-degradation.html

DOE PV Fleet Performance Data Initiative

PV plant owners and operators are invited to contribute:

PV Plant Output Power Data

CONFIDENTIAL

What data is needed?

- Time-series PV system power output for large-scale installations (>250 kW) for ≥ 5 years collected at 1-15 min intervals, with
- On-site irradiance and meteorological data
- "Metadata" (type of PV modules, location, mounting, azimuth and tilt)

- Detailed Data Partner document will be provided.
- Available public data sets will be incorporated if data meets the requirements. Pointers to those are appreciated.

Confidentiality of data protected via standardized NREL-approved NDA agreements and negotiated anonymization procedure, in progress.

SOLAR ENERGY
TECHNOLOGIES OFFICE
U.S. Department Of Energy

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Tassos.Golnas@ee.doe.gov

Fleet-scale performance and degradation analysis

Michael G. Deceglie[1], Dirk C. Jordan[1], Ambarish Nag[1], Adam Shinn[2], and Chris Deline[1]

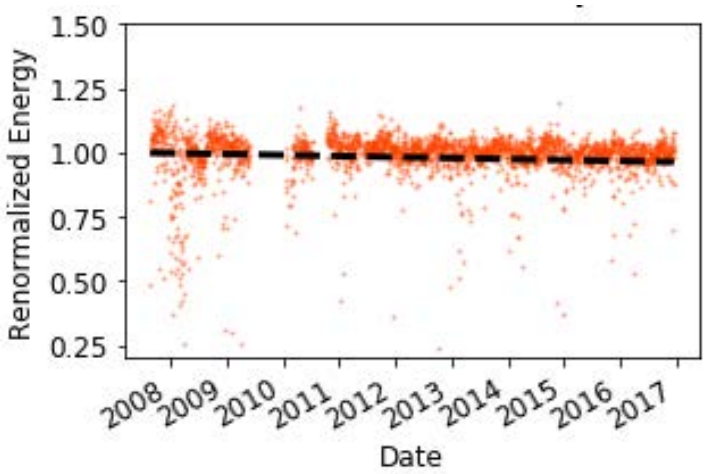
[1]National Renewable Energy Laboratory

[2]kWh Analytics

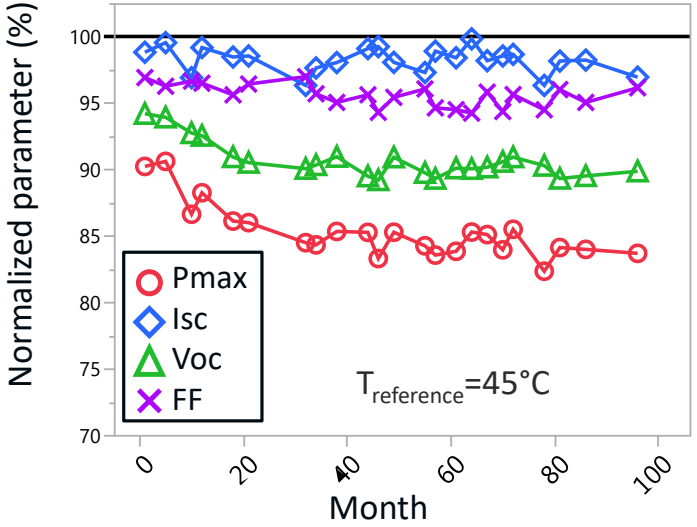
NREL Photovoltaic Reliability Workshop 2019

Case studies vs. fleet analysis

Outdoor time series



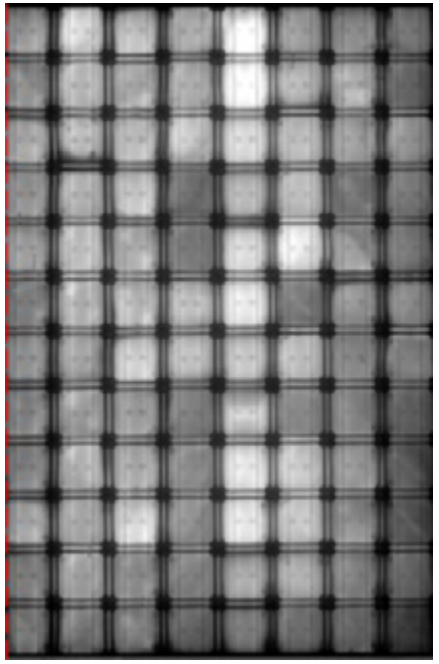
Outdoor IV



Case Study

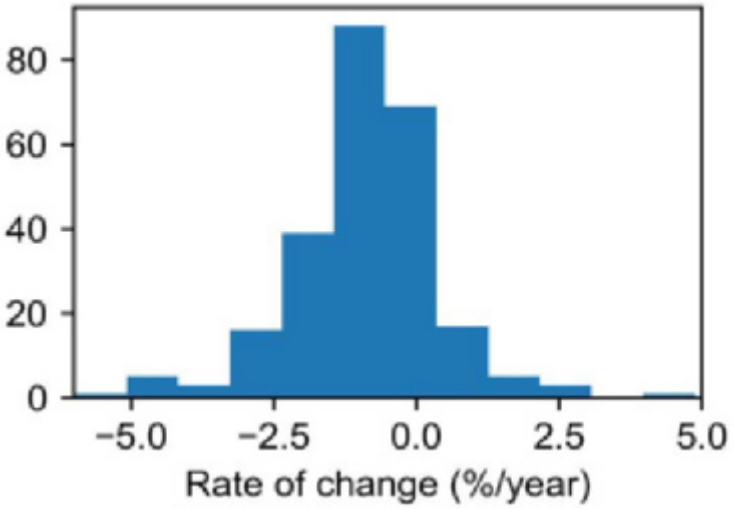
Detailed analysis on a small number of systems

Electroluminescence



Fleet analysis

Trends in large numbers of systems

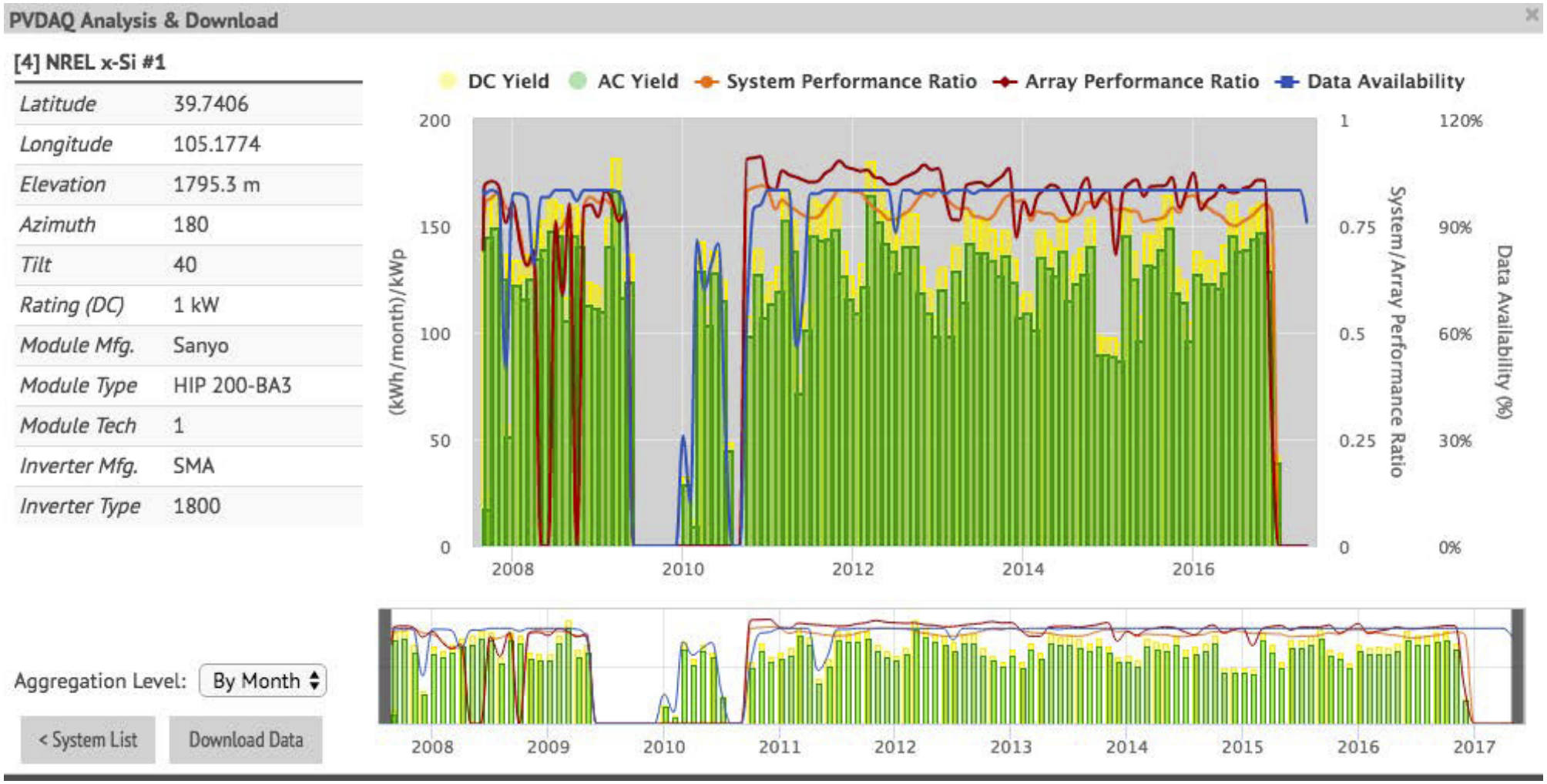


A Tale of Two Systems

Challenges with fleet scale analysis

Comparison of two systems

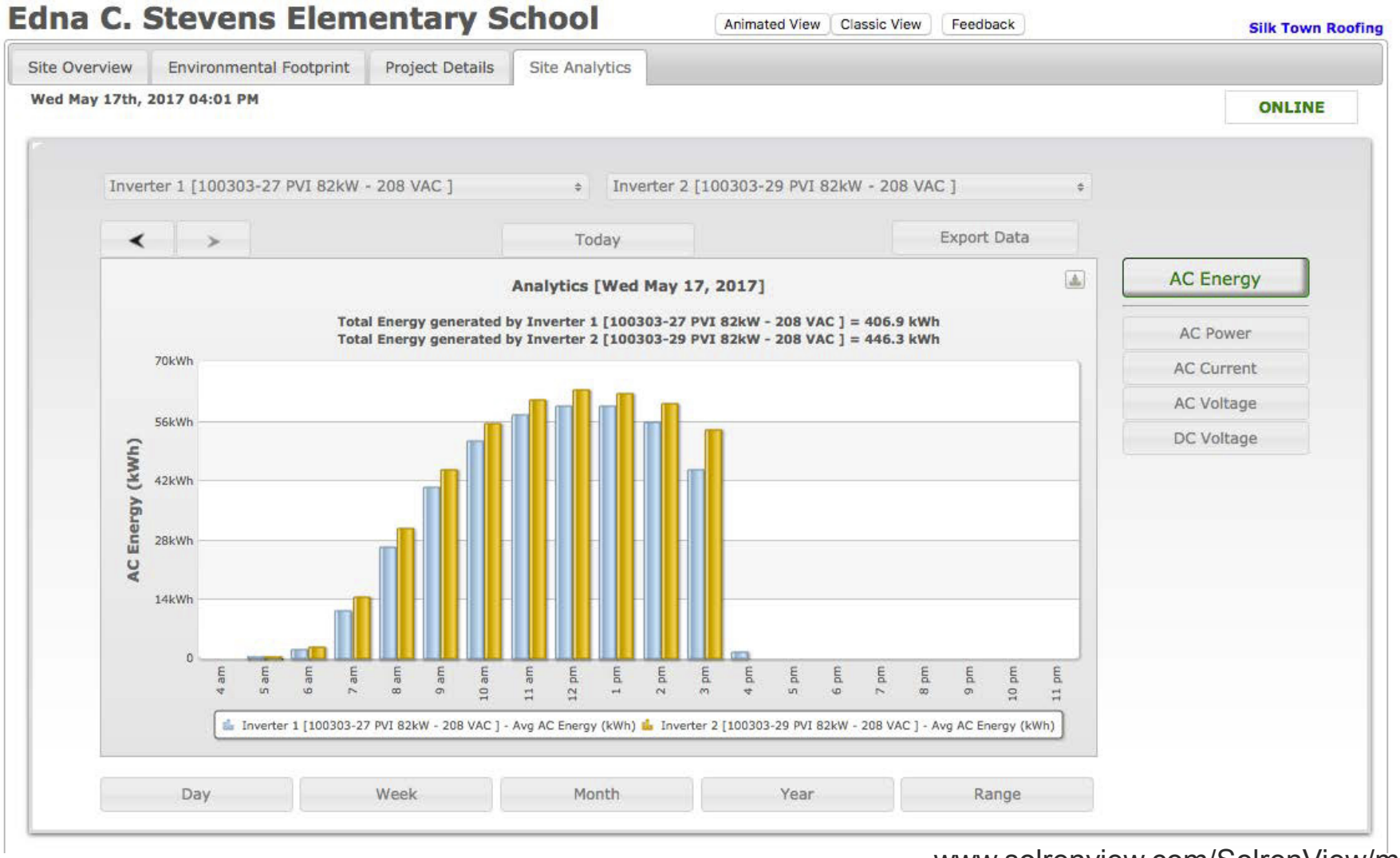
System 1: Research system at NREL



maps.nrel.gov/pvdaq

Comparison of two systems

System 2: Elementary School in Connecticut



www.solrenview.com/SolrenView/mainFr.php?siteId=726

Comparison of two systems

Research system

- Metadata:
  - Location
  - System orientation
  - Module details
  - Inverter details
- Time series:
  - 1-minute
  - AC power/current/voltage
  - DC power/current/voltage
  - Ambient temperature
  - Inverter temperature
  - 3 module temperatures
  - Plane-of-array irradiance
  - DAS diagnostics

Elementary school

- Metadata:
  - Location
  - Module details
  - Inverter details
- Time series:
  - 5-minute
  - AC power/current/voltage
  - DC voltage

Comparison of two systems

Research system

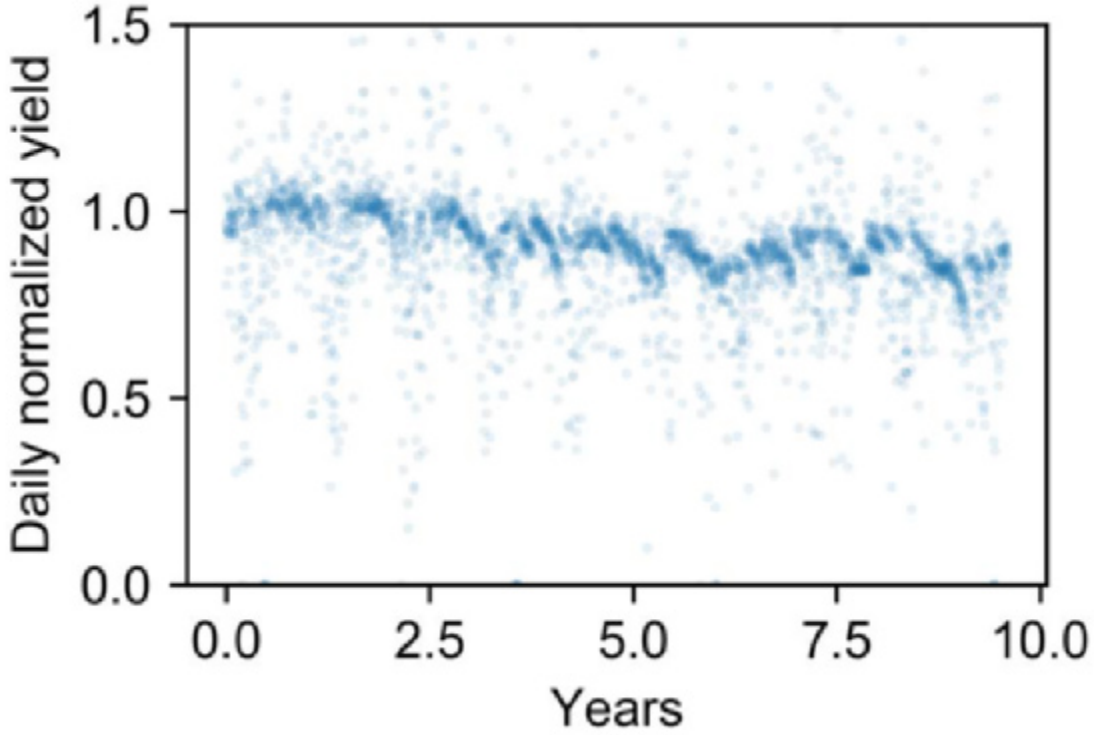
- Metadata:
  - Location
  - System orientation
  -
  -
- Tim
  -
  - AC power/current/voltage
  - DC power/current/voltage
  - Ambient temperature
  - Inverter temperature
  - 3 module temperatures
  - Plane-of-array irradiance
  - DAS diagnostics

Elementary school

- Metadata:
  - Location
  - Module details
  - AC power/current/voltage
  - DC voltage

Goal:
Robust analytics that enable comparisons between data sets from disparate systems

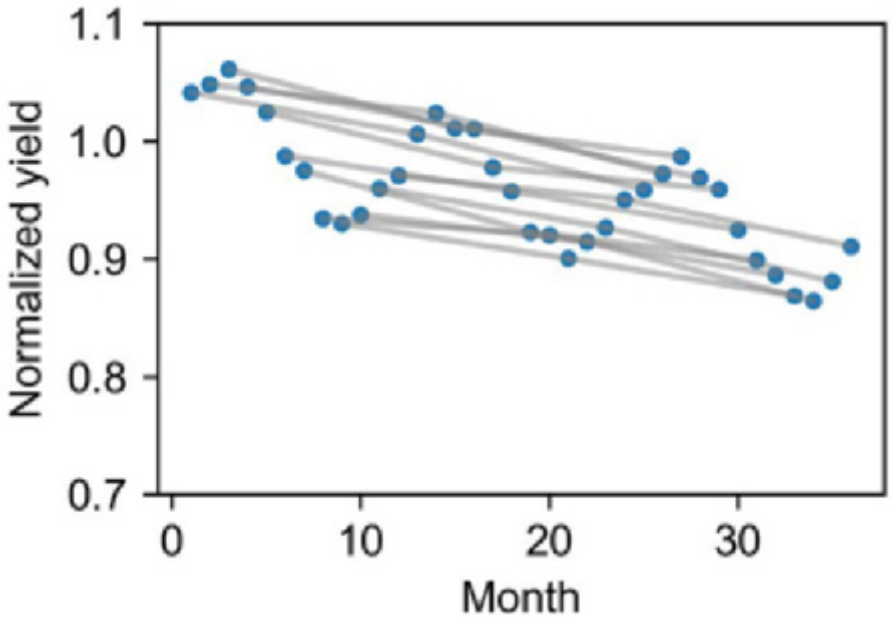
Robust degradation analysis



- Calculate at a daily normalized yield
- Use outlier-robust year-on-year technique to estimate degradation
- Use lowest-common denominator analysis
- Calculate and pay attention to the confidence intervals

Jordan et al. *PVSC*, p.0273, 2016
M. G. Deceglie et al. *IEEE Journal of Photovoltaics*, vol. 9, no. 2, pp. 476-482, 2019

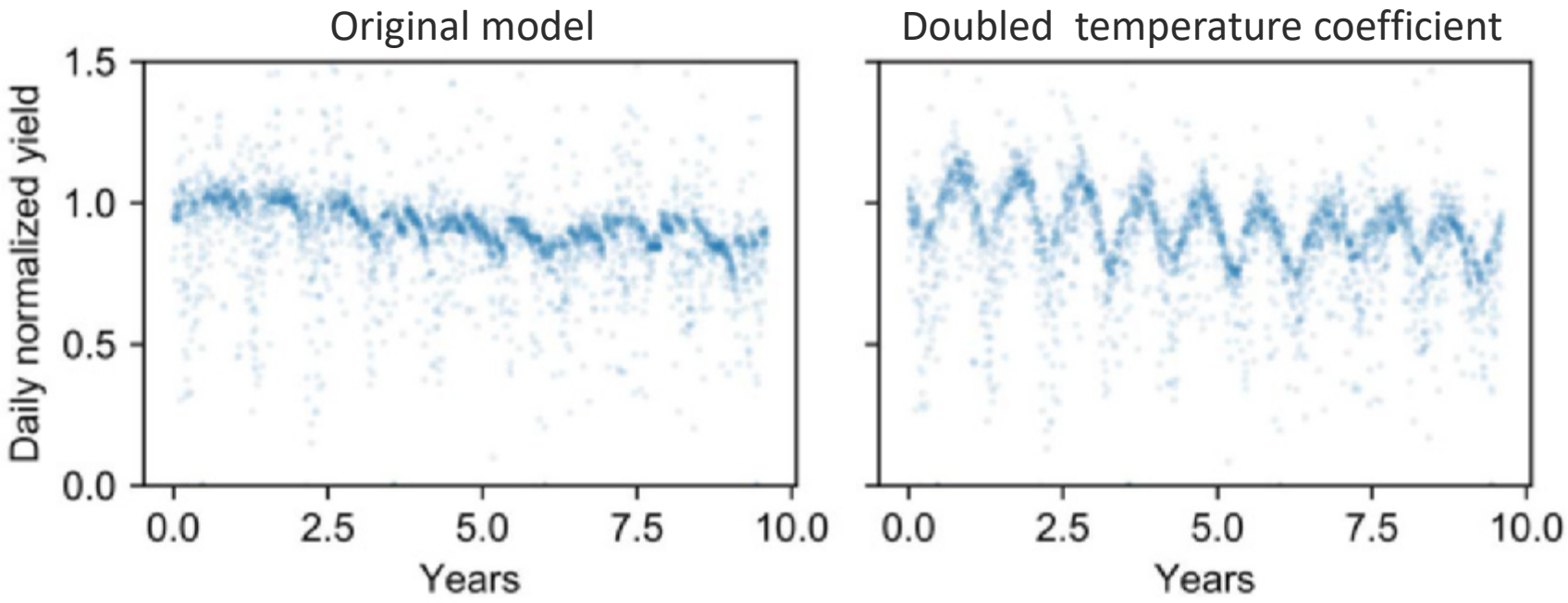
Year-on-year degradation analysis



- Year-on-year is robust to seasonality and outliers
- Steps:
  - Compare each day (or week, month, etc.) to its corresponding day a year later
  - Calculate the median of all year-on-year slopes
- Pay attention to the confidence interval

E. Hasselbrink, M. Anderson, Z. Defreitas, et al., “Validation of the PVLife model using 3 million module- years of live site data,” PVSC, p.0007, 2013
Jordan, Deceglie, & Kurtz. "PV degradation methodology comparison—A basis for a standard." PVSC, p.0273, 2016

Year-on-year is robust

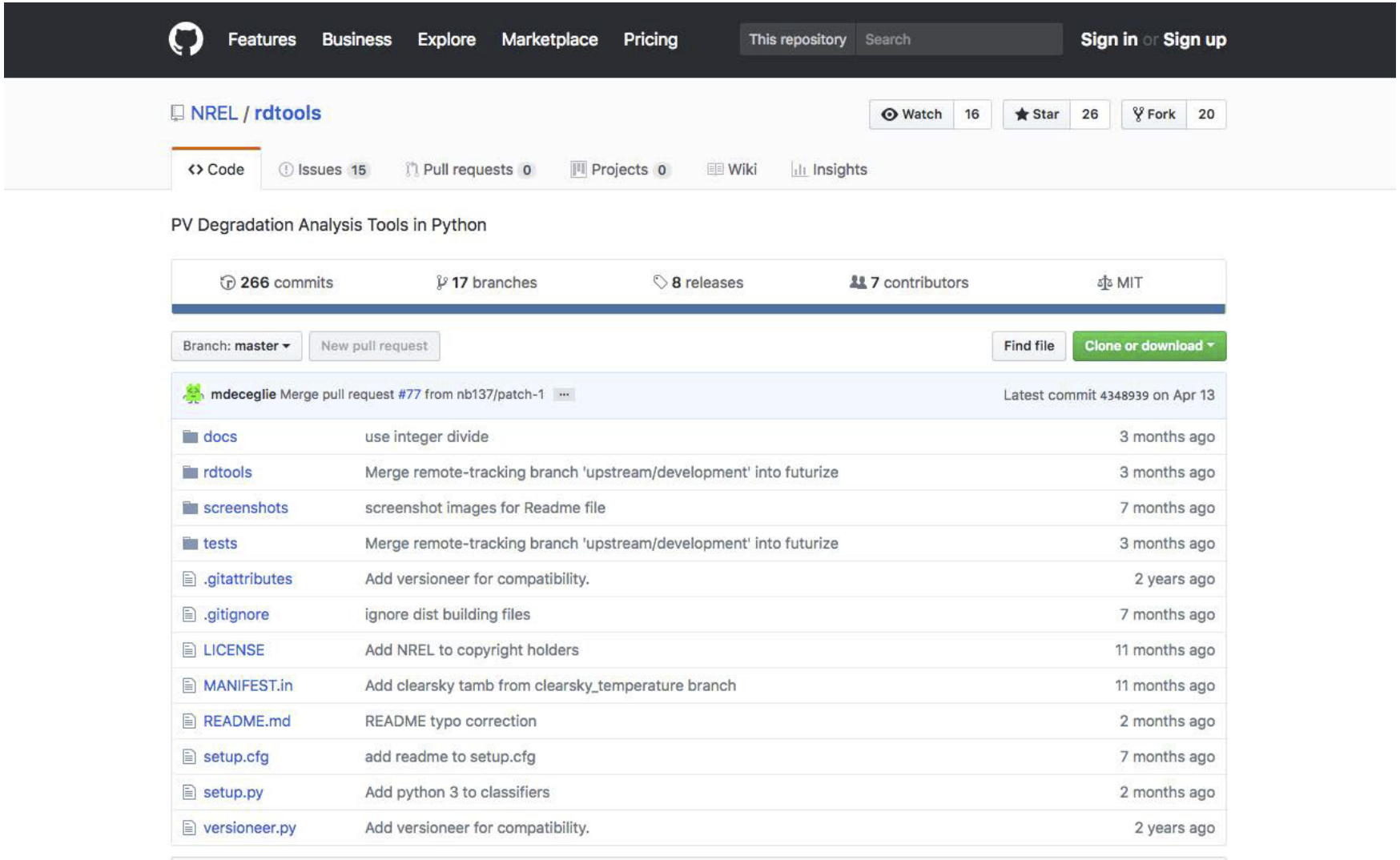


Rd: -2.2 %/year
Conf. Int.: –2.5 to –1.8 %/year

Rd: -1.9 %/year
Conf. Int.: –2.5 to –1.3 %/year

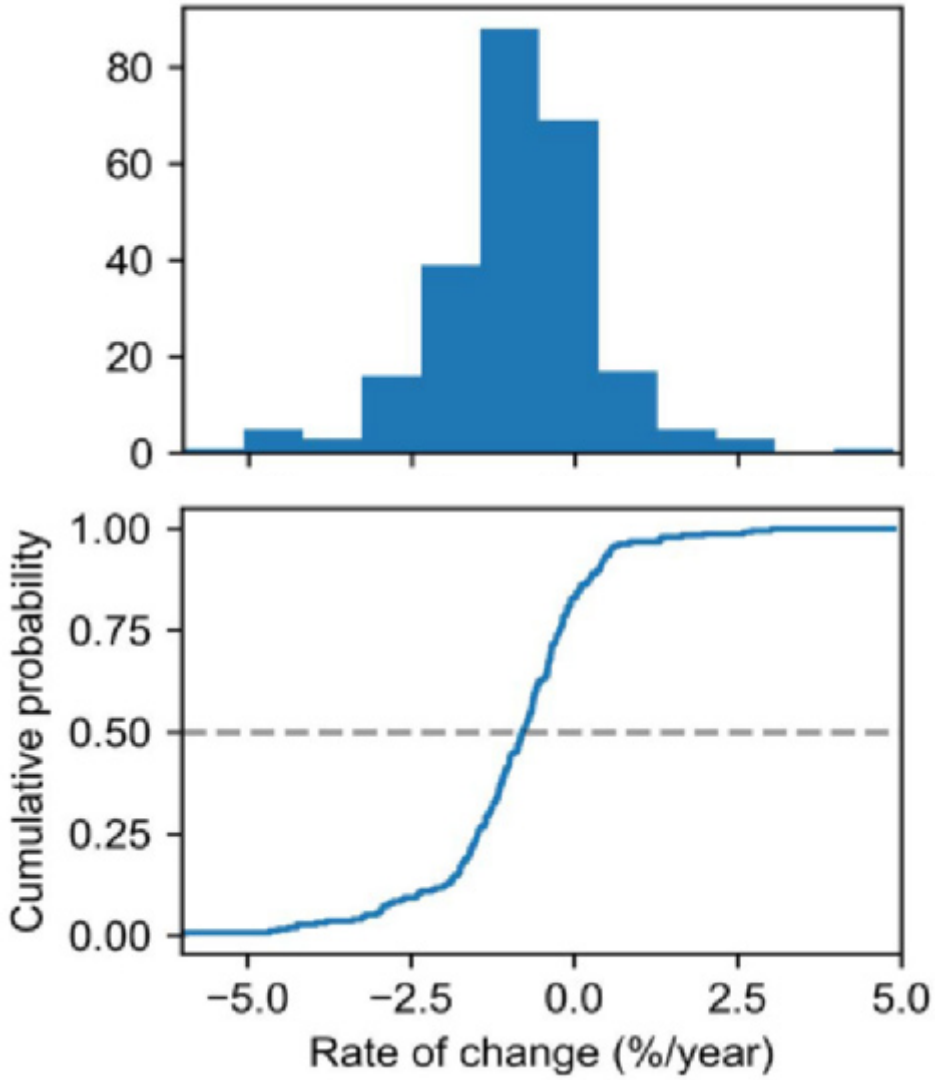
- Example: intentionally induced seasonality
- Results remain consistent
- Confidence interval appropriately expands
- **A very detailed performance model isn't needed**

All this is available in RdTools



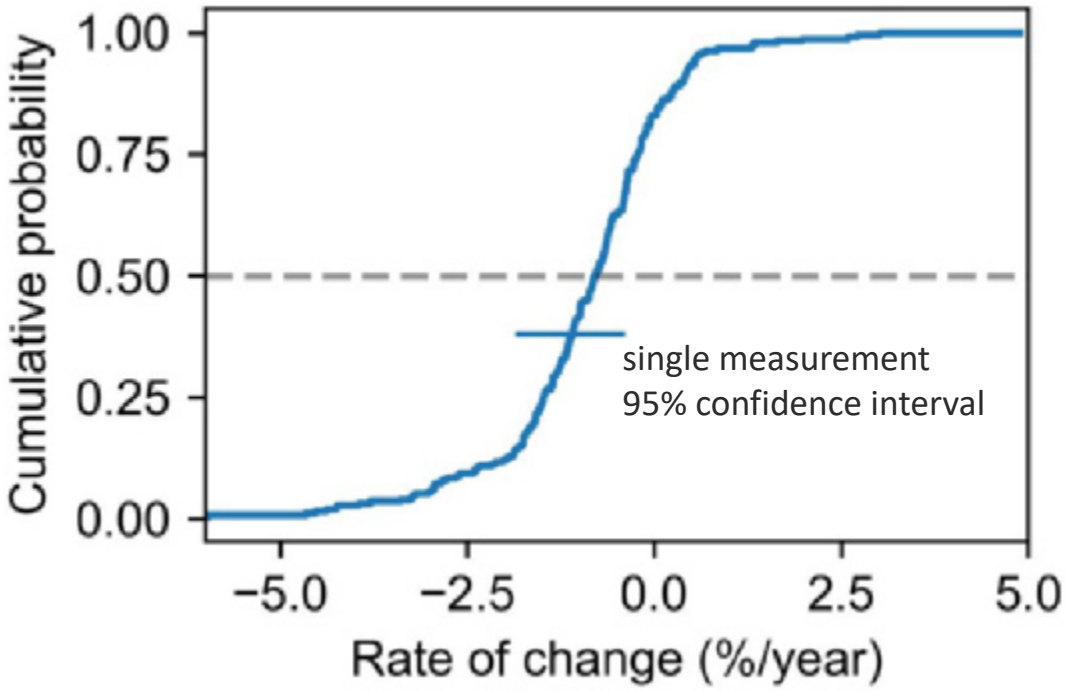
- Read me and examples: https://github.com/NREL/rdtools
- install: pip install rdtools

Cumulative distribution functions (CDFs)



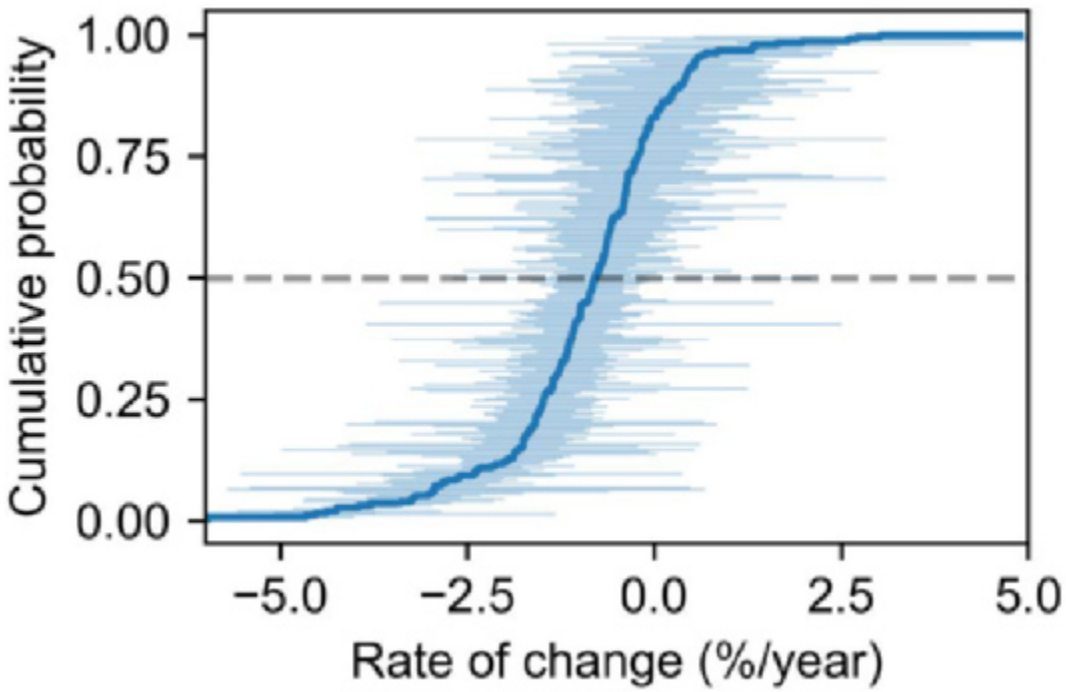
CDFs provide a way to visualize distributions, independent of bin size

CDFs with individual confidence intervals



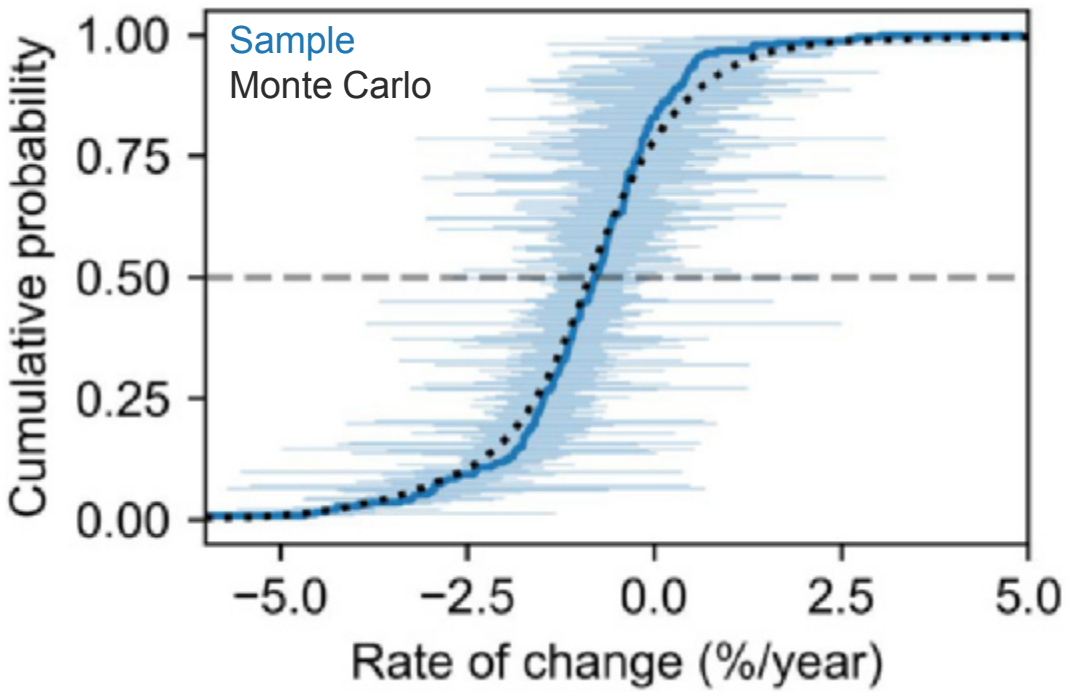
Every measurement on the CDF has its own uncertainty

CDFs with individual confidence intervals



We can include each measurement's 95% confidence interval on the plot

Uncertainty in the distribution

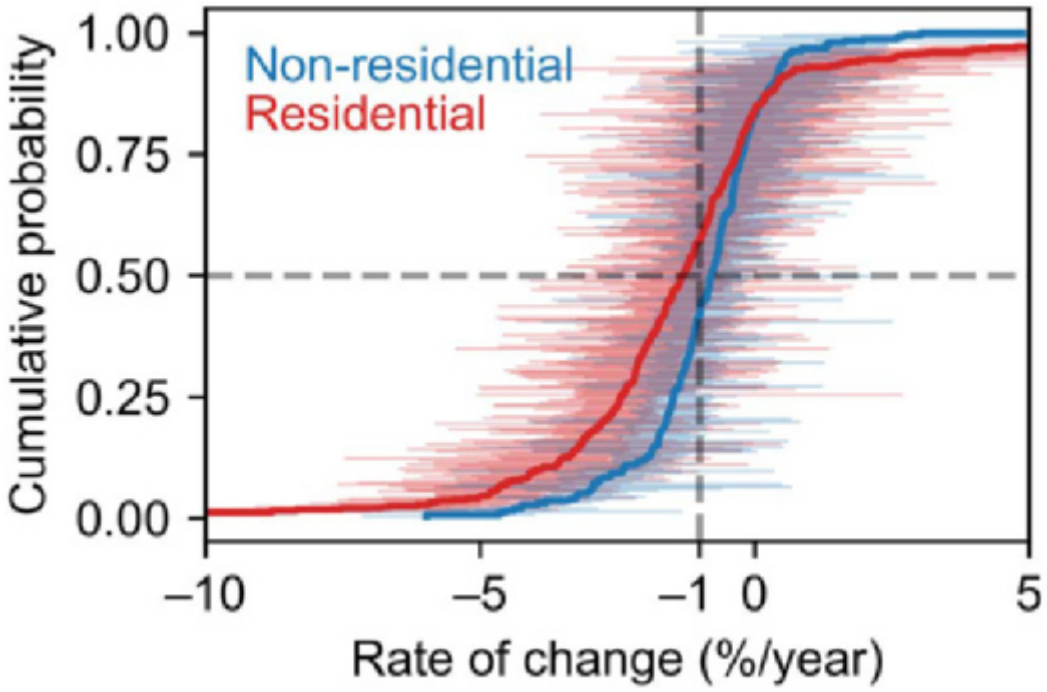


- Monte Carlo to include the effect of individual CIs on full distribution
- Resample the data (with replacement) within the individual confidence intervals many times
- CDF of this Monte Carlo resampling follows the original closely
- **For fleet-scale studies, we can sacrifice some site-level precision**

Example fleet-scale analysis

- Analyzed 634 subarrays from 503 PV systems in the United States
- 387 residential systems
- 116 larger, non-residential systems
- >3,400 system-years of time series data
- Used satellite weather data for consistency
- Study system energy-yield degradation

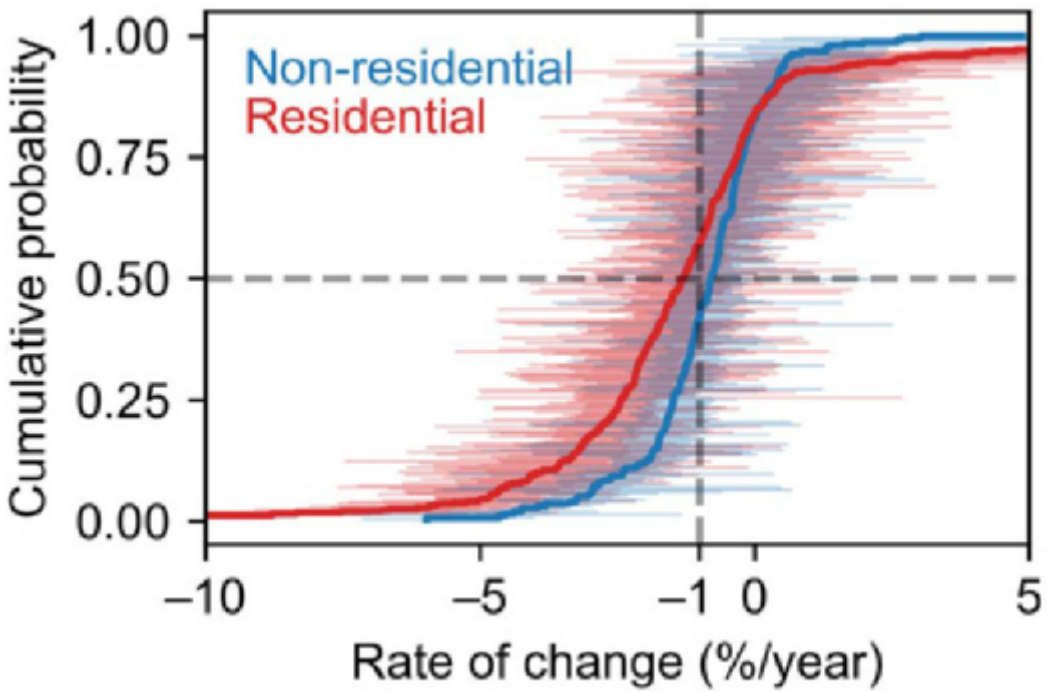
Residential vs. Non-residential



- Recall we are analyzing **system** yield degradation
- Negative rate of change = degradation (-1%/year indicated)

M. G. Deceglie et al. *IEEE Journal of Photovoltaics*, vol. 9, no. 2, pp. 476-482, 2019

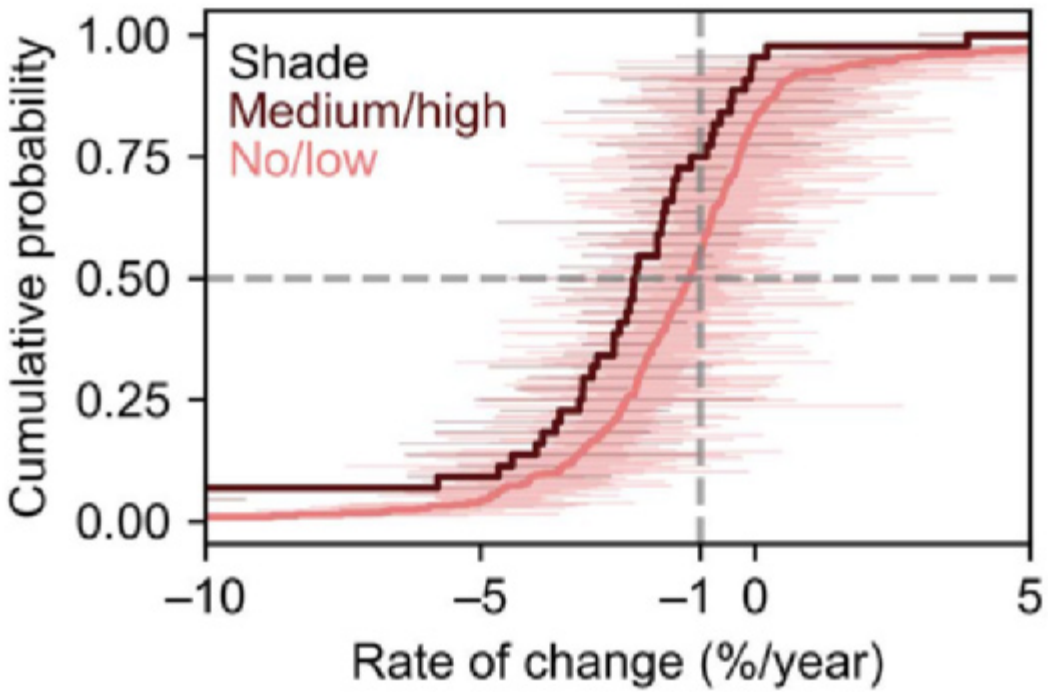
Residential vs. Non-residential



- Residential systems tended to degrade more rapidly
- 29% of residential and 38% of non-residential systems degraded slower than -0.5%/year

M. G. Deceglie et al. *IEEE Journal of Photovoltaics*, vol. 9, no. 2, pp. 476-482, 2019

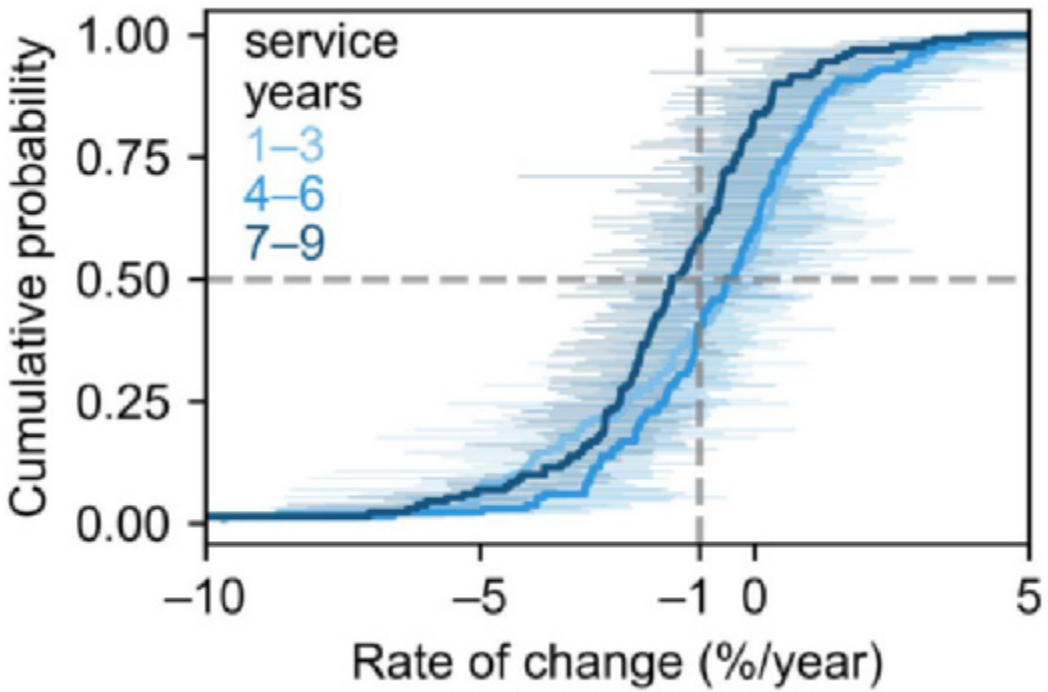
Shade in residential systems



- Systems with higher shade tended to degrade more rapidly
- Possible causes:
  - Foliage growth
  - Hot spots

M. G. Deceglie et al. *IEEE Journal of Photovoltaics*, vol. 9, no. 2, pp. 476-482, 2019

System age in non-residential systems

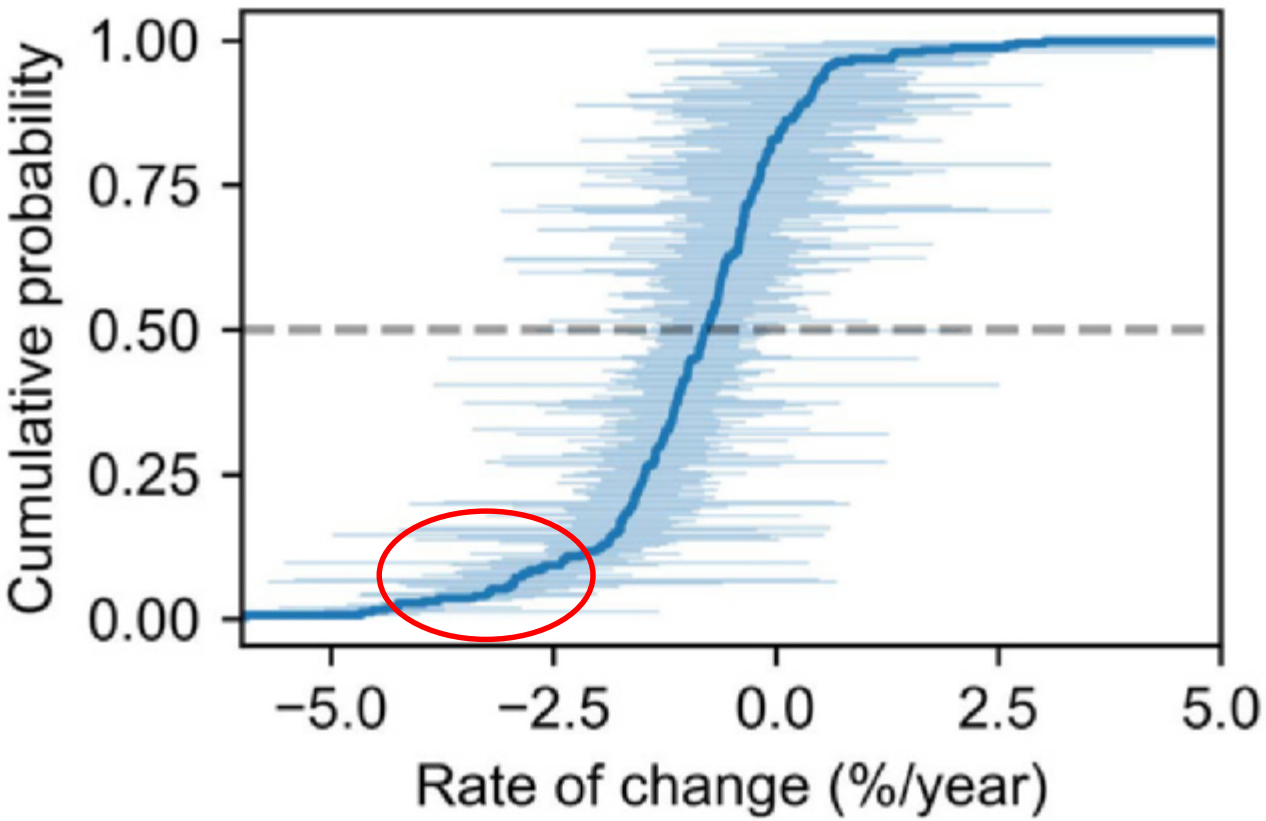


- The same 142 subarrays at 76 sites are considered over three different stages in system life
- Same systems in each CDF above
- Systems tended to show more rapid degradation later in life
- Should be careful about applying this generally

M. G. Deceglie et al. *IEEE Journal of Photovoltaics*, vol. 9, no. 2, pp. 476-482, 2019

Identifying underperforming systems

Fleet analyses can identify low performing systems for further investigation



Conclusion

- Fleet-scale analysis elucidates system degradation trends
  - Residential vs. non-residential
    - Possible causes: installation quality, shade, temperature
  - More rapid degradation observed later in system life (non-residential systems)
  - More rapid reductions in energy in shaded residential systems
- Enabled by open-source RdTools: github.com/NREL/rdtools
- **We can tolerate moderate system-by-system uncertainty in fleet-scale analyses**
- **Fleet analyses can identify underperforming systems for further investigation**

More details: M. G. Deceglie et al. *IEEE Journal of Photovoltaics*, vol. 9, no. 2, pp. 476-482, 2019

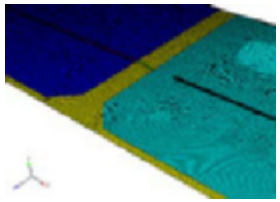
Funding provided by Solar Energy Technology Office under agreement 30295 and 34348. NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

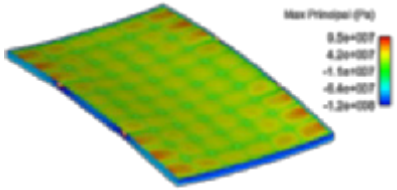
DuraMAT
Durable Module Materials Consortium

Sandia National Laboratories

DuraMAT capability area:

Multi-scale, Multi-physics Modeling for PV Reliability





PRESENTED BY

James Hartley, Ashley Maes, Joshua Stein, Scott Roberts (SNL); Nick Bosco (NREL); Laura Schelhas (SLAC)

SLAC NATIONAL ACCELERATOR LABORATORY

NREL

Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY NNSA

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SAND2019-1937 PE

Contents

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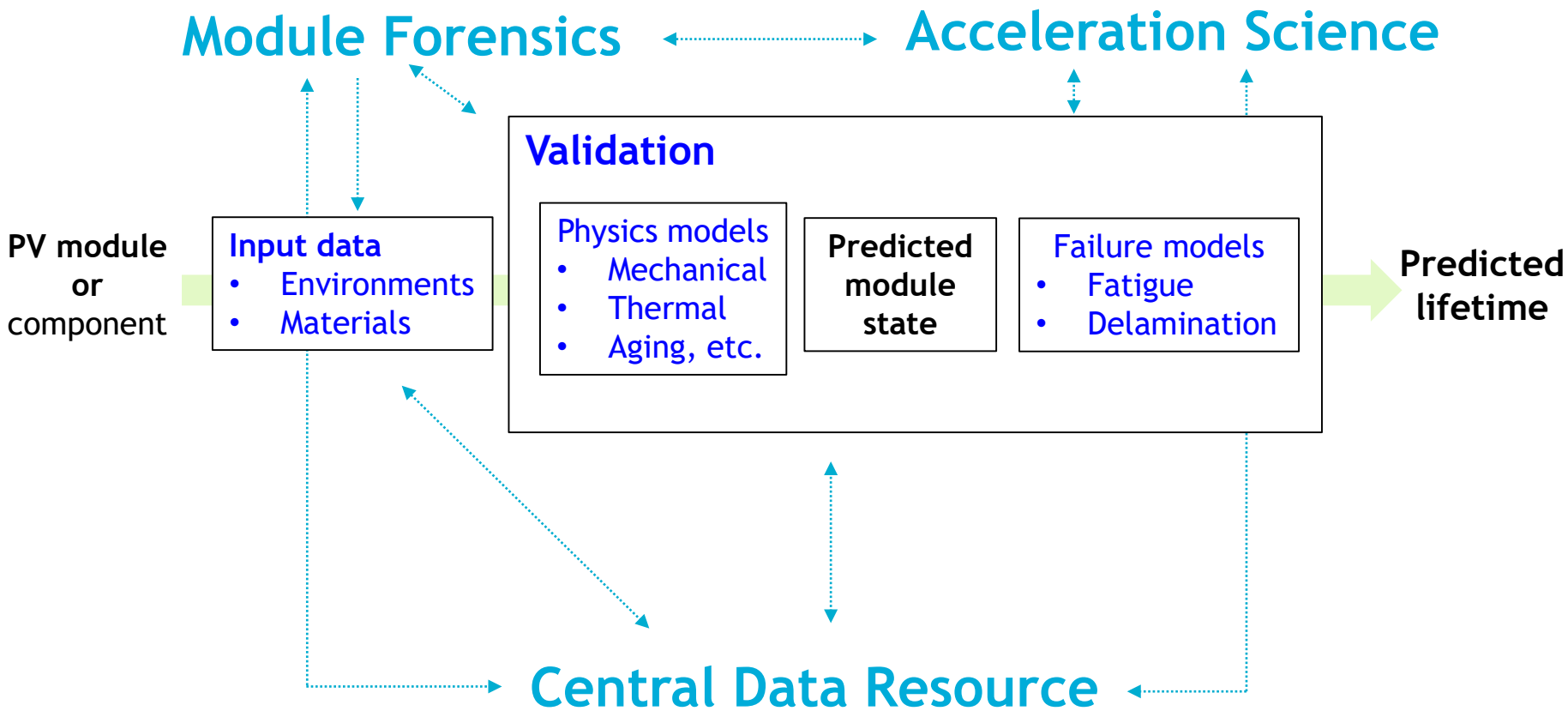
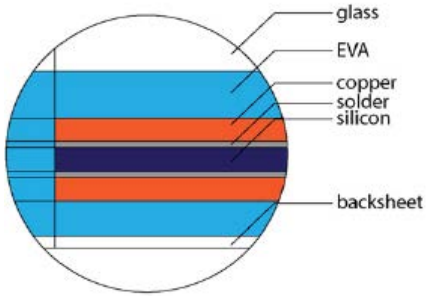
Multi-scale, Multi-physics Modeling for PV Reliability

- **Grand goal:** A modeling capability to accurately predict module lifetime
  - Applicable to multiple PV scales: From interconnects to full modules
  - Incorporating multiple degradation physics: Mechanical stress, thermal stress, materials effects, and more

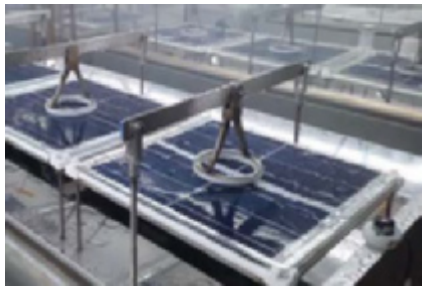


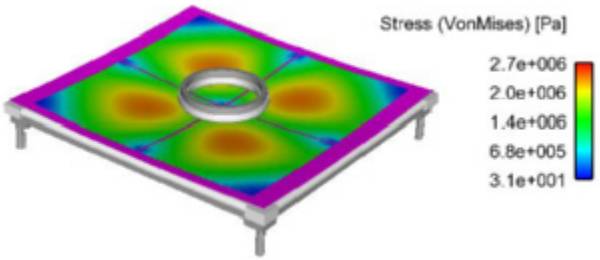
Multi-scale, Multi-physics Modeling for PV Reliability

Modeling capabilities to predict stressors at various *scales* of a PV module, leveraged with projects within DuraMAT network:

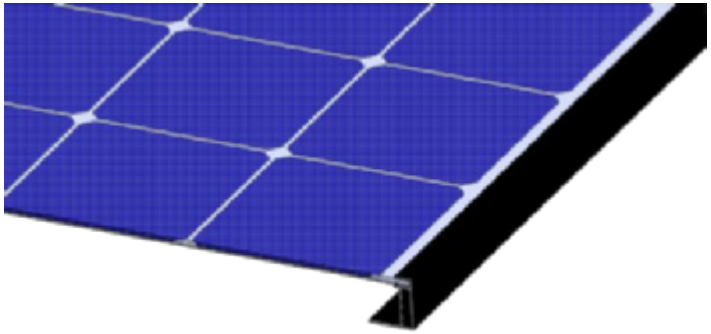


Individual Interconnections [Bosco, NREL]

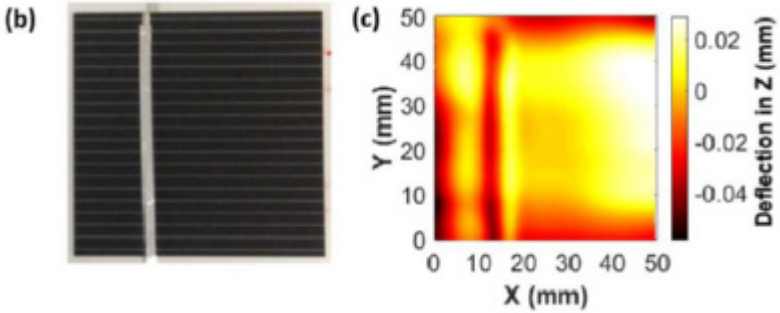




Mini-Modules [Hacke, Owen-Bellini; NREL]



Full Modules [Hartley, SNL]



Tabbed cells [Bertoni, ASU]

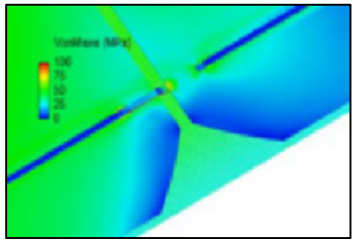
Scales NOT included are system level response (i.e. performance quantities), and molecular effects (except as manifested in material responses)

Multi-scale, **Multi-physics** Modeling for PV Reliability

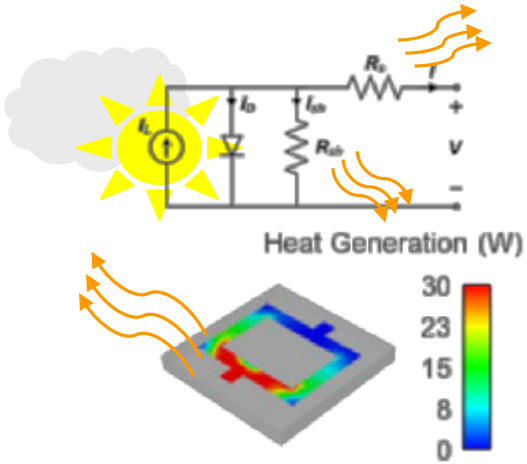
Modeling capabilities incorporate various physics causing or related to degradation:

Mechanical stress
[Hartley, SNL]

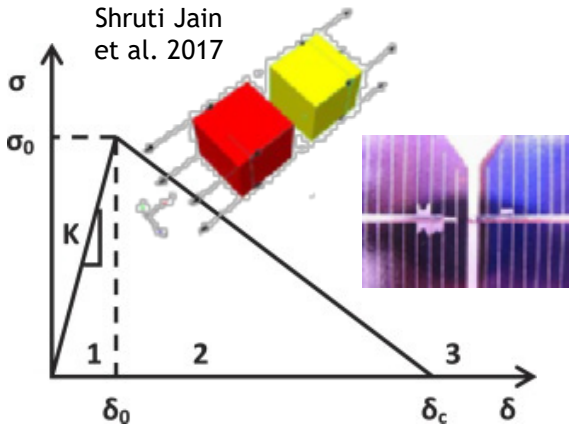
ΔT from -40°C to +85°C



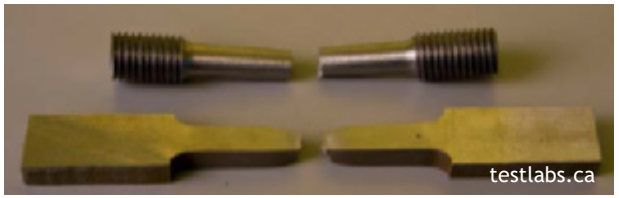
Thermal stress [SNL]



Electrical-thermal coupling [SNL]



Interfacial fracture [Bosco, NREL]



Material responses:

- Temperature dependencies [Maes, SNL]
- Viscoelasticity [Maes, SNL]
- Fatigue damage [Bosco, NREL]
- Aging effects [Owen-Bellini, NREL; Moffit, SLAC]

Additional physics could include moisture transport, corrosion chemistry, and many others!

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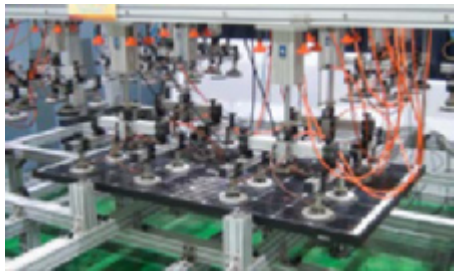
Capability highlight: A Module-Scale Mechanical Model

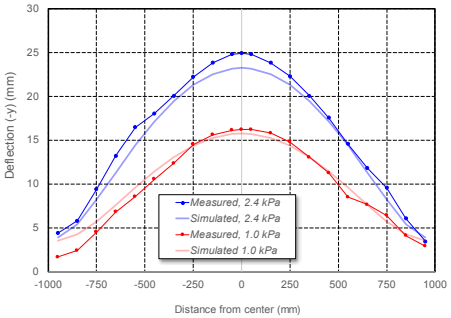
- **Goal:** Develop a full-module model predicting internal stresses under mechanical loads

- **Purpose and applications:**
  - Confirm applicability of finite element methods to PV modules
  - Develop best practices for simulating PV module scenarios
  - Confidence in full-module models enable:
    - Propagation of boundary conditions to smaller-than-module scale (mini-modules, cells, interconnects) tests
    - Parameter sensitivity studies for module and material design

Test module with datasheet and Bill of Materials (BOM)



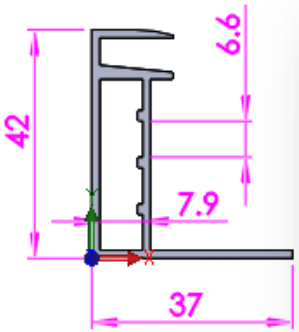
Mechanical load experiments and simulations

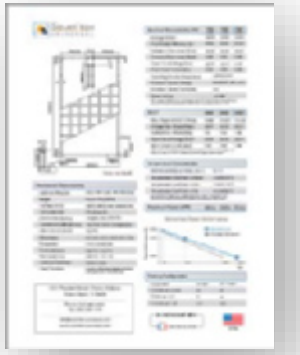


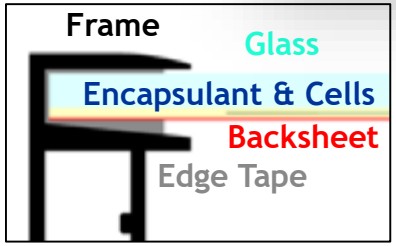
Comparison of measured vs. simulated deflections

Model Development Process

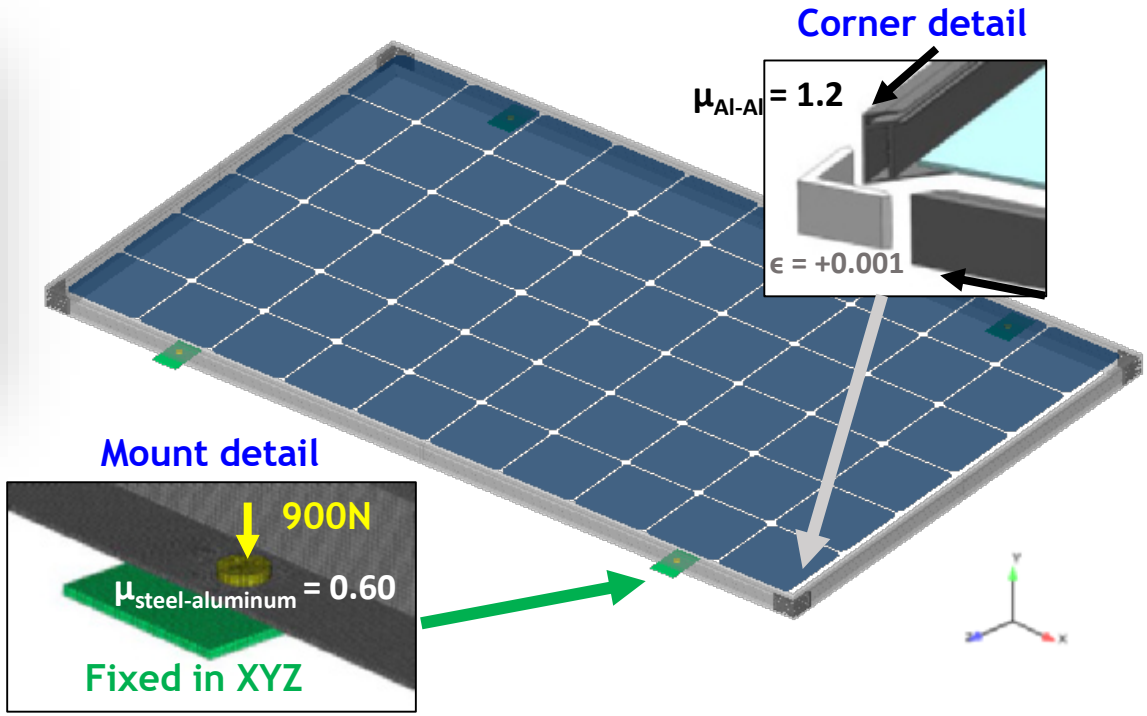
- **Test module:** SolarTech Quantum 300 Series
  - 60-cell, mono-PERC, glass-backsheet, aluminum framed
  - Chosen for representative construction and easily available example
- Computational model development mirrored actual module construction







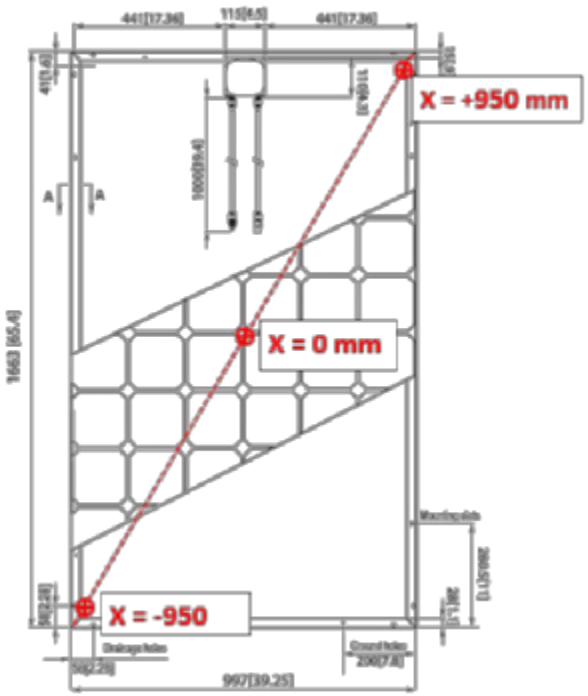
Dimensions and materials derived from module & datasheet



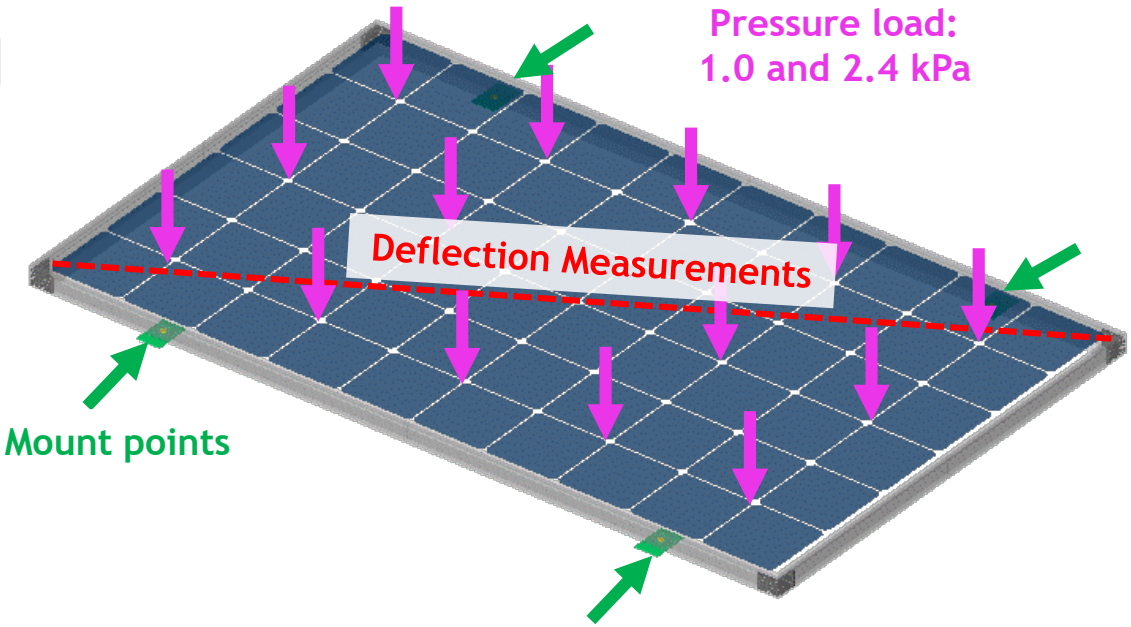
Finite element model developed to match actual features

Mechanical Tests and Simulations

- **Test condition:** IEC61215 pressure load, 1.0 kPa and 2.4 kPa
  - **Experimental case:** Mounted where specified, loaded with sandbags
  - **Simulated case:** Constrained as shown, pressure loads applied
- Deflection measured across the diagonal vs. fixed beam



Deflection measurement points

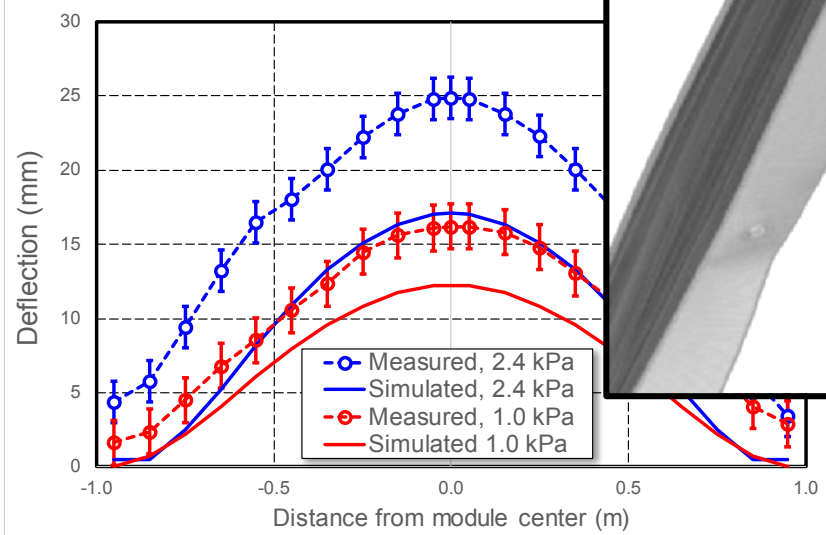


Load case boundary conditions

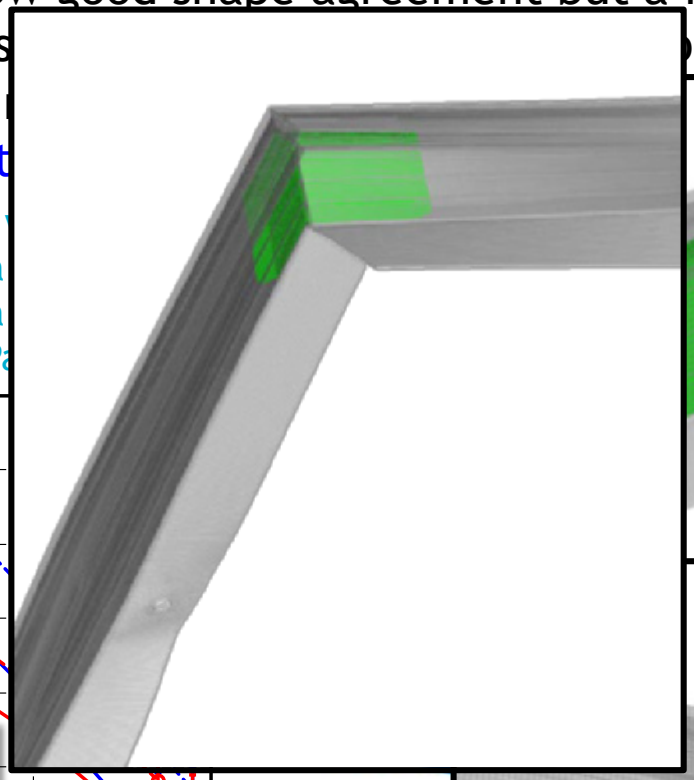
Mechanical Tests and Simulations: Results

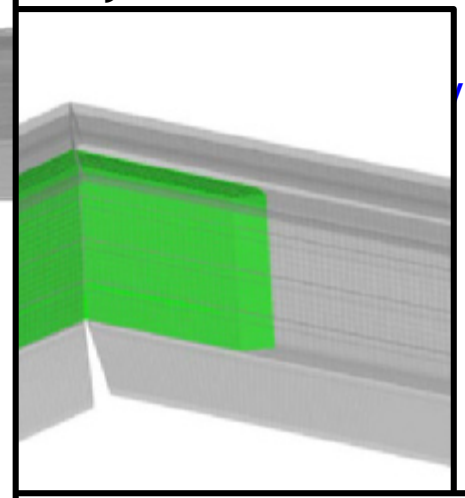
- Results comparisons show good shape agreement but a fixed deflection offset
  - **Causes:** Deflections ocally at the mount?
    - 2.4 kPa on 1.6
- Module construction det y!

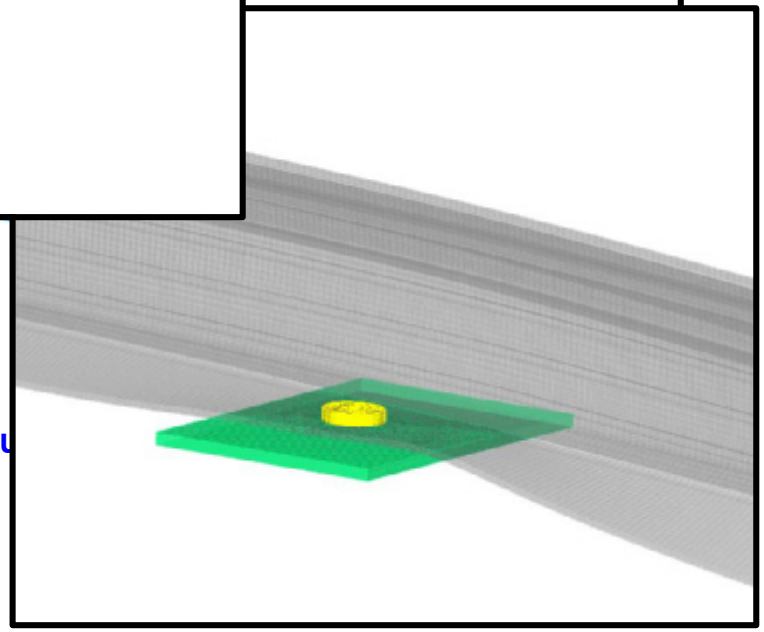
Assume offset increases linearly
0 mm offset @ 0.0 kPa
2 mm offset @ 1.0 kPa
4.8 mm offset @ 2.4 kPa



Measured vs. Simulated Deflections @ 1.0 kPa and 2.4 kPa loads





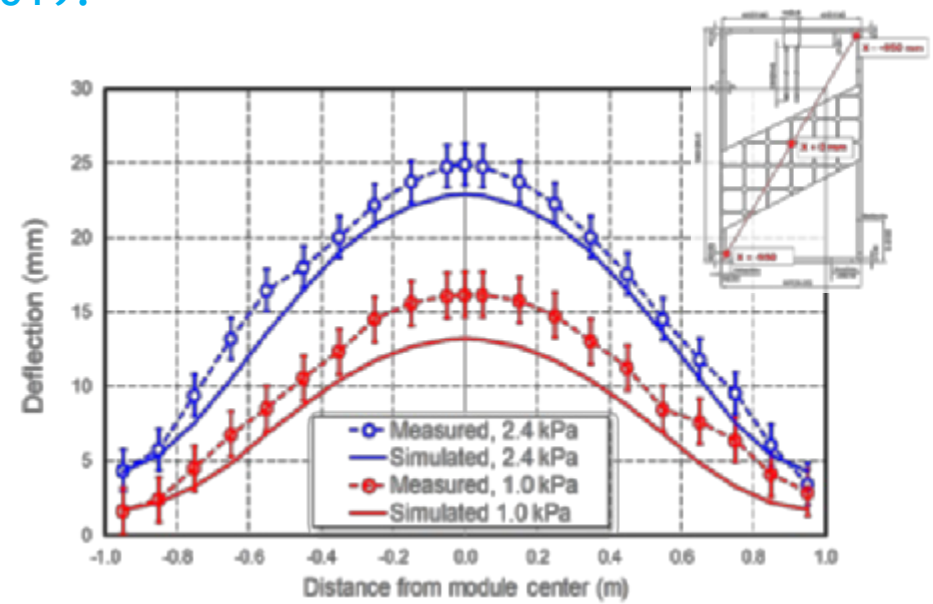


Resu

Mechanical Tests and Simulations: Results and Next Steps

- Parameter sensitivity studies and what-if analyses are in progress- answers questions such as:
  - What if a weaker glass is used?
  - What if a stronger glass but weaker edge tape is used?
- With enough samples, correlations and sensitivities can be found
  - Analyzed for this module model + a glass-glass thin-film module design
    - Full results at IEEE PVSC 2019!

Parameter	Min	Current value	Max
Glass thickness [mm]	2.2	3.2	4
Glass modulus [GPa]	65	**73**	75
Edge tape modulus [MPa]	0.5	**0.5**	2.0
Friction coefficient	0.2	0.6	1.3
…			



Measured vs. Simulated Deflections @ 1.0 kPa and 2.4 kPa loads with parameter adjustments

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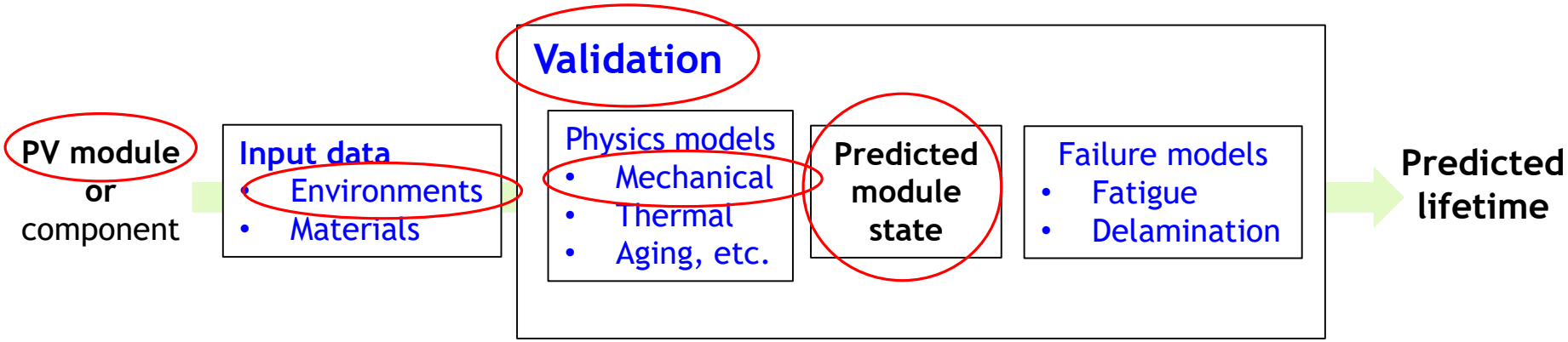
Summary

- Introduced the multi-scale, multi-physics modeling capability area



- Highlighted one capability: a module scale mechanical model, which took a:
  - Full scale PV module;
  - under mechanical pressure loading environments;
  - through predicted deflection under load with experimental validation

- Much more capability development! Some immediate next steps:
  - **Apply model:** To correlate full module mechanical results against mini-modules; build platform for failure model integration
  - **Add physics:** Incorporate material viscoelasticity

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

DuraMAT
Durable Module Materials Consortium

Combined- and sequential-accelerated stress testing for derisking photovoltaic modules

Peter Hacke
NREL

NREL Team: Michael Owen Bellini, David Miller, Dana Sulas, Hannah North, Michael Kempe
AIST Team: Tadanori Tanahashi, Keiichiro Sakurai Aalborg U: Sergiu Spataru
Dupont Team: Bill Gambogi Mitsui Chemical: Tsuyoshi Shioda Itek Energy
PVQAT TG3 members

NREL PVRW | 2019 | Lakewood, CO

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.

Combined- and sequential-accelerated stress testing for derisking photovoltaic modules

- Motivation
- Road to sequential and combined-accelerated stress testing (C-AST)
- Testing and results
- Framework
- Summary/next steps

Motivation

- **Numerous field failures seen in modules that pass qualification testing (IEC 61215)**
  - We create mechanism-specific tests only after the failure mode has been found in the field
- **Numerous parallel tests getting time consuming and expensive**
- **Stakeholders considering buying into new technologies, materials, and designs incur residual risk, increasing LCOE**
  - Risk of new designs/materials (like PERC, n-PERT)
  - Risk from incremental changes (like going to thinner cells)
  - Risks from failure of critical parts (like an edge seal for moisture-sensitive PV cells)
- **PV module reliability standards subject to interests of those contributing**
  - More objectivity sought
- **$US Billion industry. Risks as well as benefits of progress are substantial**
- **Addressing this, differing PV testing paradigm required**

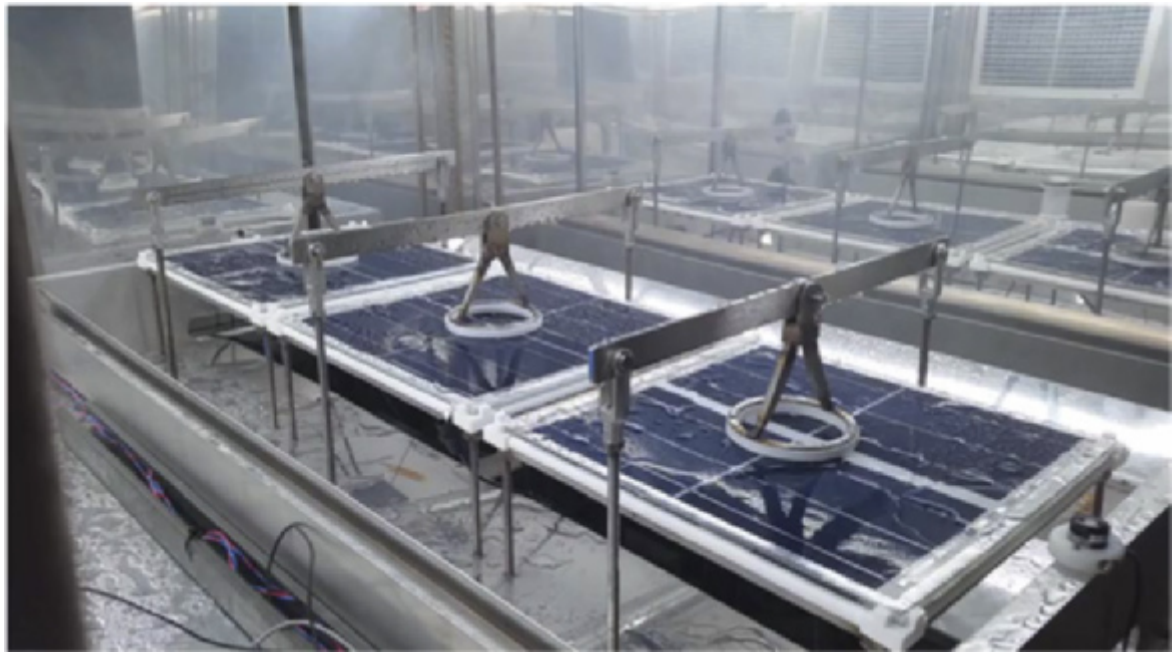
Combined and sequential tests being developed

Background - The Road to sequential and combined-accelerated stress testing (C-AST)

General understanding that single factor tests are insufficient to forecast module reliability

- Sequential tests and combined test of **DH** & **UV light** to better show various interactions; added **TC**
  - Koehl, Hoffmann, and Weiss, Fraunhofer ISE (2011-2017)
  - NEDO team (2006-2009); Ngo, Heta, Doi, and Masuda (2016), AIST
- NREL Test-to-failure, **DH with Voltage & TC** sequencing showing PID & backsheet cracking
  - Hacke and NREL team (2009-2014)
- MAST sequential tests, including **DH**, **UV**, **TC** to reproduced backsheet field failures
  - Gambogi, and DuPont team (ongoing)

Combined-accelerated stress testing



Modified Atlas XR-260 Weatherometer

S. Spataru, & coworkers "Combined-Accelerated Stress Testing System for Photovoltaic Modules," WCPEC-7 (2018)

Combining stress factors

- Heat
- Light
- Humidity
  - Condensing
  - Non-condensing
- Mechanical pressure
- System voltage
- Reverse bias *(in progress)*

In-situ Metrology

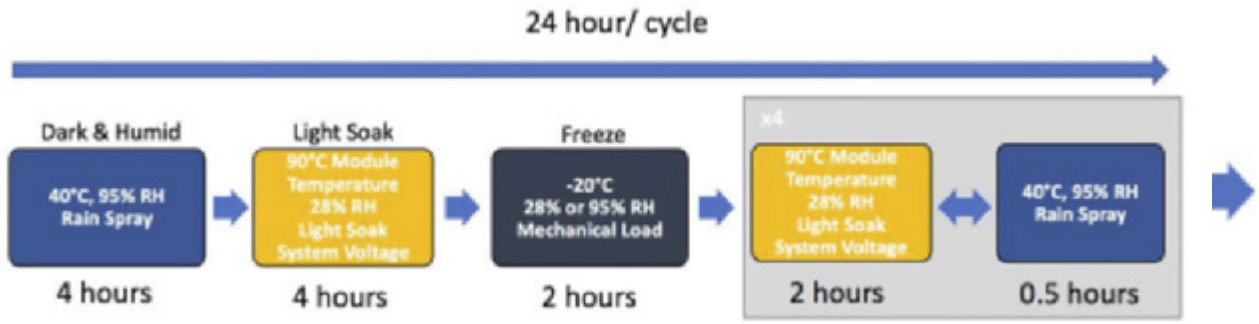
- RH, T_{module}, *I-V*, EL

Discover potential weaknesses in module designs, both known and not *a-priori* recognized, reduce risk, accelerate time to market, bankability and reduce costly overdesign, to lower the levelized cost of electricity.

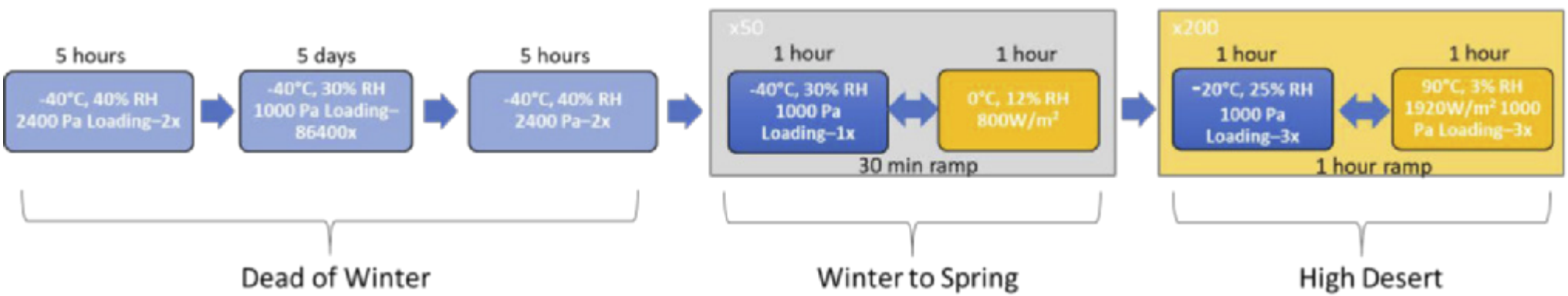
Test protocol

Phase 1 – Based on ASTM D7869 for tropical conditions

- replicates paints & coatings failures 8 × - 16 × acceleration factor
- + electrical stress, + freeze



Phase 2 – Multi-season



- Field relevant levels: maximum temperature & humidity level of tropics
- No light + rain combination
- PID voltage bias with light only

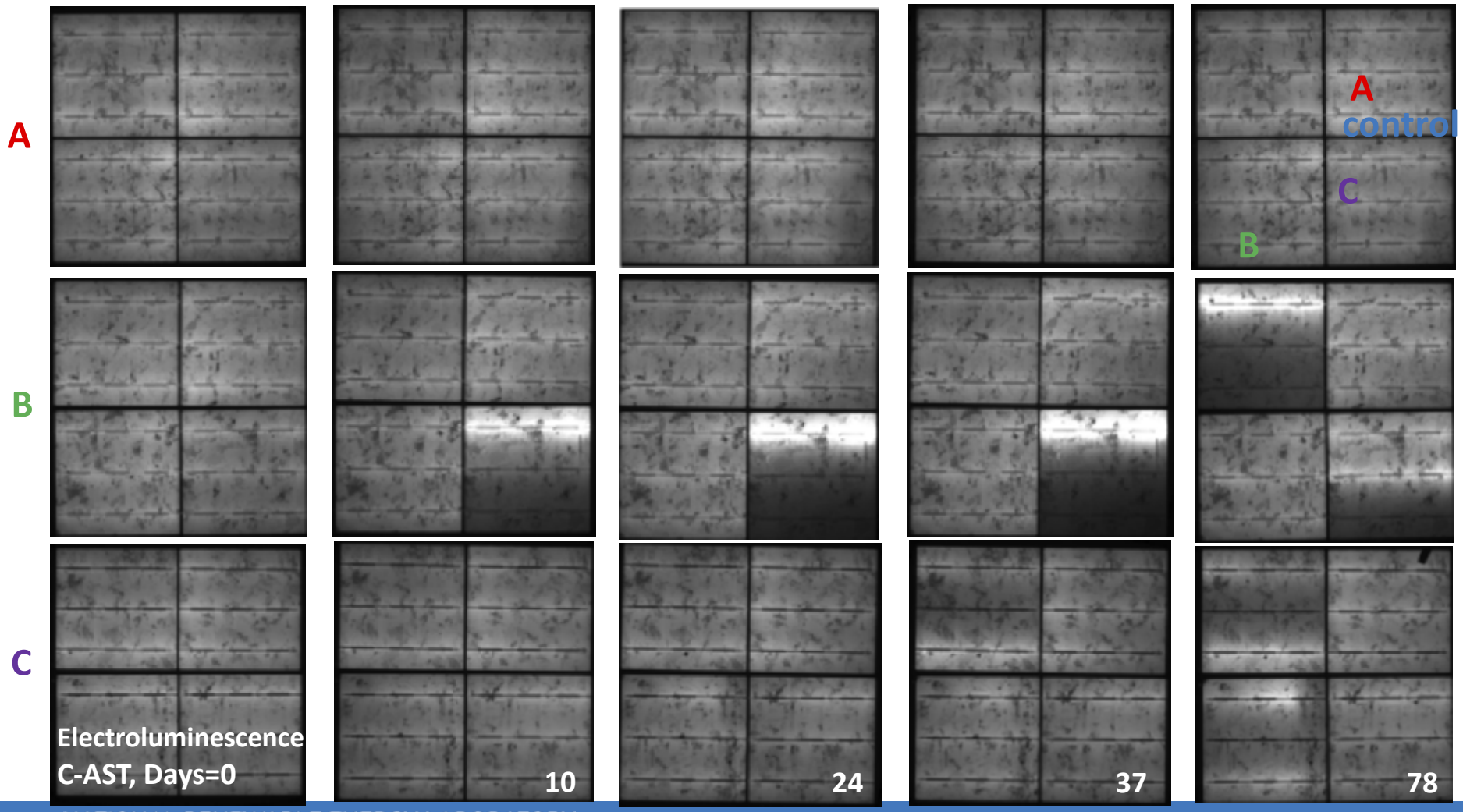
→ See poster 85. M. Owen-Bellini and coworkers "Combined-accelerated stress testing for advanced reliability assessment of photovoltaic modules"

Results

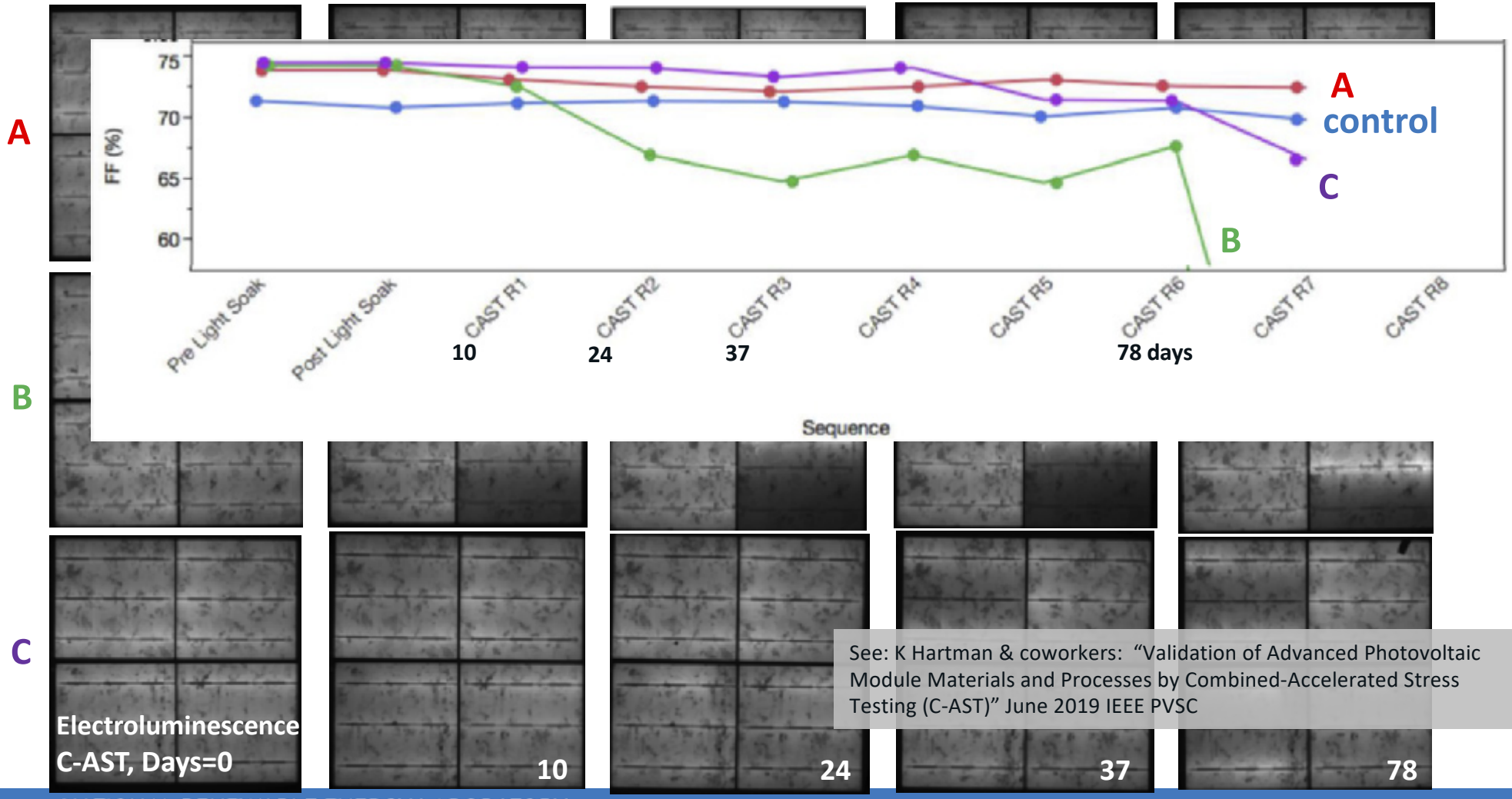
- Modes
- Types of failure/issues/mechanisms
- Stress factors
- Combined accelerated testing results
  - Field results, other chamber results
- IEC tests that cover them (or missing tests)
  - **The count: how many individual IEC tests in sequence needed to show the mode vs. C-AST**

Modes	Types/issues	Stress factors	IEC	C-AST
Fatigue, breakage (→burns)	Cell spacing, cell thickness/nature, ribbon dimensions/bends, non-solder distance, solder/ECA quality	Mechanical and thermomechanical stress on conductors. Current leading to joule heating in the conductors	IEC 61215 MQT 11 TC IEC 62782 – DML + IEC 62759 (transp.): 50 TC, 20 HF, ML 2400 Pa)	***1***

5

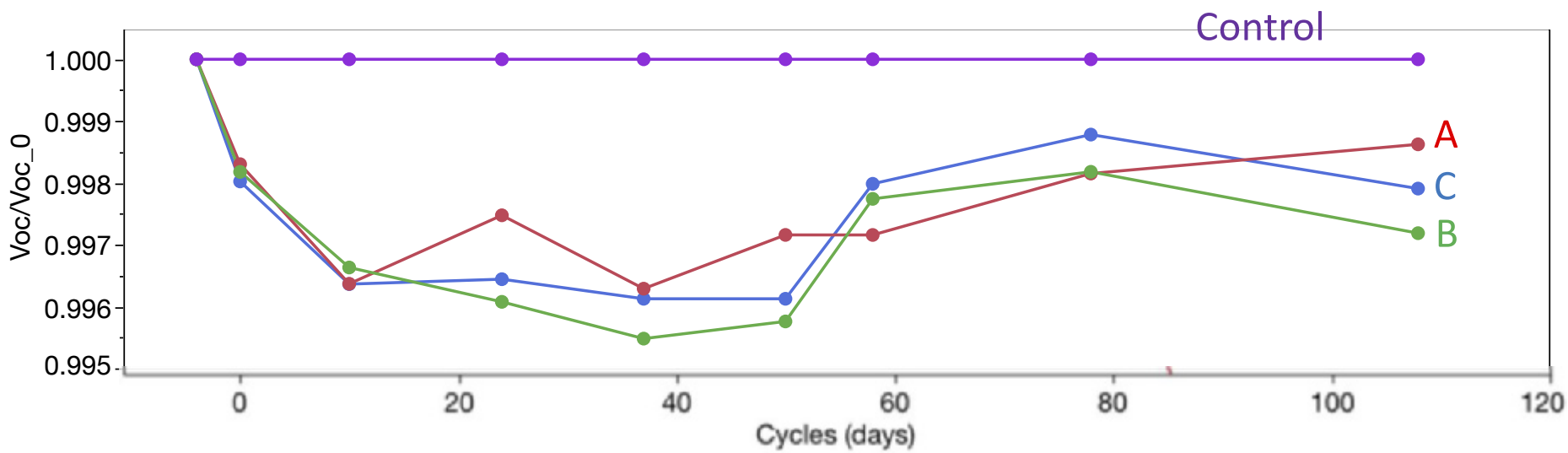


Modes	Types/issues	Stress factors	IEC	C-AST
Fatigue, breakage (→burns)	Cell spacing, cell thickness/nature, ribbon dimensions/bends, non-solder distance, solder/ECA quality	Mechanical and thermomechanical stress on conductors. Current leading to joule heating in the conductors	IEC 61215 MQT 11 TC IEC 62782 – DML + IEC 62759 (transp.): 50 TC, 20 HF, ML 2400 Pa) *5*	*1*



See: K Hartman & coworkers: "Validation of Advanced Photovoltaic Module Materials and Processes by Combined-Accelerated Stress Testing (C-AST)" June 2019 IEEE PVSC

Modes	Types/issues	Stress factors	IEC	C-AST
Light-induced degradation	B-O, Fe-B, sponge LID	Sunlight + temperature	IEC 61215 MQT 19 Stabilization	
	Light & elevated temperature degradation 1) c:Si 2) Thin Film		c-Si / Thin Film	
	UV LID (H, charges)		IEC 61345 module UV test (withdrawn)	



C-AST

LeTID signature, with 90°C module temperature, 1.9 Suns

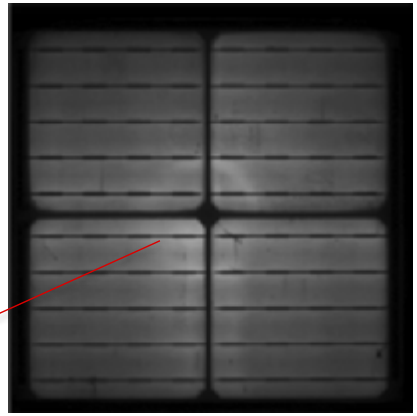
Conventional cells: BSF limited, so effect is small

Modes	Types/issues	Stress factors	IEC		C-AST
Light-induced degradation	B-O, FeB, Sponge LID	Sunlight + temperature	IEC 61215 MQT 19 Stabilization		
	Light & elevated temperature degradation 1) c:Si 2) Thin Film		c-Si	thin film	
	UV LID (H, charges)		IEC 61345 module UV test (withdrawn)		

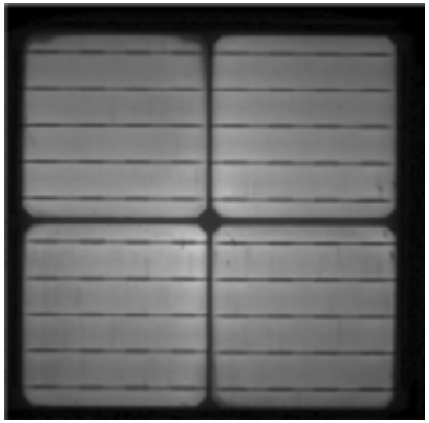
Shadowed region showing higher minority carrier lifetime

Electroluminescence

TPT UV Pass EVA

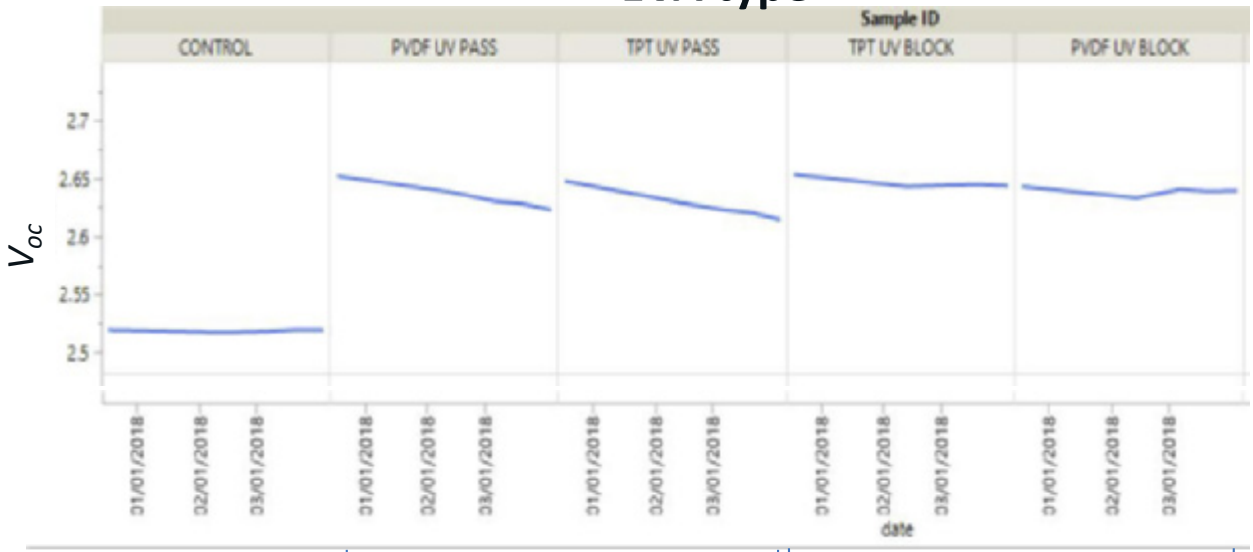


TPT UV Block EVA

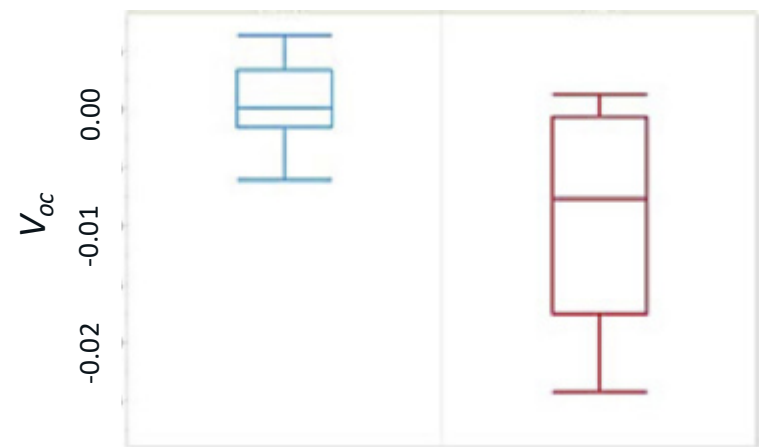


Modes	Types/issues	Stress factors	IEC	C-AST
Light-induced degradation	B-O, FeB, Sponge LID	Sunlight + temperature	IEC 61215 MQT 19 Stabilization	
	Light & elevated temperature degradation 1) c:Si 2) Thin Film		c-Si / thin film	
	UV LID (H, charges)		IEC 61345 module UV test (withdrawn)	

EVA type



UV PASS EVA UV BLOCK EVA



UV block UV pass

EVA type

See Poster 10. P. Hacke and coworkers: "Module-level solutions for cell-front ionization damage"

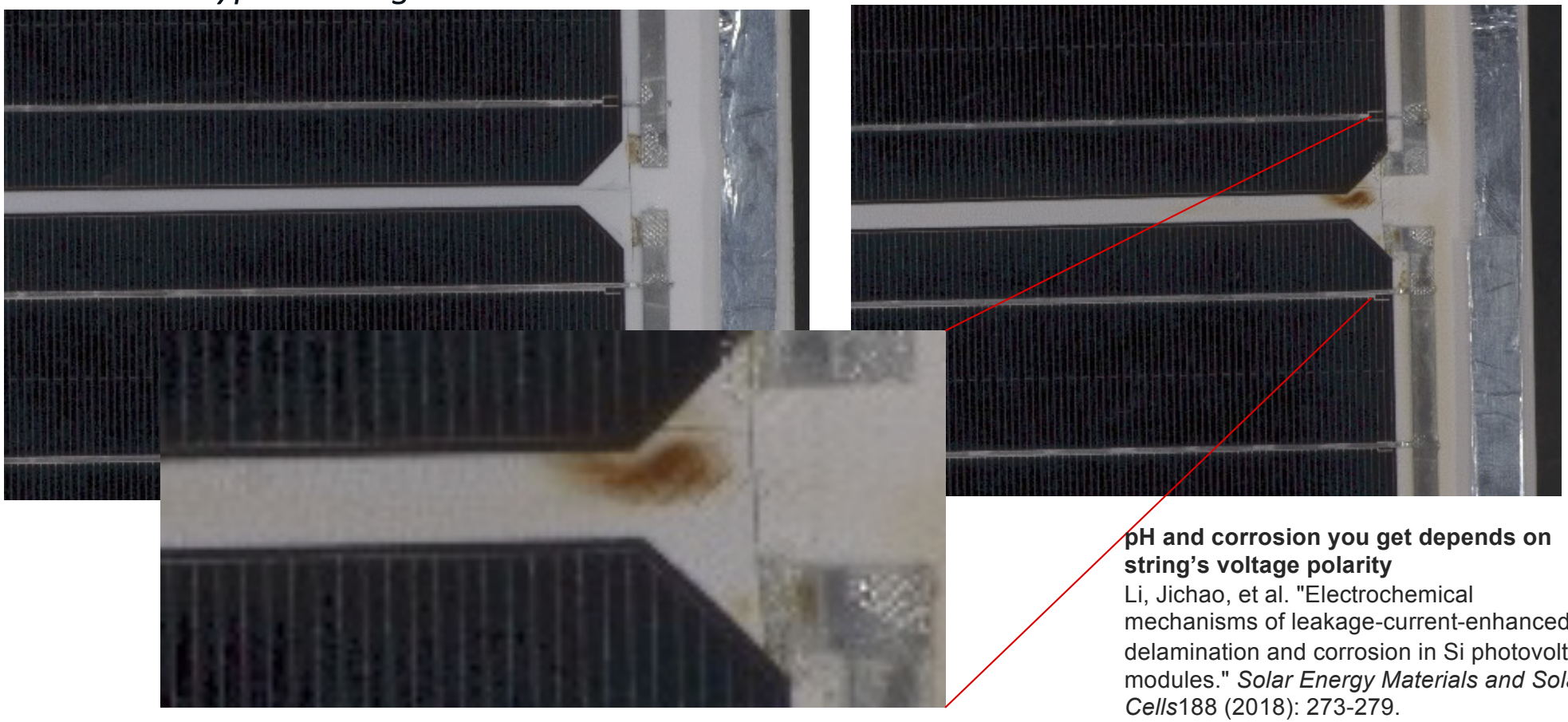
Modes	Types/issues	Stress factors	IEC	C-AST
Light-induced degradation	B-O, FeB, Sponge LID	Sunlight + temperature	IEC 61215 MQT 19 Stabilization	***1***
	Light & elevated temperature degradation 1) c:Si 2) Thin Film		c-Si / thin film	
	UV LID (H, charges)		IEC 61345 (withdrawn)	

*5 + 1+2M = **6+2M***

Modes	Types/issues	Stress factors	IEC	C-AST
Yellowing & module packaging optical losses	Photochemical degradation of polymers, ion migration	Sunlight, temperature, humidity, electrical-bias	IEC 62788-7-2 (coupon testing, coupon not precisely defined, does not include electrical bias)	***1***

*6 +2M + 1M = **6+3M***

2 module types through C-AST:



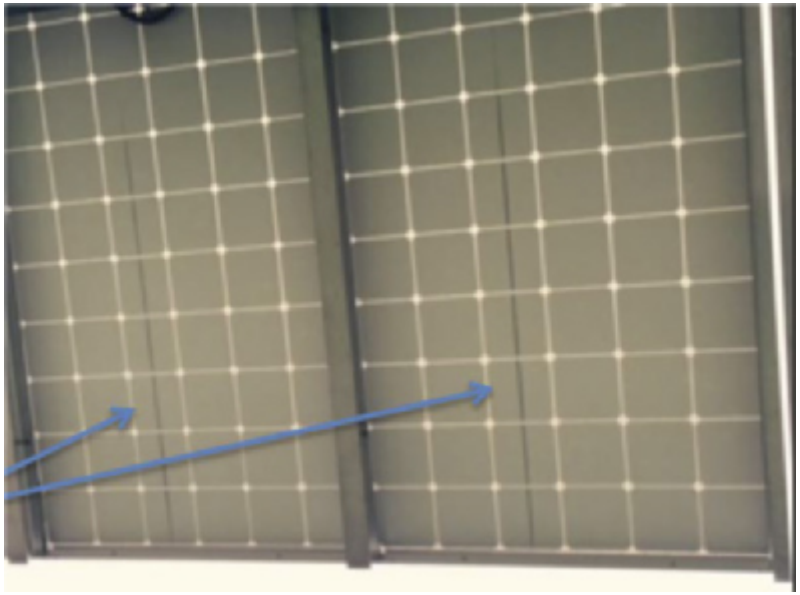
pH and corrosion you get depends on string's voltage polarity
Li, Jichao, et al. "Electrochemical mechanisms of leakage-current-enhanced delamination and corrosion in Si photovoltaic modules." *Solar Energy Materials and Solar Cells*188 (2018): 273-279.

Modes	Types/issues	Stress factors	IEC	C-AST
Backsheet cracking and delamination	Oxidative, photo, hydrolytic reactions, localized stress	Heat, sunlight, voltage moisture and mechanical stress	IEC 61730-2 Seq B: DH 200/UV 60/ HF 10/UV 60/HF 10	

Field Results

Polyamide backsheet
Albuquerque NM, 4 y

Polyamide backsheet- detail
Albuquerque NM, 4 y



PVDF
Saskatchewan Canada, 5 y
(photo credit: DuPont)

Modes	Types/issues	Stress factors	IEC	C-AST
Backsheet cracking and delamination	Oxidative, photo, hydrolytic reactions, localized stress	Heat, sunlight, voltage moisture and mechanical stress	IEC 61730-2 Seq B: DH 200/UV 60/ HF 10/UV 60/HF 10	

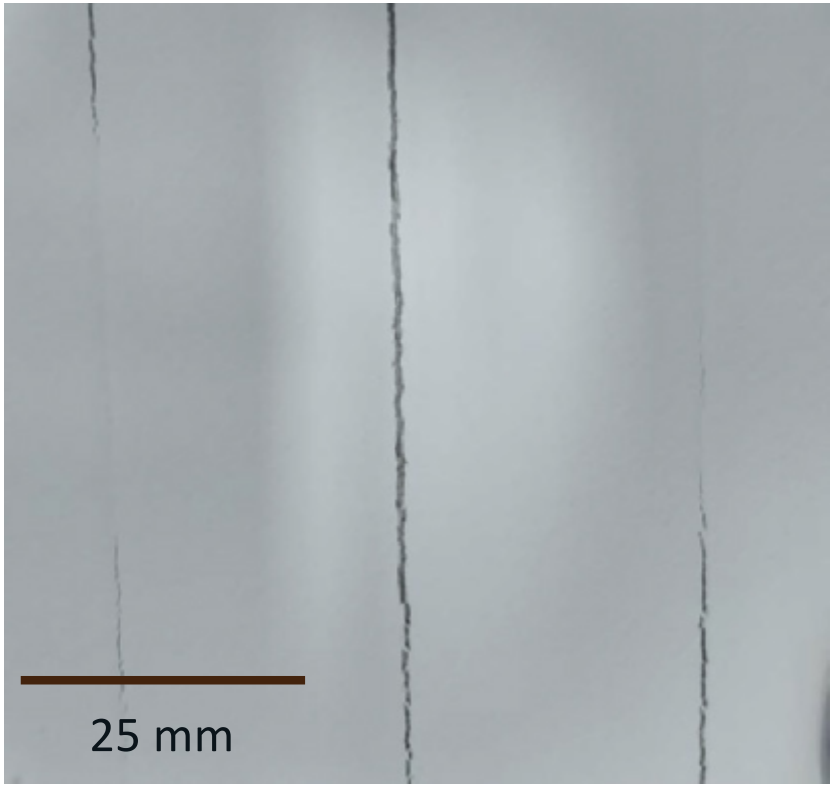
→ Apply C-AST to identify failures in backsheets failed in field but failures not detected in conventional testing

Backsheet

Encapsulant	PVF	PA	PVDF
UV Pass EVA	✓	✓	✓
UV Block EVA	✓	✓	✓

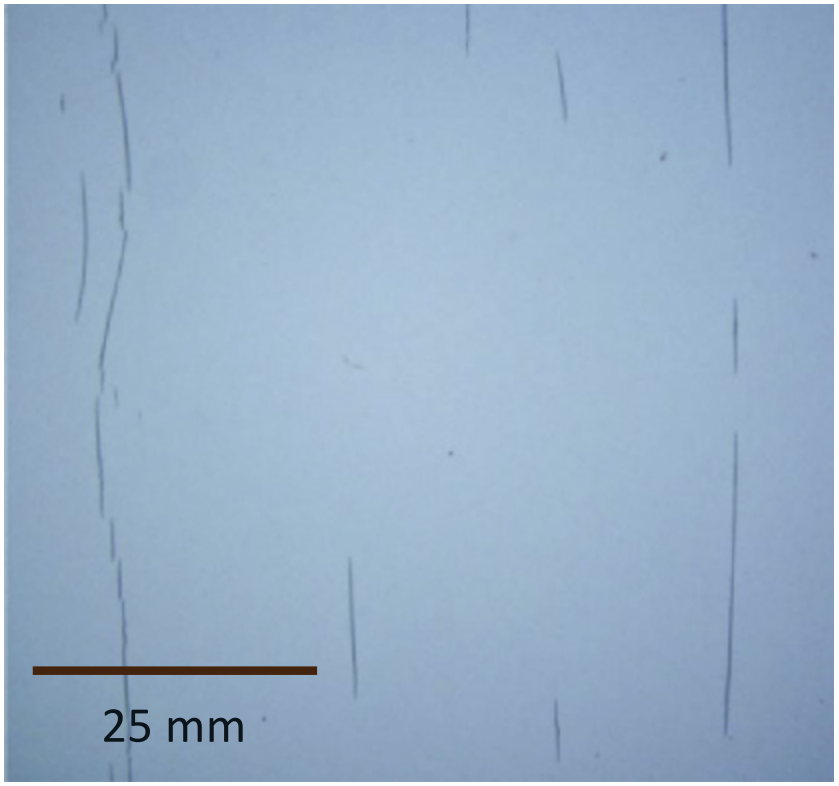
Modes	Types/issues	Stress factors	IEC	C-AST
Backsheet cracking and delamination	Oxidative, photo, hydrolytic reactions, localized stress	Heat, sunlight, voltage moisture and mechanical stress	IEC 61730-2 Seq B: DH 200/UV 60/ HF 10/UV 60/HF 10	

PA Backsheet cracking



Major cracking over cell tabbing, but microcracking is present through backsheet (tropical stress)

PVDF Backsheet cracking

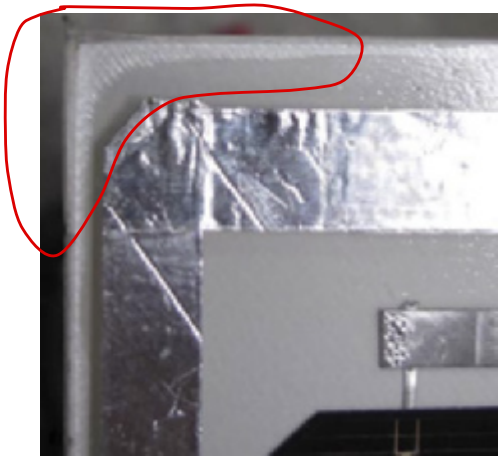


Cracking initiated along cell tabbing but quickly spread to areas between tabbing (tropical → 2 wks. multi-season)

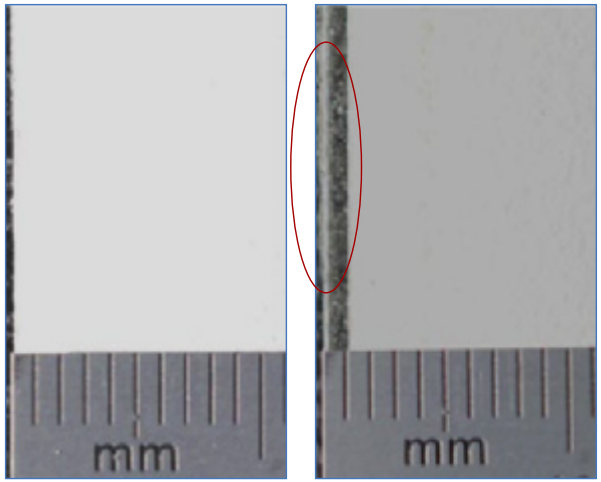
Modes	Types/issues	Stress factors	IEC	C-AST
Backsheet cracking and delamination	Oxidative, optical, hydrolytic reactions, localized stress	Heat, UV, voltage mechanical moisture and mechanical stress	IEC 61730-2 Seq B: DH 2000 UV 60/ HF 10 UV 60 HF 10	***1***

*6+3M + 5 = **11+ 3M***

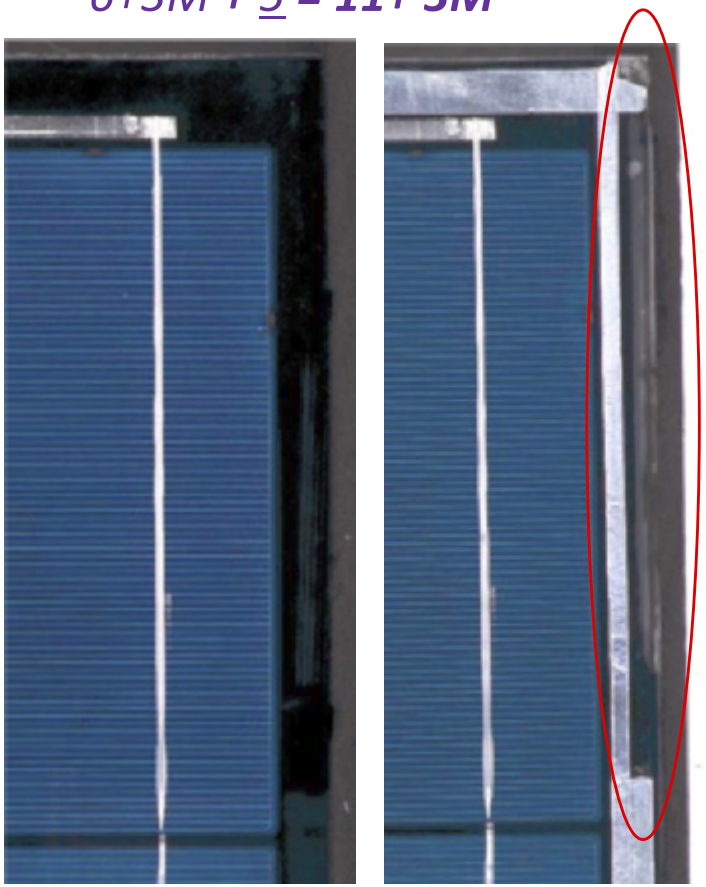
Delamination of PA edge seen at week 8 of C-AST



Associated with shrinkage of backsheet offset from glass edge of about 1 mm shown at week 22 on the right



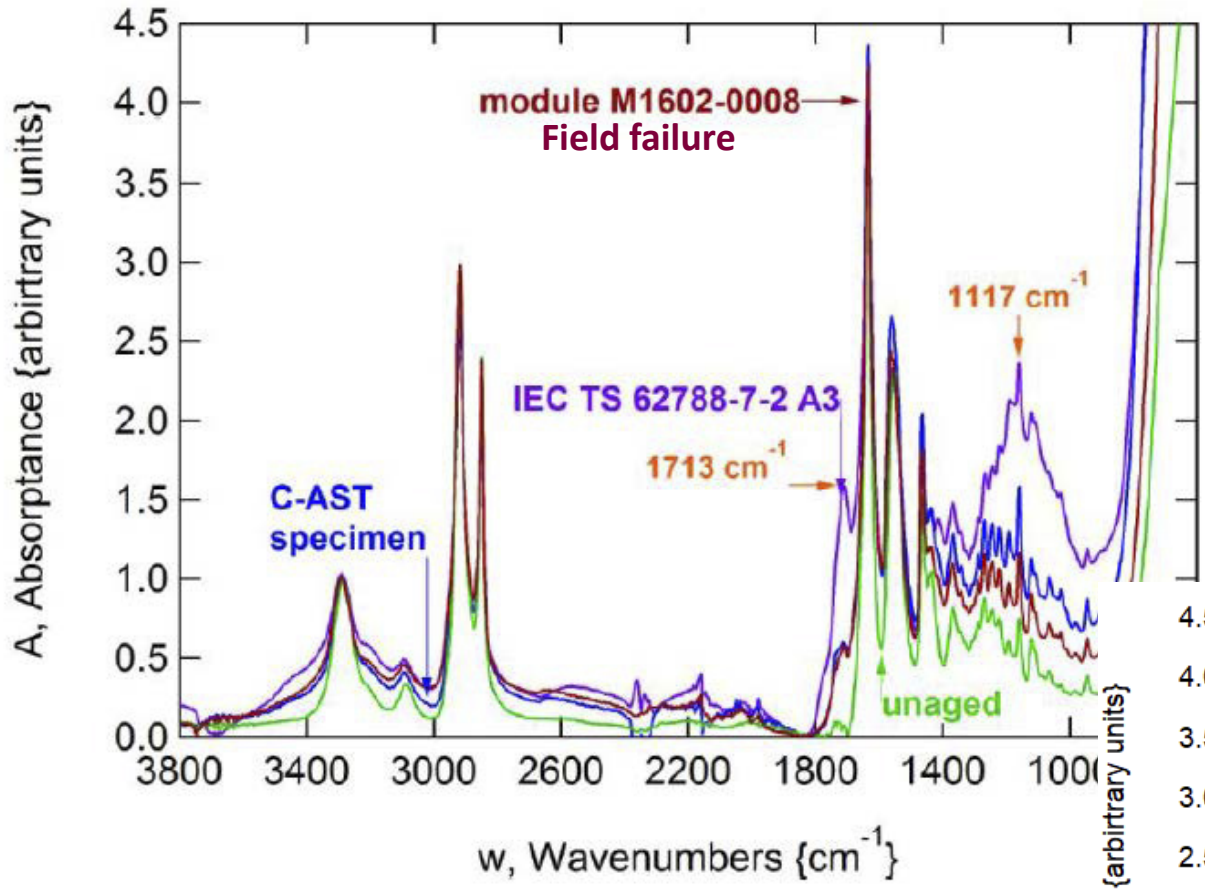
Representation of module size size critical

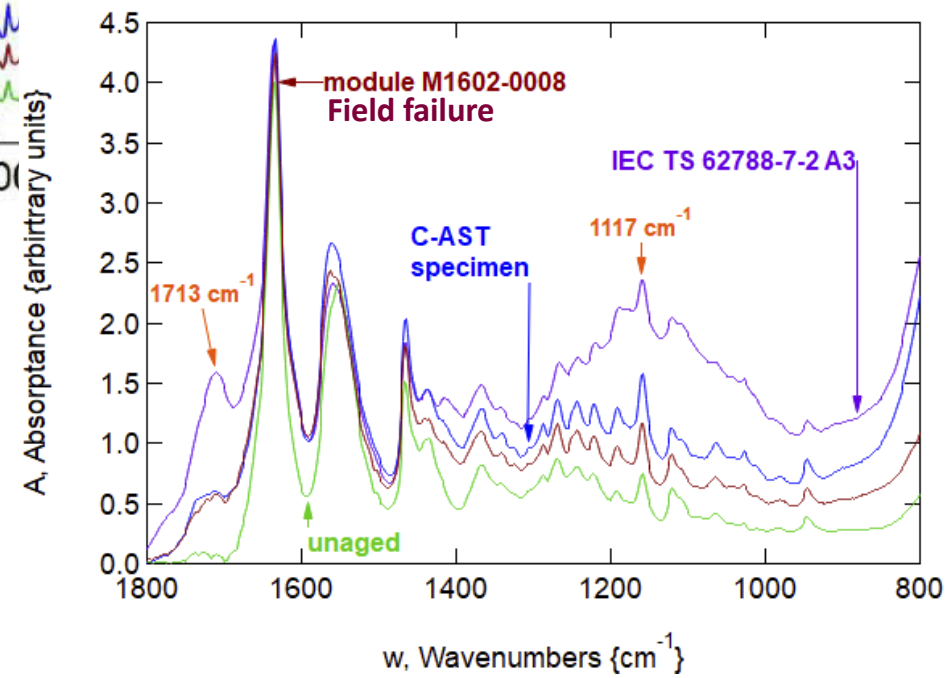


initial final

Delamination at module edge (experimental EVA alternative) in C-AST

Field relevant degradation signature of PA backsheet in C-AST





- FTIR signature of field failed module (M1602-0008) aligns with C-AST specimen.
- Specimen aged with IEC TS 62788-7-2 A3 demonstrates different signature.
- Suggests C-AST is relevant to field failure mechanism.

Modes	Types/issues	Stress factors	IEC		C-AST
Corrosion, cell-front delamination	Oxidative, hydrolytic; electro & photo-catalytic reactions 1) c-Si 2)thin-film	Heat, humidity, sunlight, and system voltage bias, mechanical stress (on edge seal)	62804-1-1 c-Si DH/ HV bias *missing light*	Thin film *missing mechanical stress*	***1***

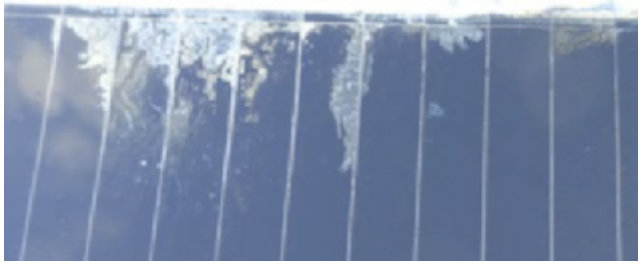
*11+ 3M + 3M = **11+6M***

c-Si

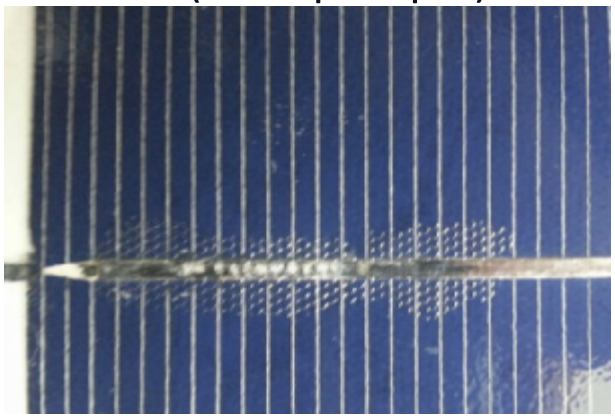
Field (Albuquerque)

Chamber (-V_{sys} to cells)

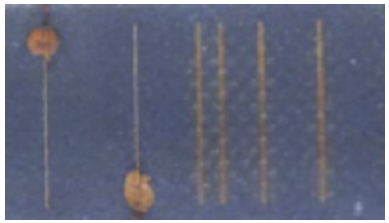
Thin-film

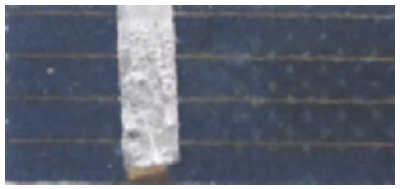


Field (Florida)

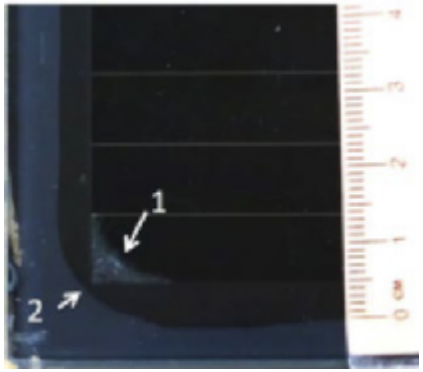


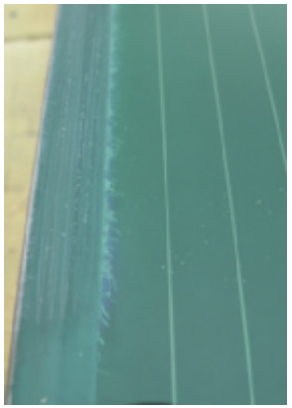
Field (Yemen)





Chamber (+V_{sys} to cells)



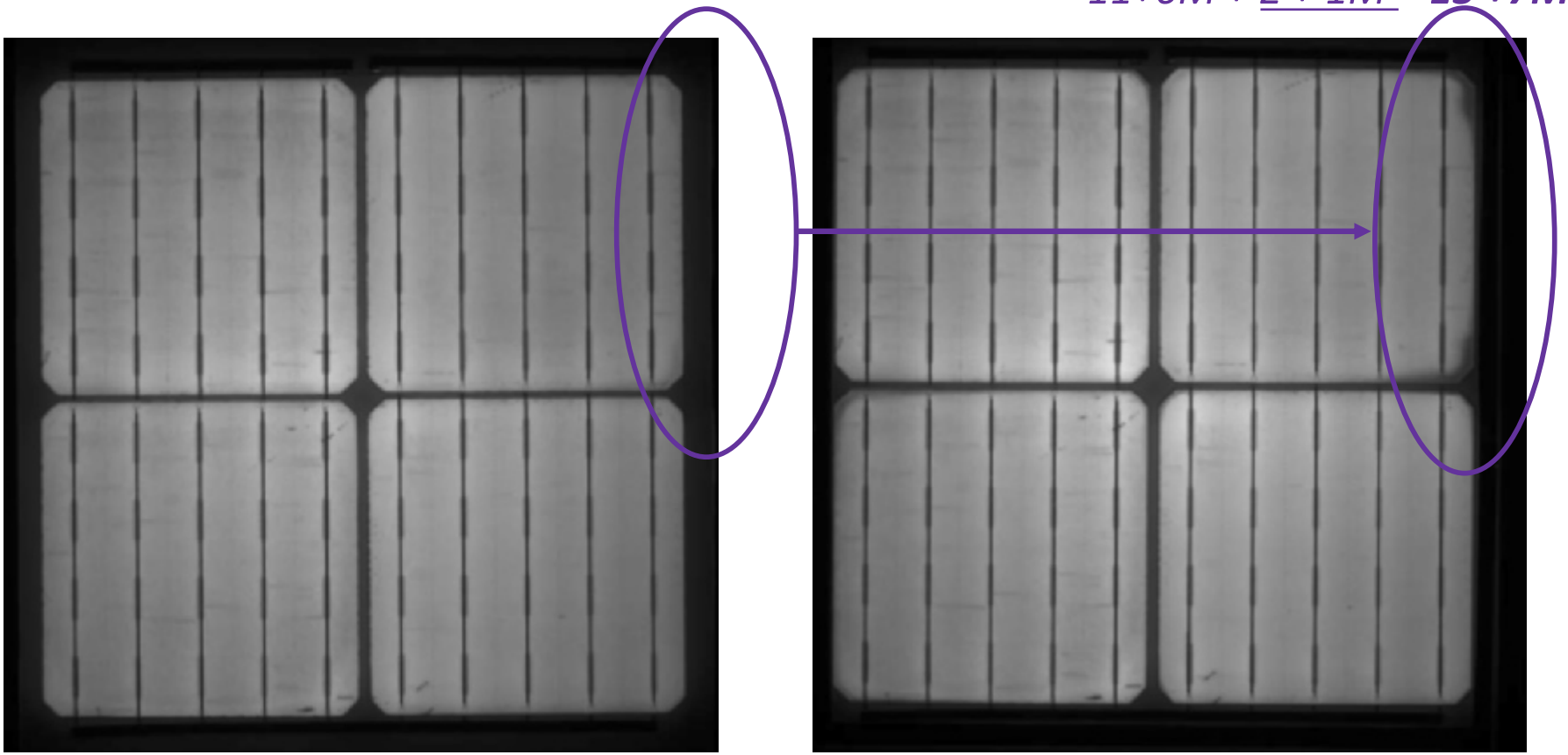


Chamber (-V_{sys} to cells)

Not C-AST chamber results

Modes	Types/issues	Stress factors	IEC	C-AST
Potential-induced degradation	Polarization, shunting ion migration, insufficient isolation	Heat, humidity and system voltage bias, modulated by sunlight	62804-1: light soak → DH & V_{sys} bias Light + V_{sys} simultaneously	***1***

*11+6M + 2 + 1M = **13 +7M***



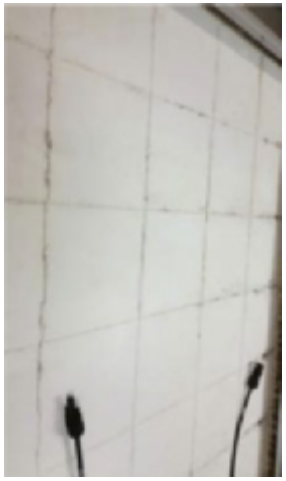
initial → ***final***

C-AST (tropical stress cycle)

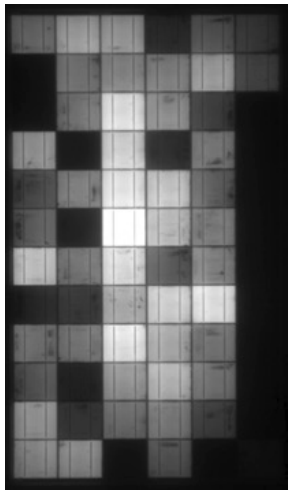
The Tally

IEC protocol tests, existing or missing ***vs*** ***C-AST***

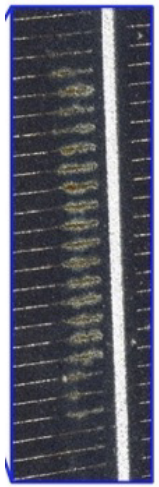
13 + 7M = 20 ***1***



Polyamide backsheet

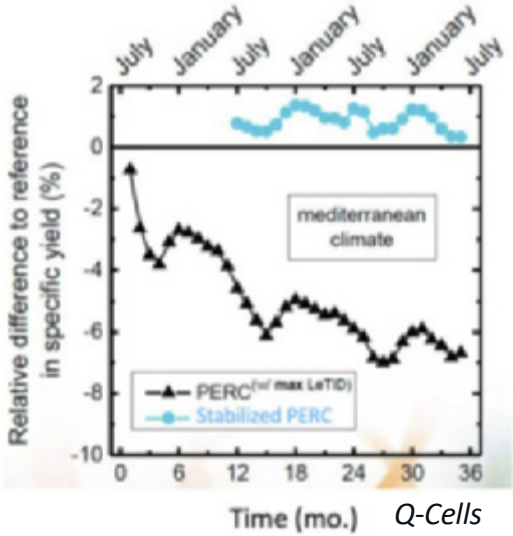


PID



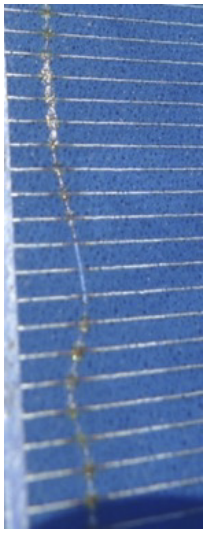
Corrosion

Edge seal failure

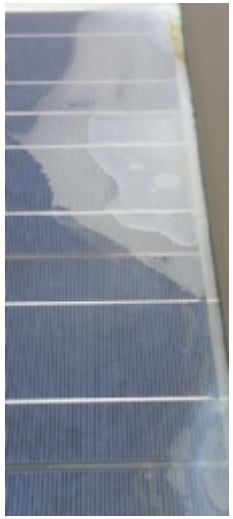


Q-Cells

LeTID



Snail trails



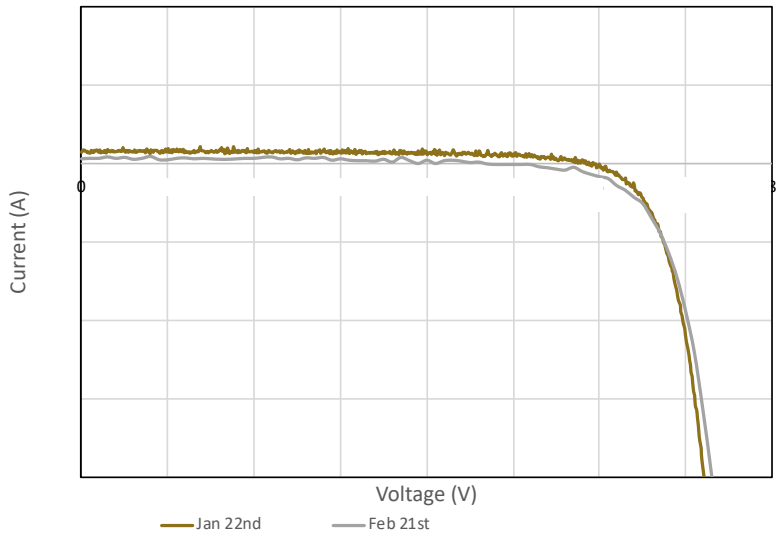
Delam.

Multiple factors working in combination leading to the degradation

Further features of C-AST

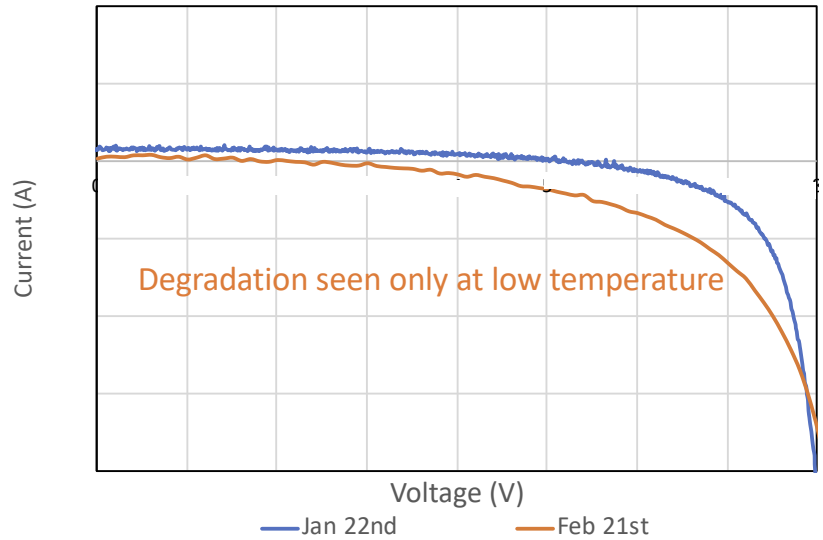
In situ-IV

0 °C



initial Post-High Desert

-40 °C



initial Post-High Desert

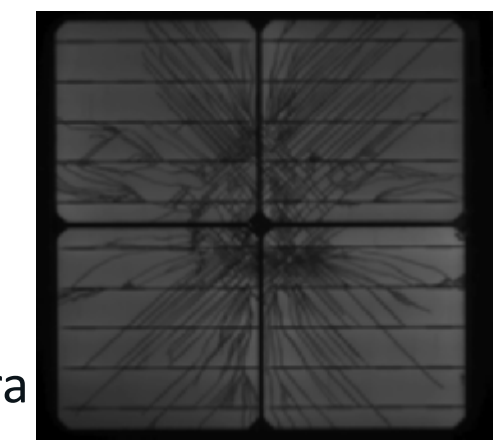
In situ-EL (in progress)

Aluminum heat sink

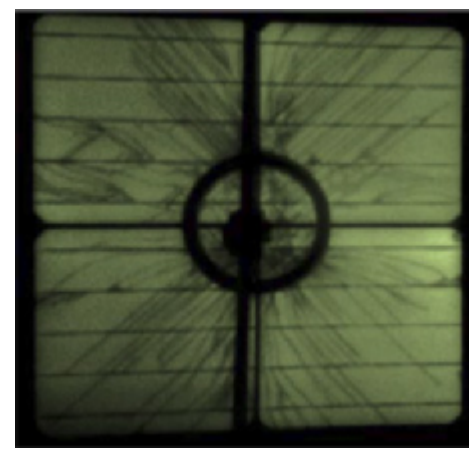
PTFE housing

Raspberry pi IR Camera

Heated glass cover



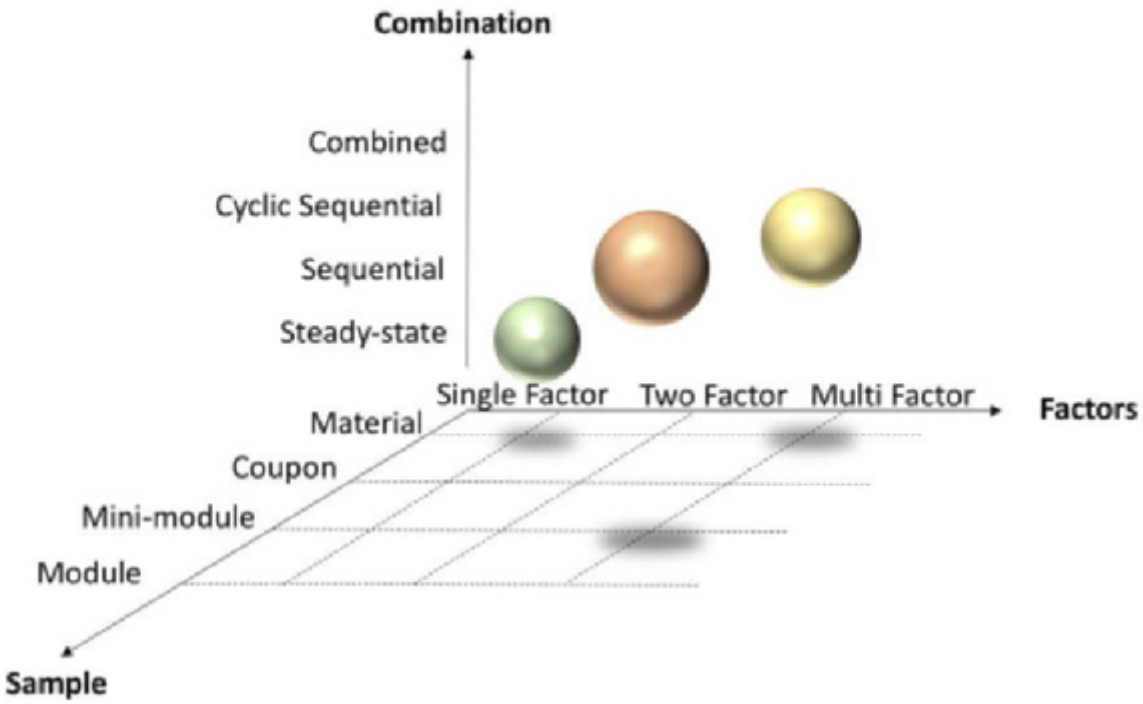
Lab EL camera



Raspberry pi IR camera

Framework for sequential and combined stress testing

"comprehensiveness"

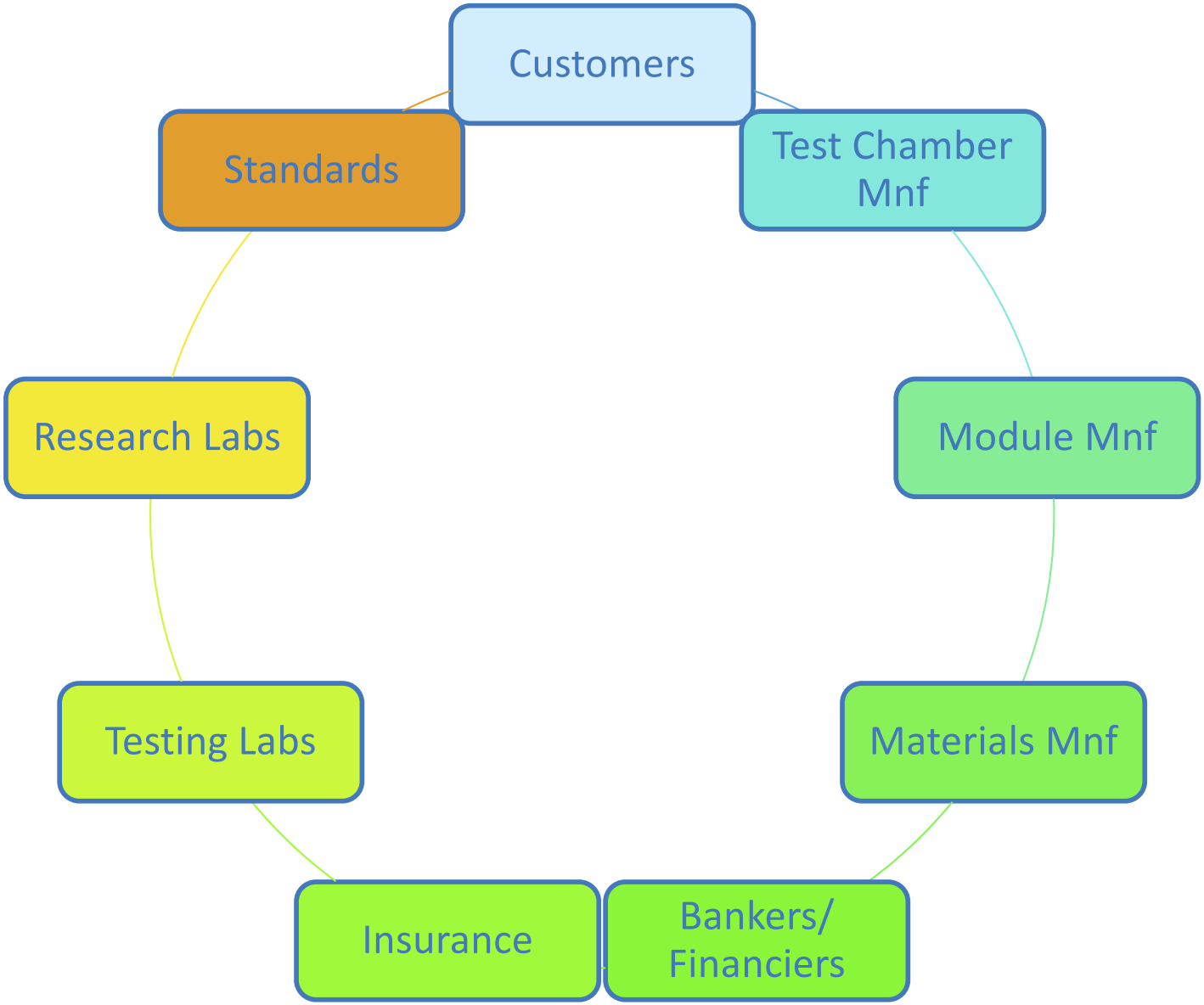


"Sample": representation of the materials interfaces, boundary conditions of the shipping module

"Factors": extent of inclusion of the stress factors of the natural environment

"Combination": representation of the actual combination of stress factors as in the natural environment and their balance (exceeding vs not exceeding real-world stress levels)

Combined-accelerated stress testing – the value chain



Summary/ next steps

Combined-accelerated stress testing

- *To de-risk modules, we must represent:*
  - The sample
  - Stress factors of the natural environment
  - Their combination
    - → success at reproducing field failures
- *Future work:*
  - Further show field-failure mechanisms
  - Engagement of all segments of the value chain,
  - Further develop value proposition
  - Acceleration factor studies
- *Join our discussions:*
  - PV Quality Assurance Taskforce (PVQAT- Task Group 3)
  - IEC Technical Committee 82 Working group 2
- *Contact:*
  - peter.hacke@nrel.gov
  - michael.owenbellini@nrel.gov
  - tadanori.tanahashi@aist.go.jp

Thank you !

Thanks to Edward Hsi (Swiss Re) and Atsushi Masuda (AIST) for helpful conversations, and Teresa Barnes and Dana Olsen for various encouragement.

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DuraMAT
Durable Module Materials Consortium

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Modes	Types/issues	Stress factors	IEC	
Fatigue, breakage (burns)	Cell spacing, cell thickness/nature, ribbon dimensions/bends, non-solder distance, solder/ECA quality	Mechanical and thermomechanical stress on conductors. Current leading to joule heating in the conductors.	IEC 61215 MQT 11 (*too few cycles*) IEC 62782 – DML + IEC 62759 (transp.): : 50 TC, 20 HF, ML 2400 Pa)	C-AST
Light-induced degradation	B-O, FeB, Sponge LID	Sunlight + temperature effects	IEC 61215 MQT 11	C-AST
	Light & Elevated Temperature LID 1)c:Si 2) Thin Film		61215ed 4 c-Si / 61215ed 4, thin film	
	UV LID (H, charges)		IEC/EN 61345	
Yellowing & module packaging optical losses	Photochemical degradation of polymers, ion migration	Sunlight, temperature, humidity, electrical-bias	IEC 62788-7-2 (coupon undefined)	
Backsheet cracking and delamination	Oxidative, optical, hydrolytic reactions, localized stress	Heat, UV, voltage mechanical moisture and mechanical stress	IEC 61730-2 Seq B: DH 200/UV 60/HF 10/UV 60/HF10	C-AST
Corrosion, cell-front delamination	System voltage, humidity, mechanical stress 1) c-Si 2)thin-film	Heat, humidity, UV and system voltage bias.	62804-1-1 c-Si / Thin-film	C-AST
Potential-induced	Polarization, shunting Ion migration	Heat, humidity and system voltage bias, modulated by	62804-1 (does not include light)	C-AST

DuraMAT
Durable Module Materials Consortium

Materials forensics for understanding PV module material durability

Laura Schelhas
SLAC National Accelerator Laboratory

Collaborators:
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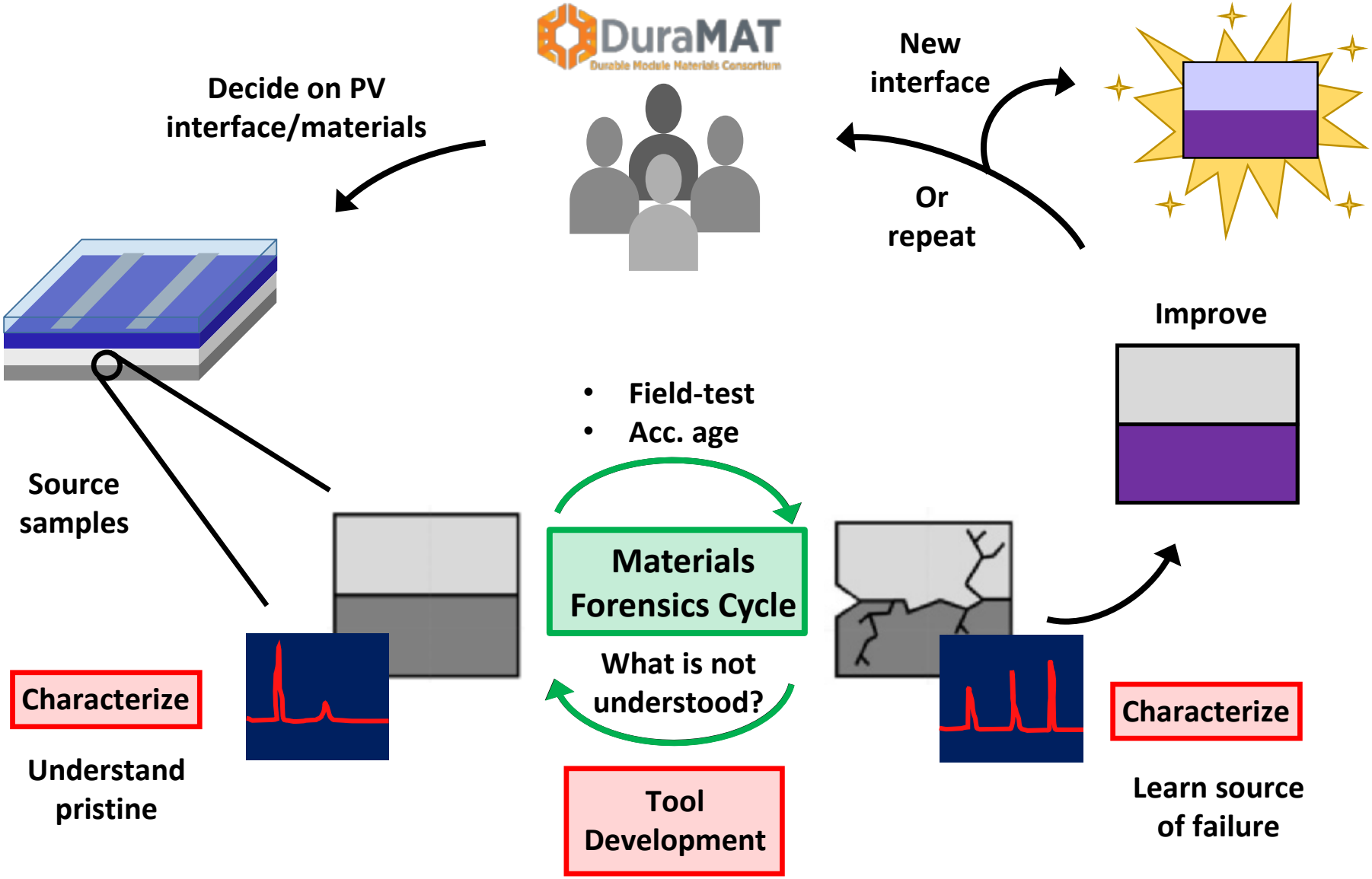
Robert (Drew) Fleming, Corey Thompson (WattGlass)
Margaret Gordon, Patrick Burton (Sandia)
Nick Bosco, Andriy Zakutayev, Conor Riley (NREL)
(Daisy) Pak Yan Yuen, Reinhold Dauskardt (Stanford)

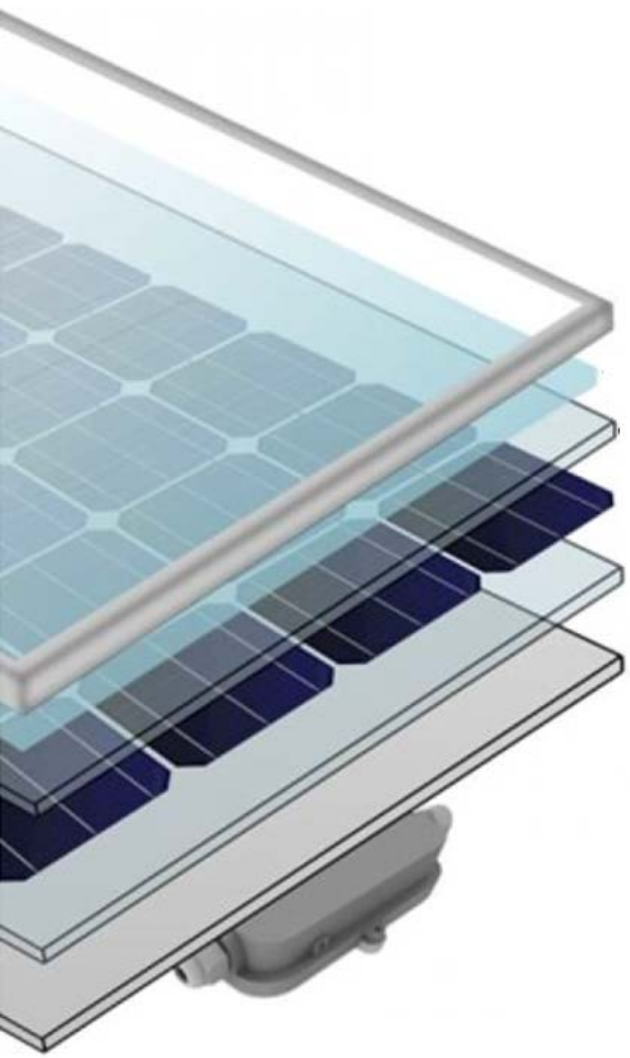
Energy Materials Network
U.S. Department of Energy
NREL
Sandia National Laboratories
BERKELEY LAB
SLAC NATIONAL ACCELERATOR LABORATORY

What is materials forensics?

And how can it help PV reliability?



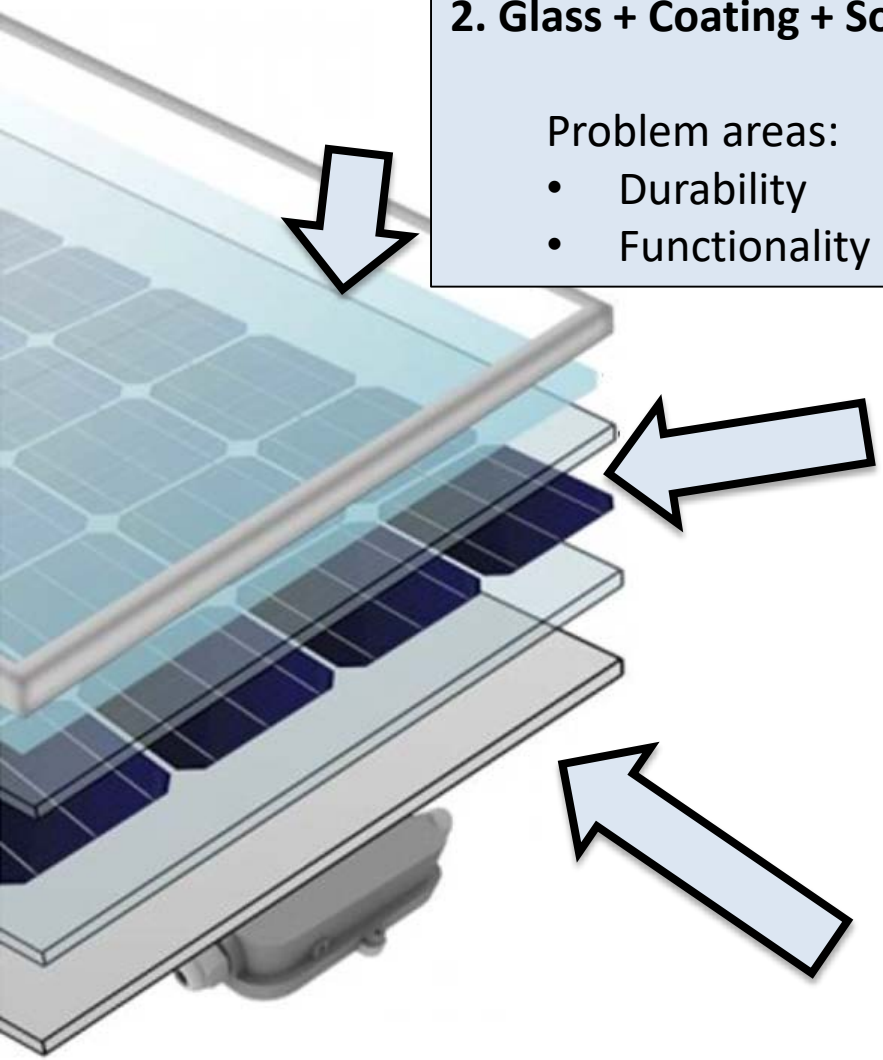
Interfaces & surfaces common failure points



1. Identify which interfaces are the biggest concern

2. Develop methods for understanding failure mechanisms
- Chemistry
- Morphology
- Functional mechanical properties (e.g. adhesion)

Interfaces & surfaces common failure points



2. Glass + Coating + Soil

Problem areas:
- Durability
- Functionality

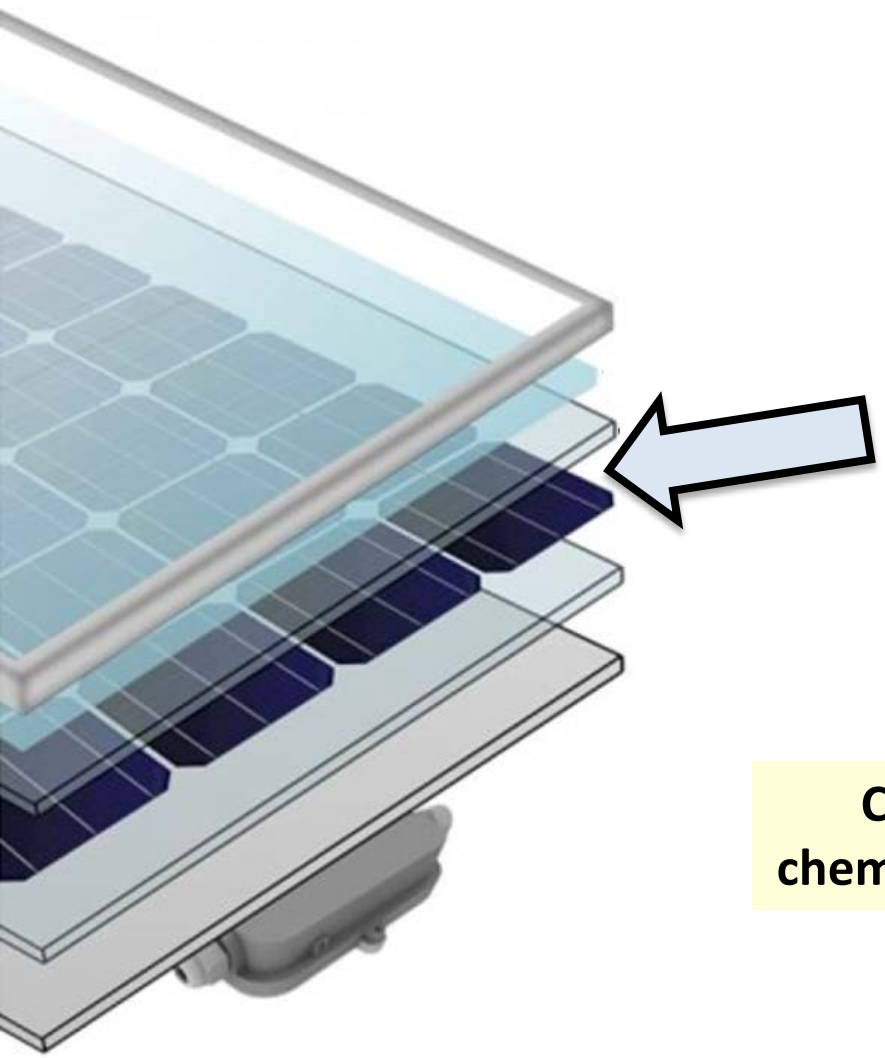
1. Encapsulant + Metallization

Problem areas:
- Delamination
- Corrosion

3. Backsheets (layered polymers)

Problem areas:
- Cracking
- Delamination

Interfaces & surfaces common failure points



NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Nick Bosco

1. Encapsulant + Metallization

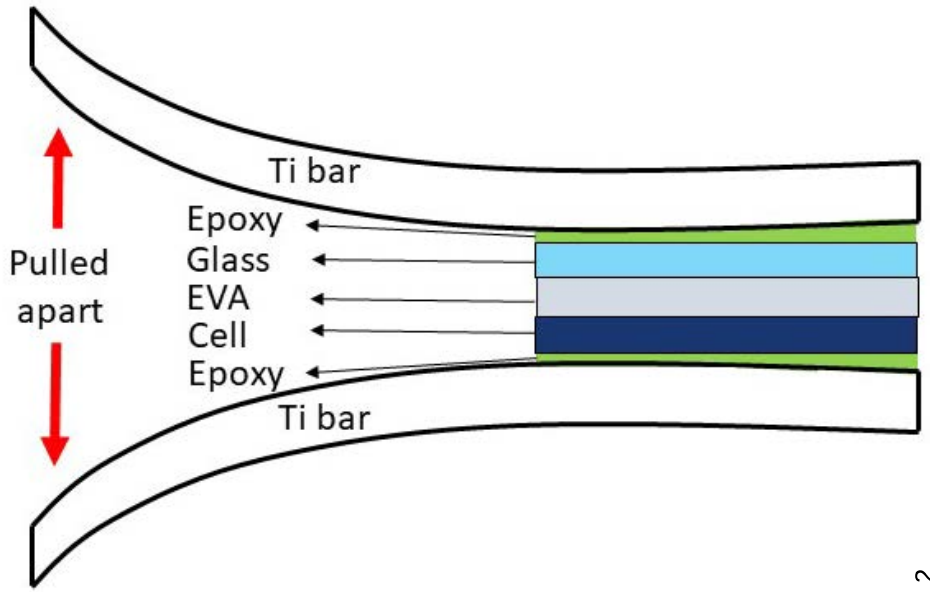
Problem areas:

- Delamination
- Corrosion

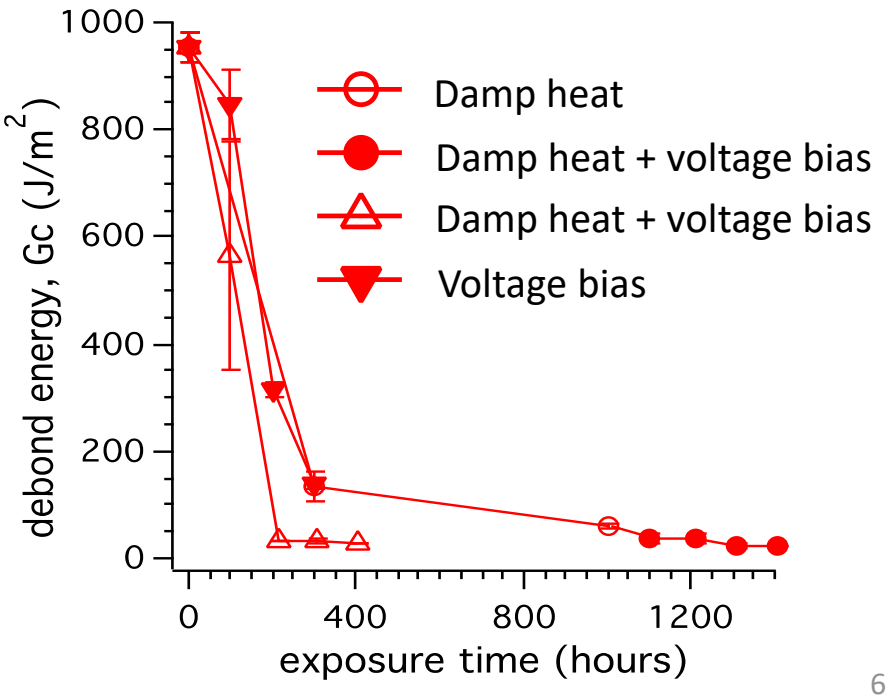
Can we determine the interfacial chemistry responsible for delamination?

Adhesion degradation at encapsulant/metallization interface

Nick Bosco



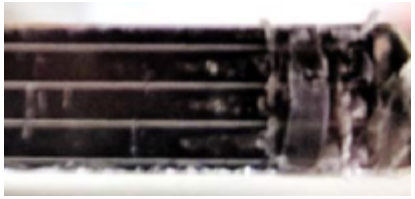
Debonding energy of encapsulant/metallization interface drops off when exposed to damp heat and/or high voltage

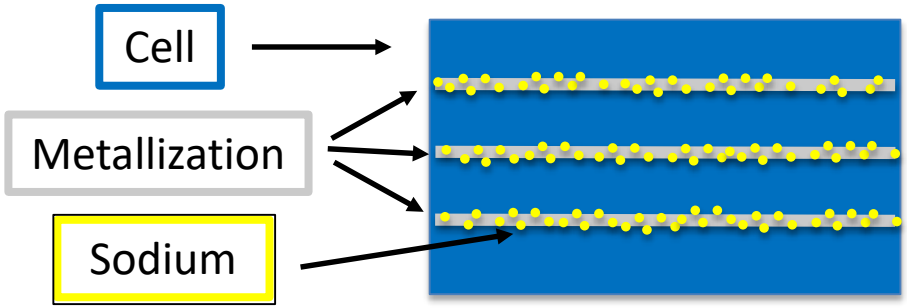


Voltage bias induces sodium migration

X-ray photoelectron spectroscopy → Provides chemical information at a material surface

- 400 hours
- Damp heat
- Voltage bias

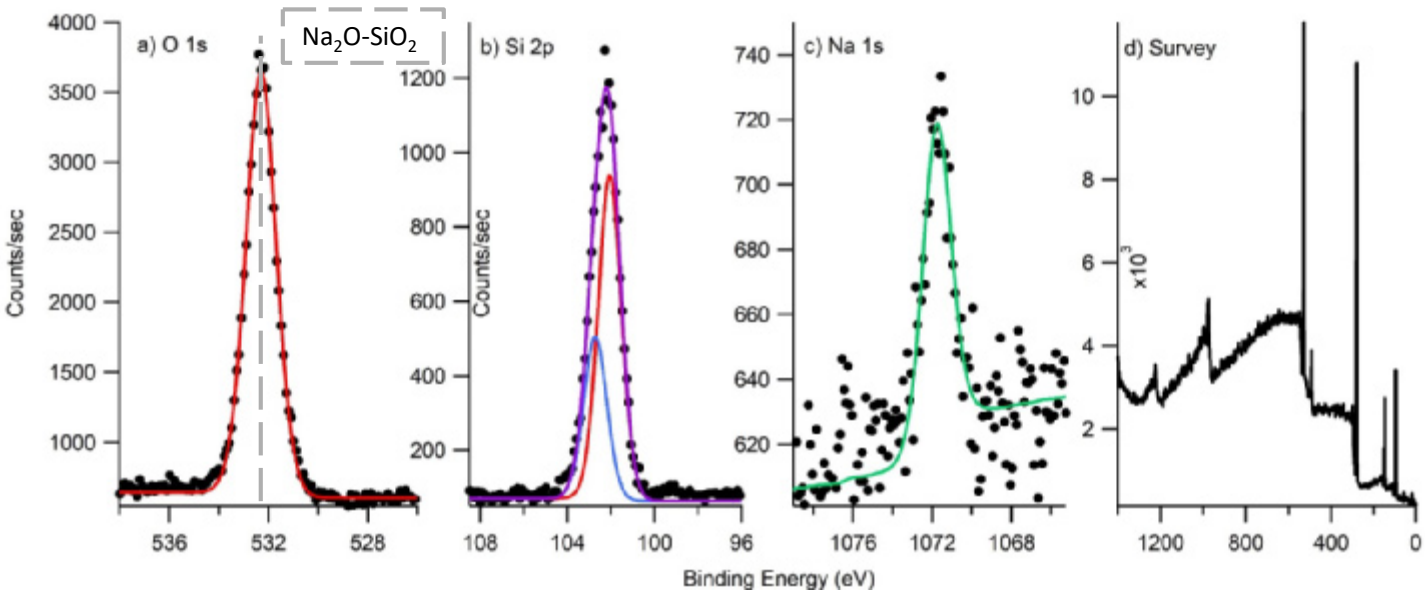




N. Bosco, S. L. Moffitt, L. T. Schelhas, "Mechanisms of Adhesion Degradation at the Photovoltaic Module's Cell Metallization-Encapsulant Interface," *Progress in Photovoltaics*, (2018)

Voltage bias induces sodium migration

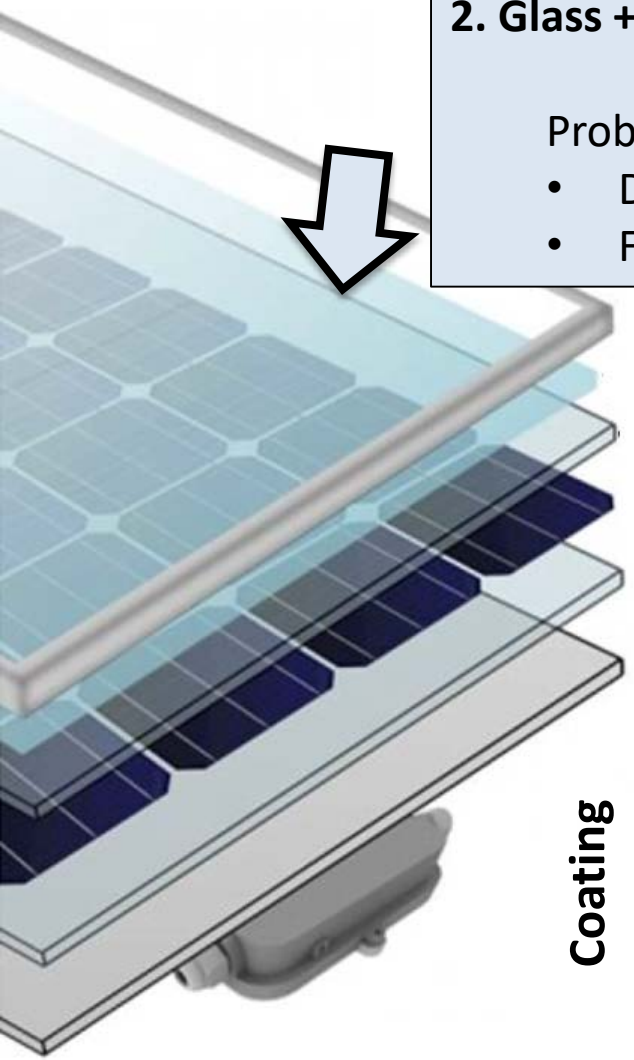
X-ray photoelectron spectroscopy → Provides chemical information at a material surface



Hypothesis: Sodium Silicate (Na_2O-SiO_2) is forming at gridlines
Evidence: Chemical state of Na, Si, and O consistent with Na_2O-SiO_2

N. Bosco, S. L. Moffitt, L. T. Schelhas, "Mechanisms of Adhesion Degradation at the Photovoltaic Module's Cell Metallization-Encapsulant Interface," *Progress in Photovoltaics*, (2018)

Interfaces & surfaces common failure points



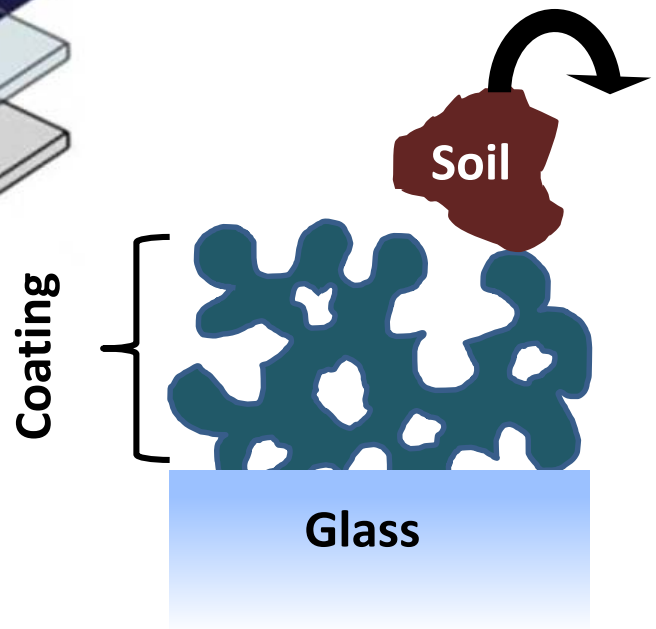
2. Glass + Coating + Soil

Problem areas:

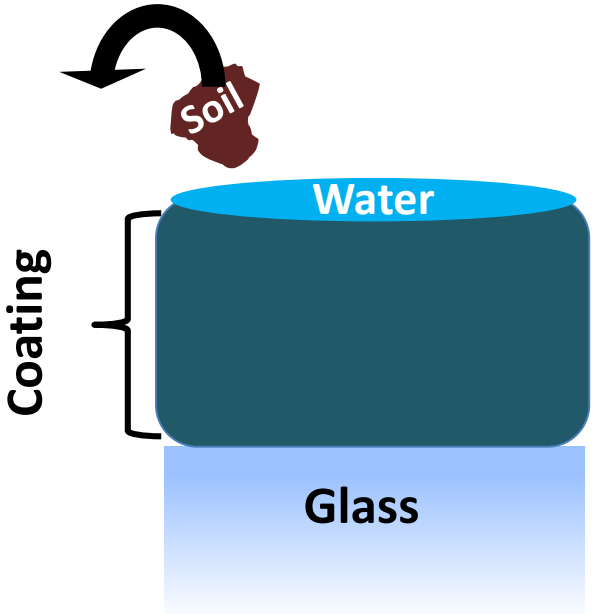
- Durability
- Functionality

WattGlass
Glass Coatings Perfected

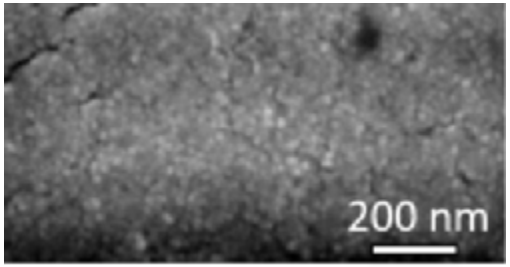
Coating morphology

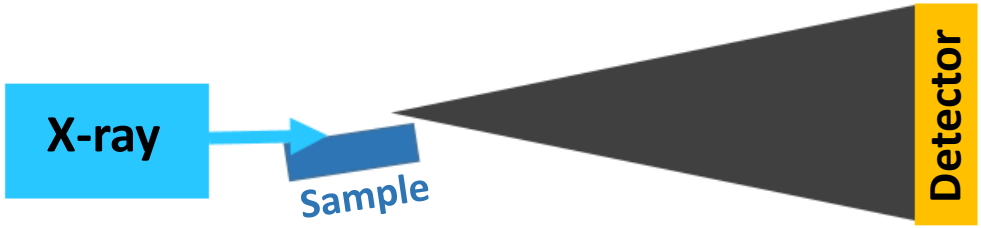


Coating chemistry



Characterization methods for coating morphology





Current technique:
Microscopy

Vs.

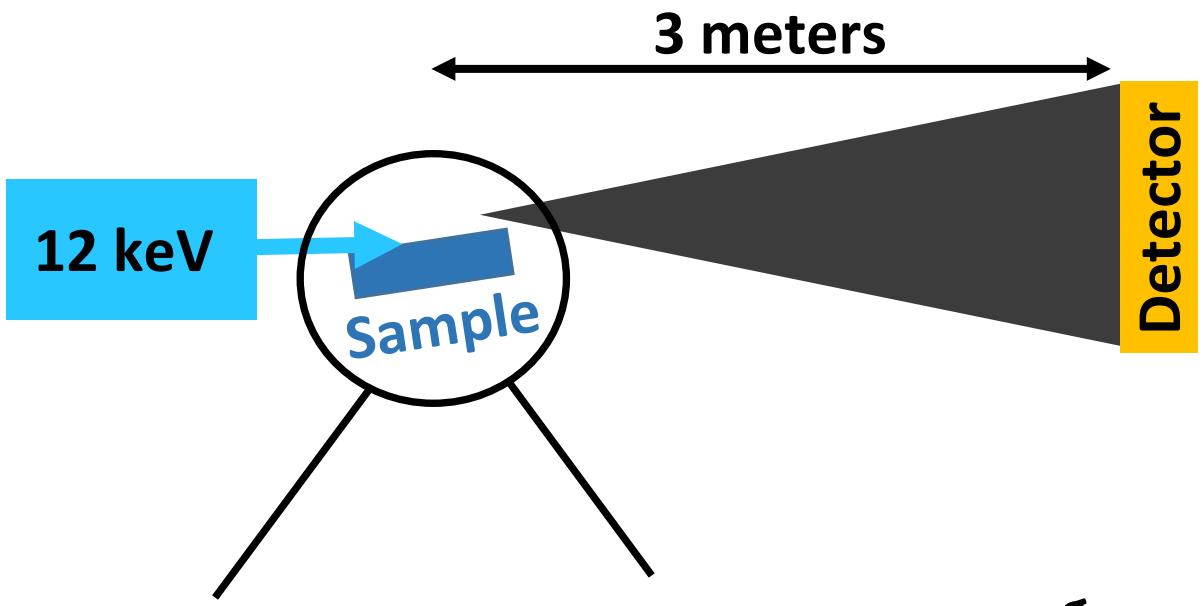
New technique:
Small-angle X-ray scattering (SAXS)

- Limited to a vacuum chamber
- Unable to visualize coating below dirt layer
- Spot size is typically micron-scale

- Performed under ambient conditions (including humidity)
- Can measure coating morphology despite the presence of surface dirt
- Spot size can be centimeter-sized

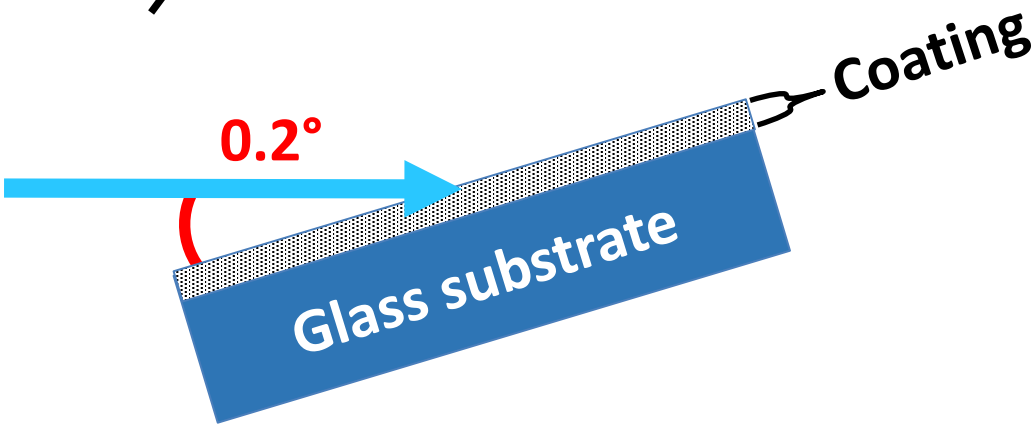
Small-angle X-ray scattering

X-ray source



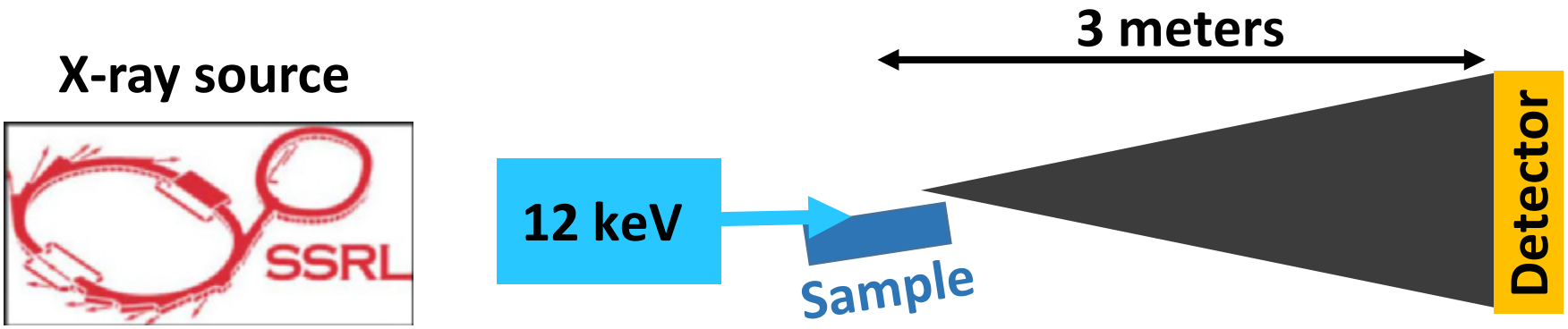
Grazing Incidence

X-ray path through the coating is maximized



Small-angle X-ray scattering

X-ray source



$$Q = 2\pi/d$$

Feature size

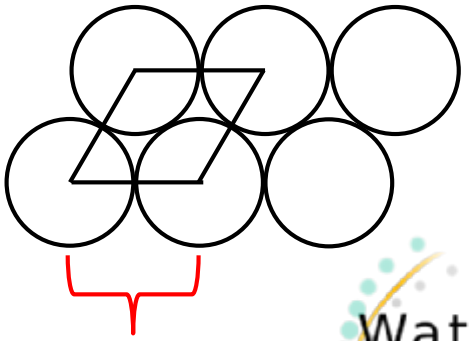
Scattering vector

$$Q = \left(\frac{4}{\lambda}\right) sin\theta$$

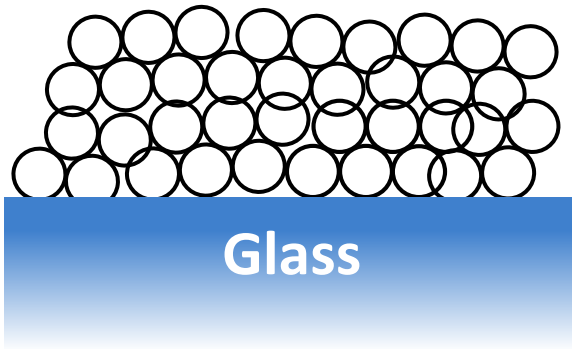
Wavelength

Scattering angle

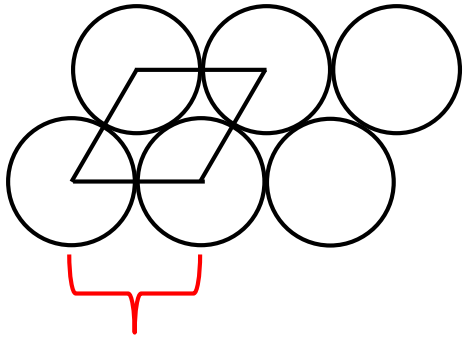
Closed-packed SiO_2 spheres



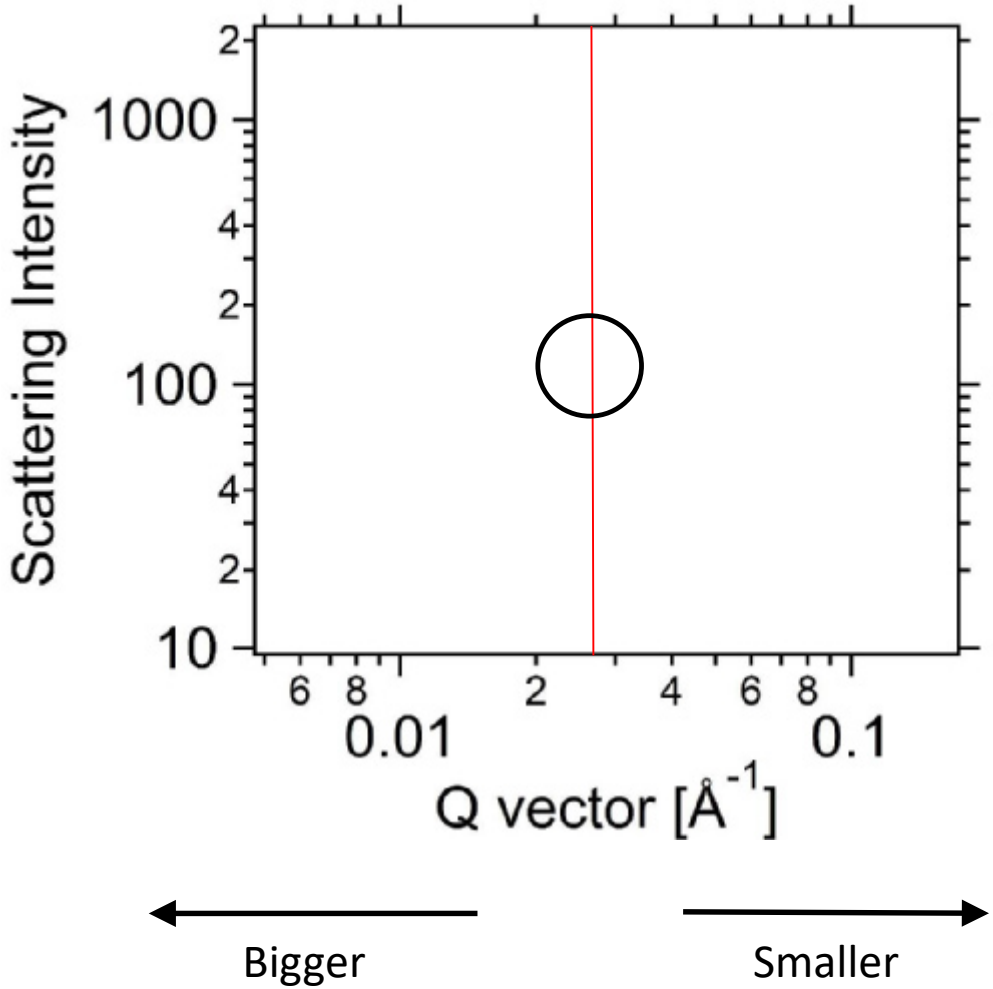
SAXS of WattGlass coating



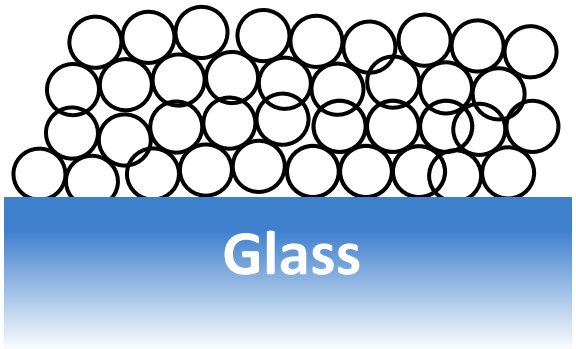
Closed-packed
SiO_2 spheres



20-30nm



SAXS of WattGlass coating



Closed-packed
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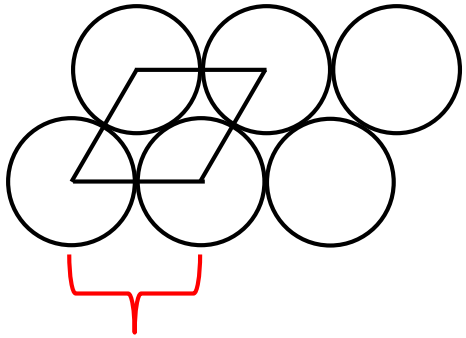
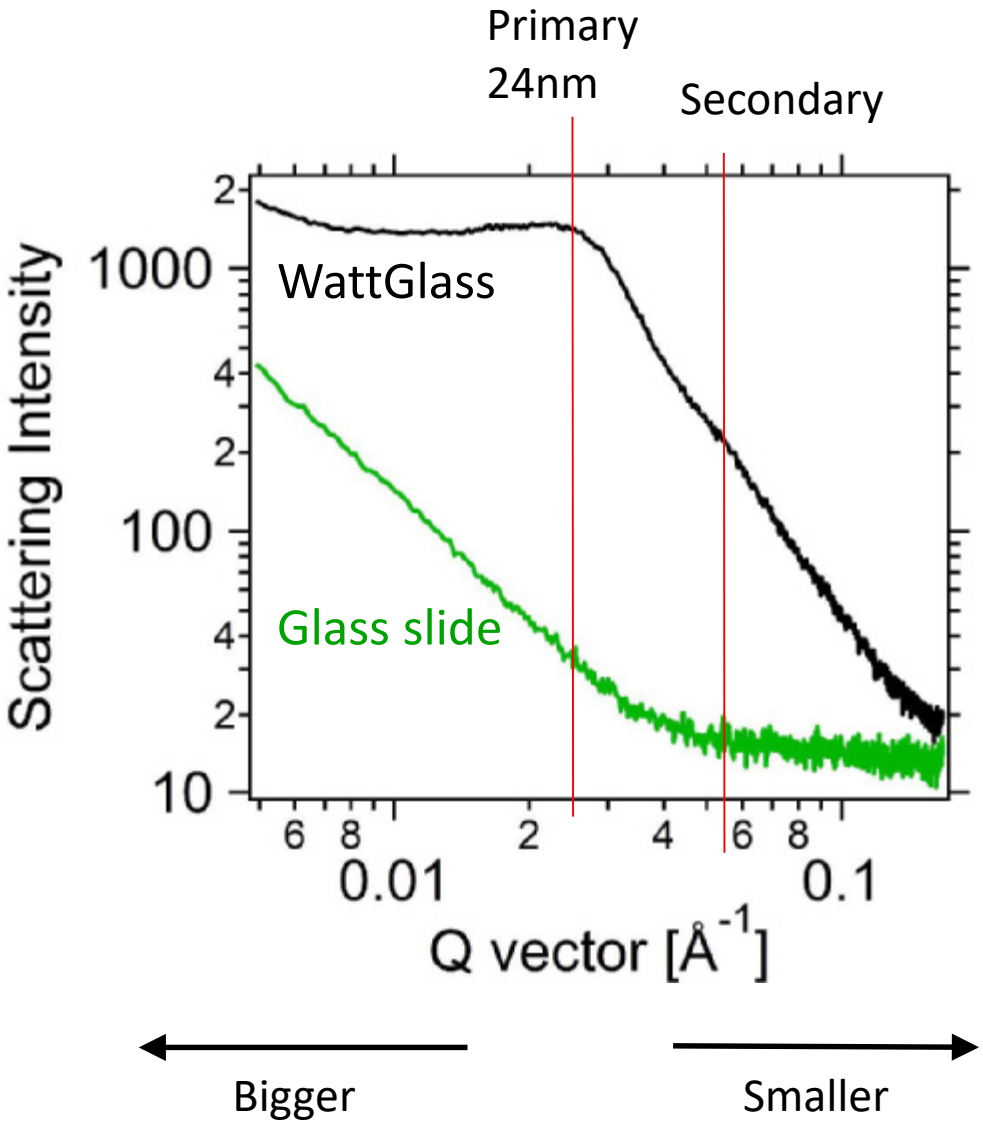
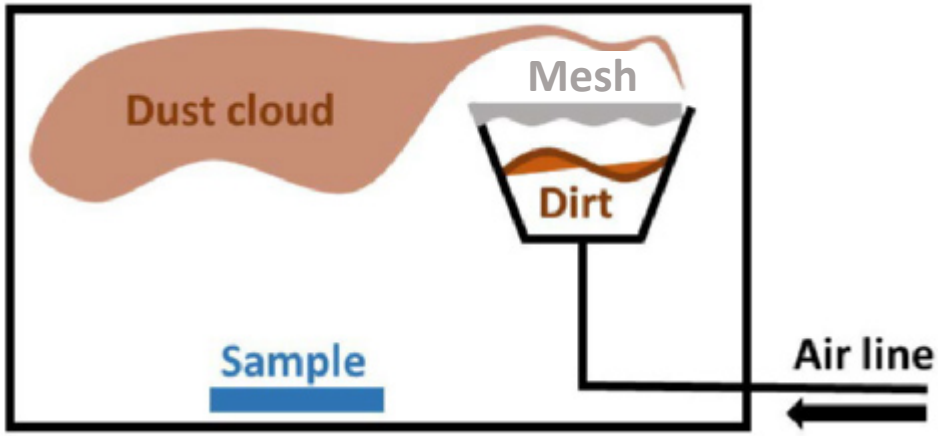
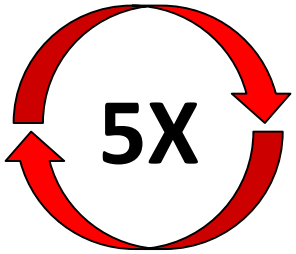


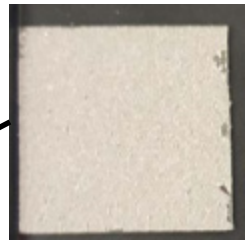
24nm

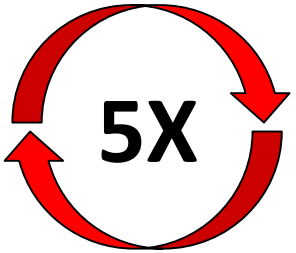


Soiling

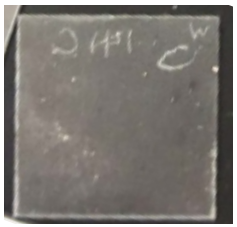






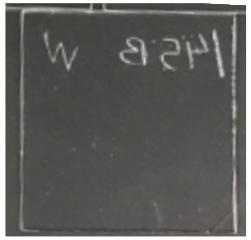


"dry-air" cleaning protocol



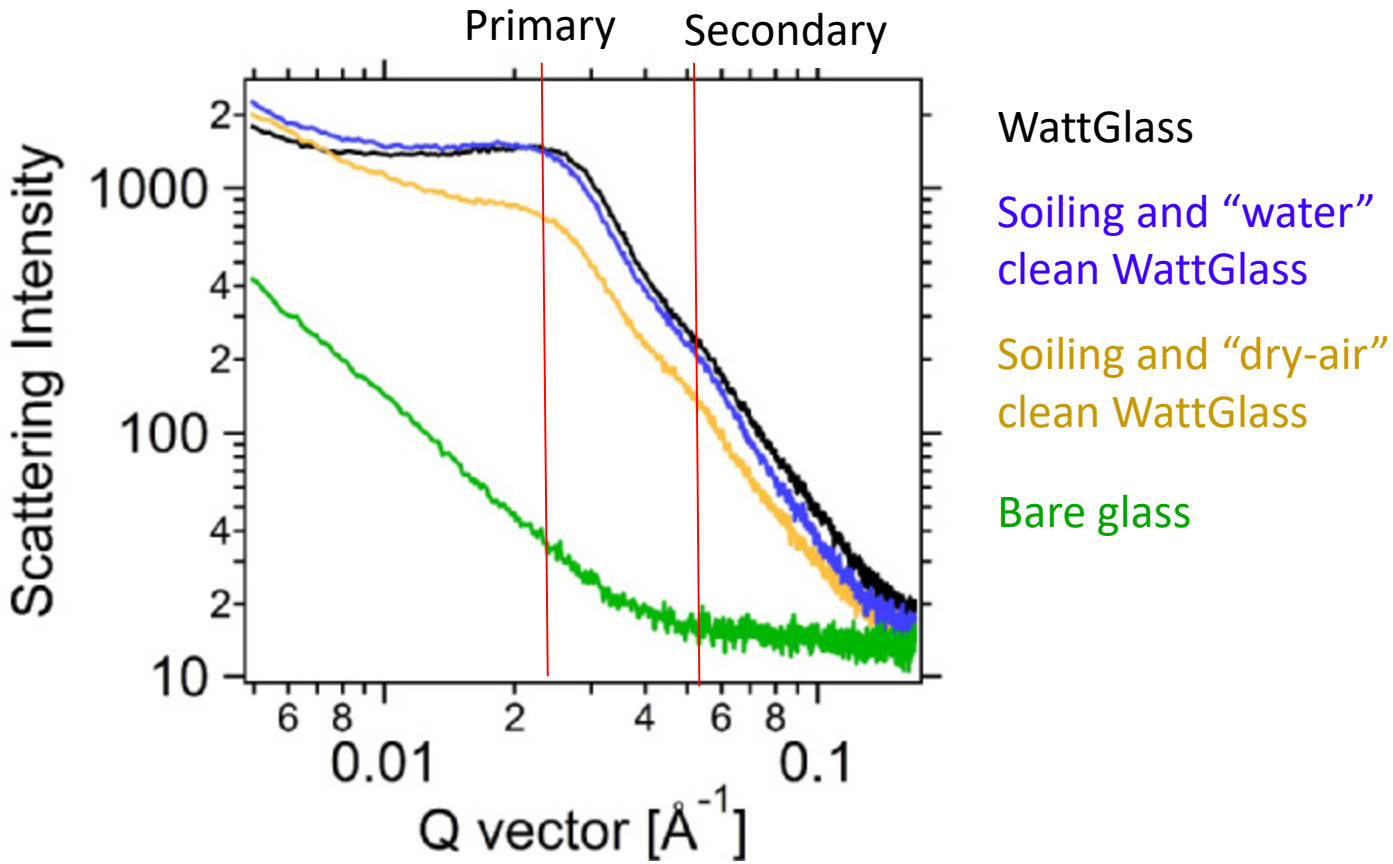
Compressed air with a low flow rate is blown over the sample surface

"water" cleaning protocol



Distilled water is flowed over the sample from a squeeze bottle

Soiled WattGlass SAXS



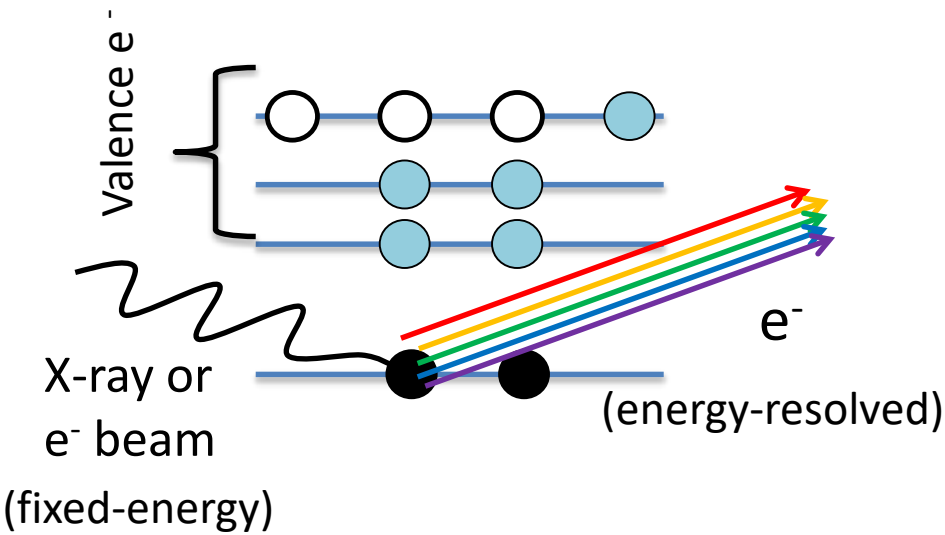
- Scattering features indicative of the coating morphology do not change
- Upturn in scattering intensity at small Q due to presence of µm-sized soil
- Slight damping of scattering intensity due to surface soil

Characterization methods for coating chemistry

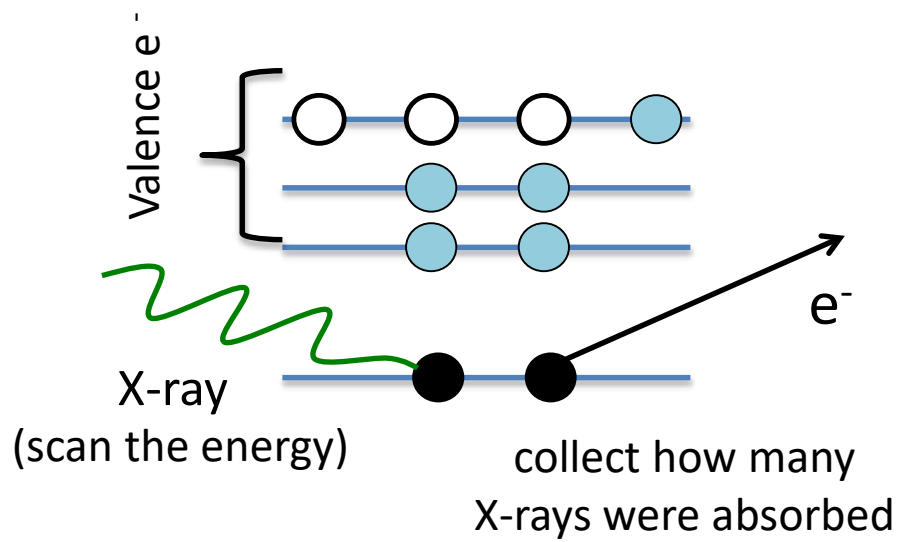
Current techniques: **Vs.** **New technique:**

X-ray photoelectron spectroscopy (XPS)

Energy dispersive spectroscopy (EDS)

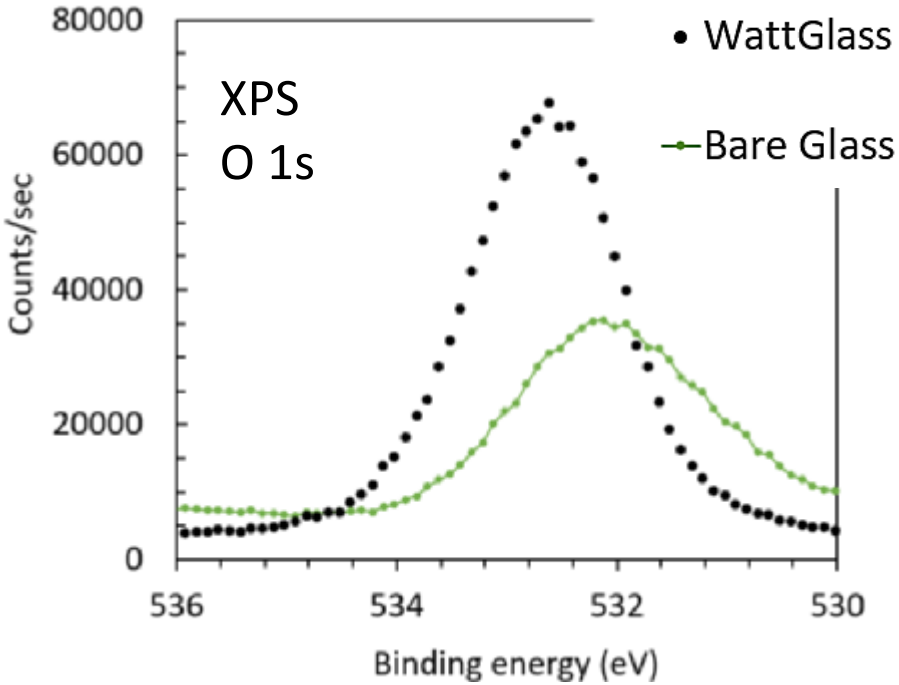


X-ray absorption spectroscopy (XAS)

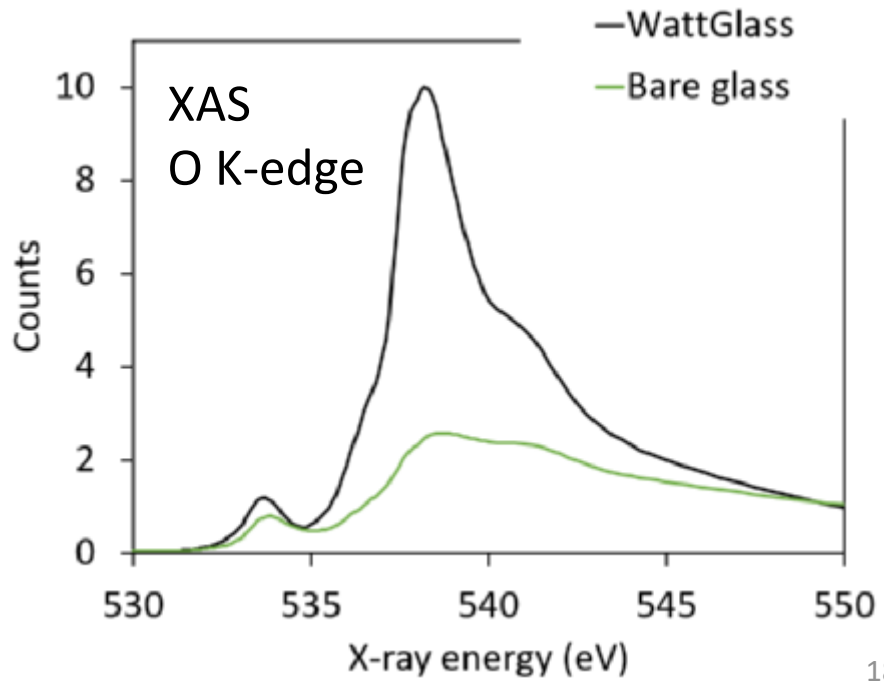


- Option for greater penetration depth
- Larger spot size
- More sensitive to chemistry changes

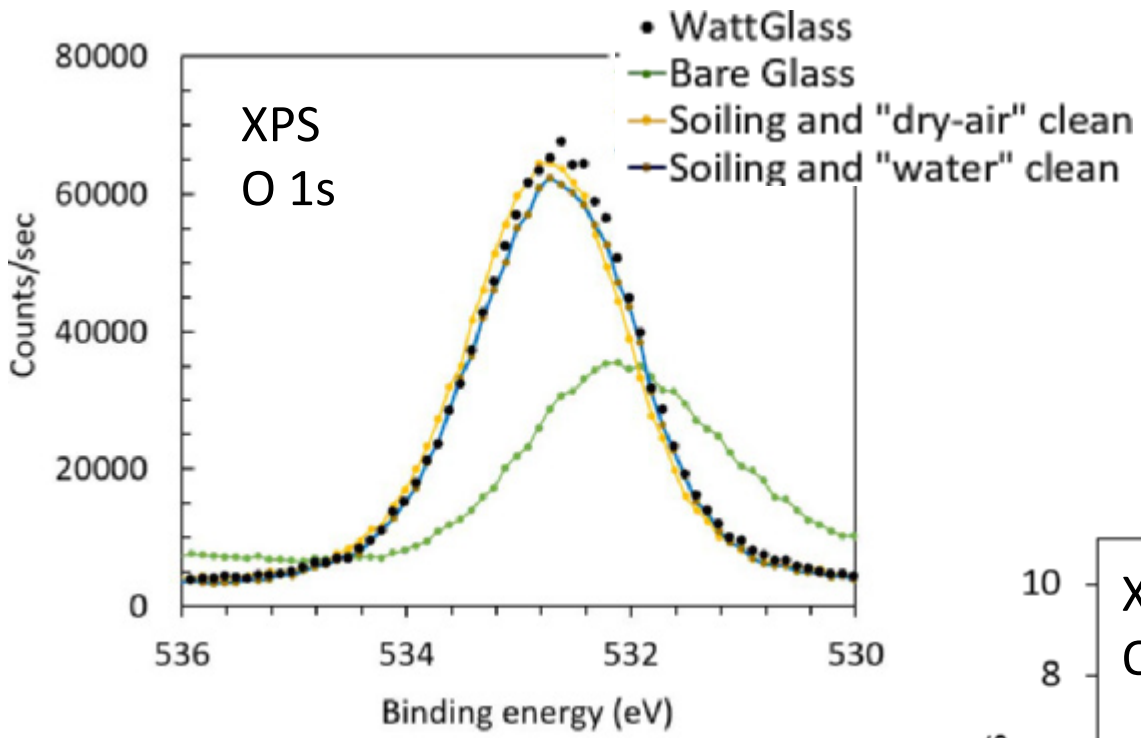
XAS and XPS of WattGlass coating O-chemistry



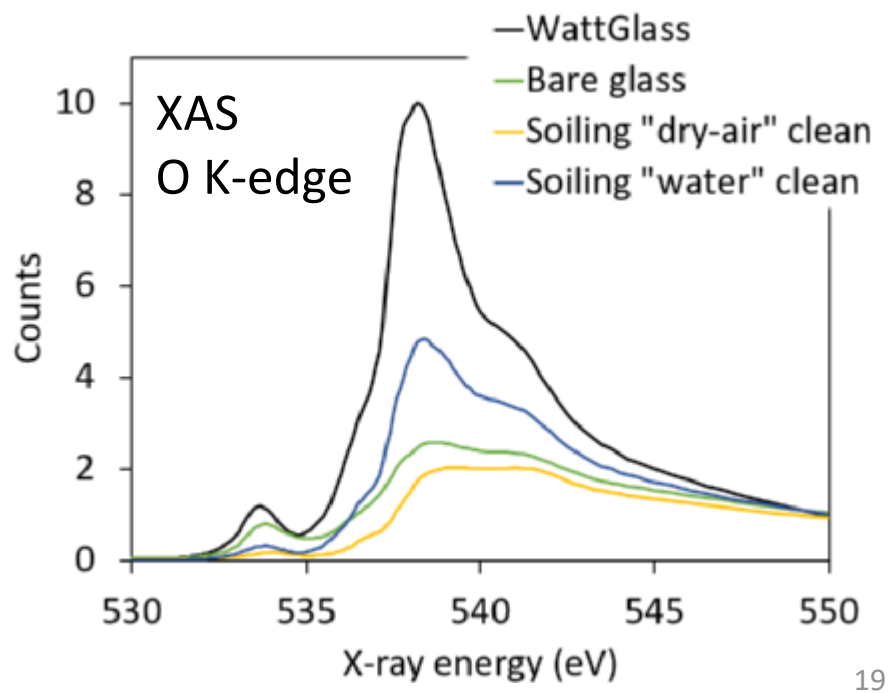
Coating is easily differentiated from bare glass by both techniques

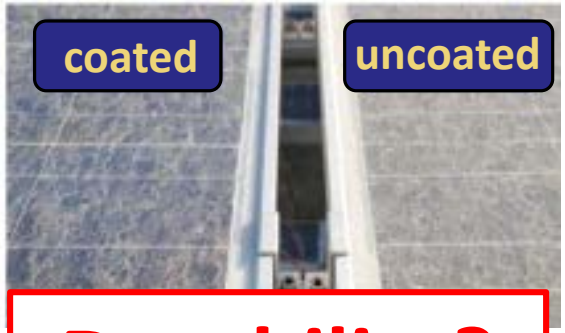


XAS and XPS of WattGlass coating O-chemistry



Changes in the coating O-chemistry after soiling can only be seen in XAS measurement





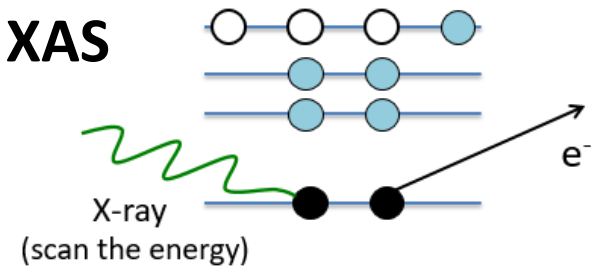
Durability?

Morphology

Measure morphology under ambient conditions when soil is present

Chemistry

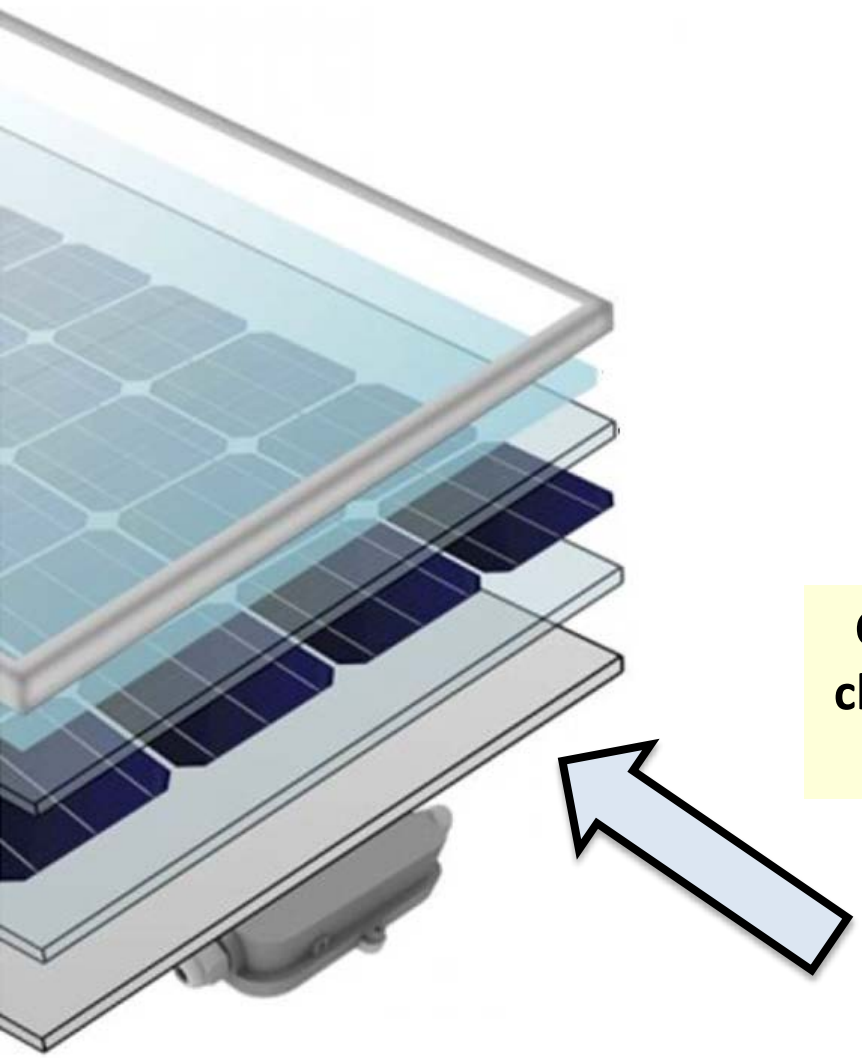
XAS



Higher sensitivity to subtle changes in coating chemistry

Interfaces & surfaces common failure points

Dauskardt group



Can we determine the microstructural changes associated with the mechanical degradation?

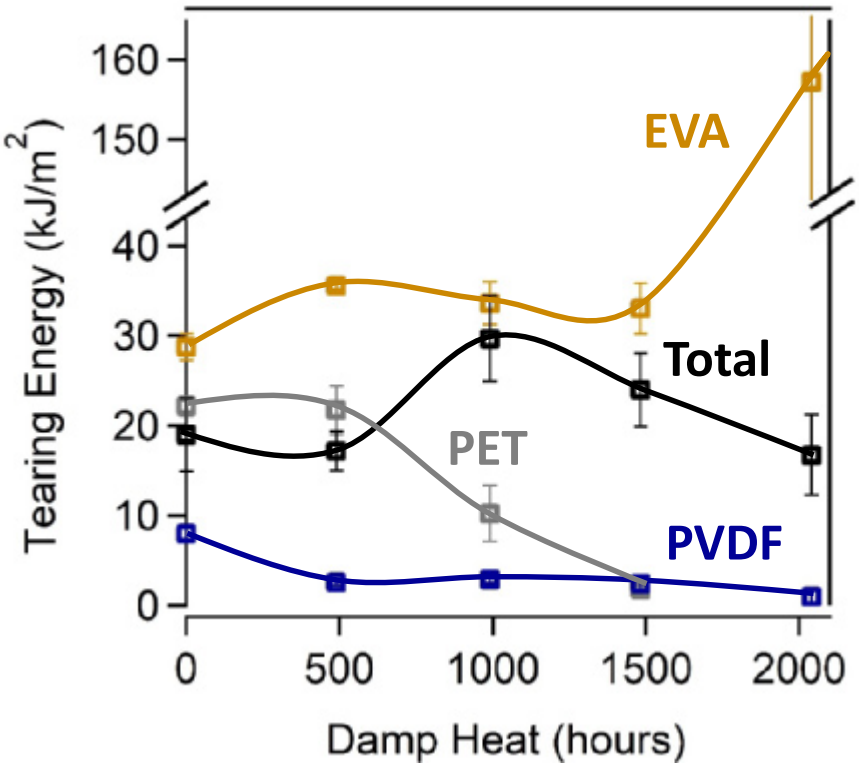
3. **Backsheets** (layered polymers)

   Problem areas:
   - Cracking
   - Delamination

1. Backsheet polymers degradation after damp heat

Dauskardt group

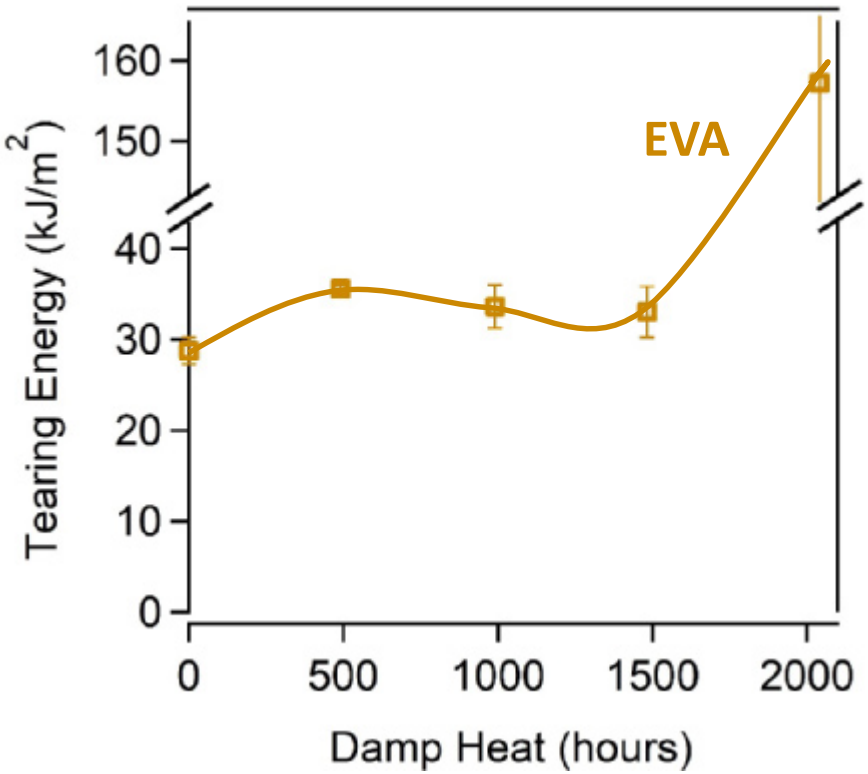
Evolution after damp-heat aging of tearing energy is different for each backsheet polymers layer



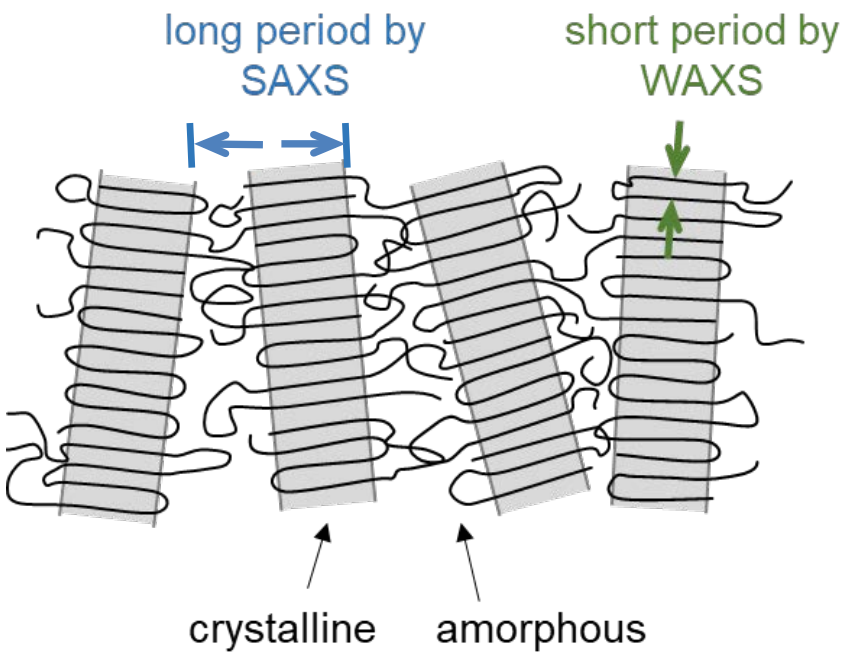
1. Backsheet polymers degradation after damp heat

Dauskardt group

Evolution after damp-heat aging of tearing energy is different for each backsheet polymers layer



X-ray scattering measures polymer structure

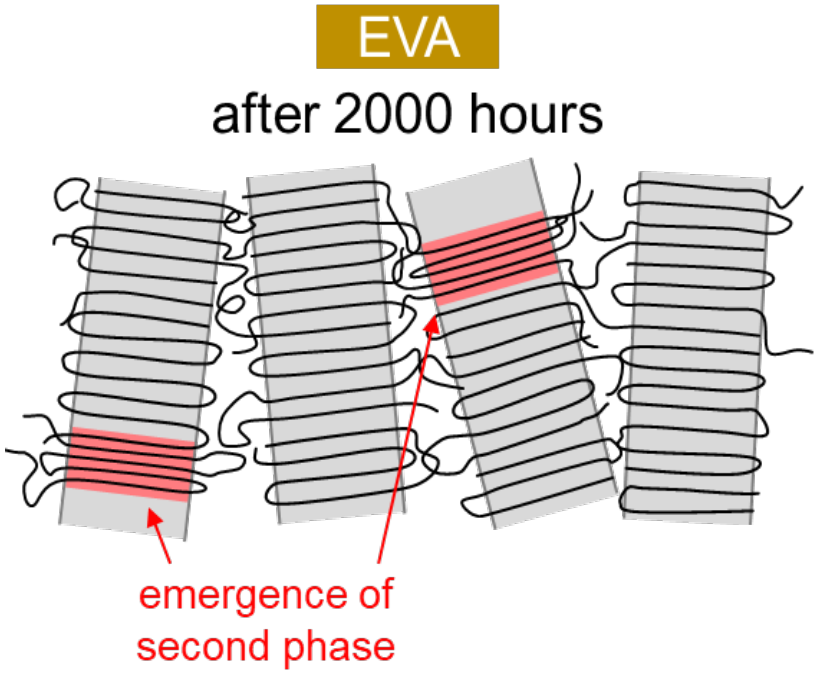


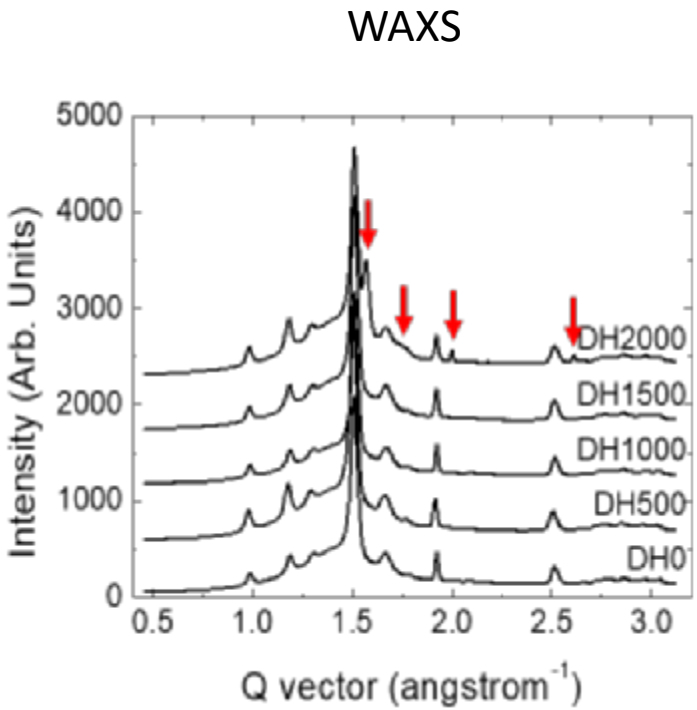
SAXS: Small-angle
X-ray scattering

WAXS: Wide-angle
X-ray scattering

Pak Yan Yuen, Stephanie L. Moffitt, Fernando D. Novoa, Laura T. Schelhas, Reinhold H. Dauskardt, "Tearing and reliability of photovoltaic module backsheet structures," (submitted)

Structure change linked to increased yield strength

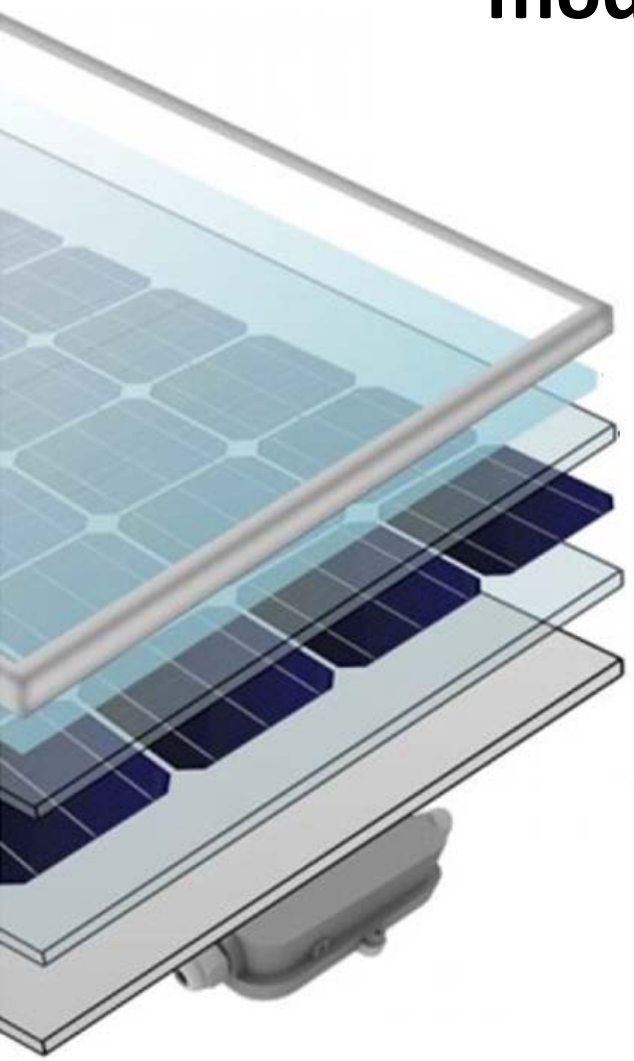




The change in molecular structure leads to the toughening of the EVA such that both the tearing energy and strain energy density at failure increase significantly.

Pak Yan Yuen, Stephanie L. Moffitt, Fernando D. Novoa, Laura T. Schelhas, Reinhold H. Dauskardt, "Tearing and reliability of photovoltaic module backsheet structures," (in progress)

Materials forensics for understanding PV module material durability



- Tested methodologies to characterize interface degradation
- Focused on:
  - Chemistry
  - Morphology
  - Mechanical properties

- What's next for module forensics?
  - Fielded module testing
    - In-field testing
    - Forensics without the BOM
  - Validation of acceleration science

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Acknowledgements

Stephanie Moffitt (Left)
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Corey Thompson
Robert (Drew) Fleming

Pak Yan (Daisy) Yuen
Reinhold Dauskardt

Nick Bosco

Characterizing Adhesives and Edge Seals for Roll To Roll Photovoltaics Packaging

Michael Sulkis[1], Jinho Hah[1], Samuel Graham[1], Jack Moon[1], C. P. Wong[1], Suresh Sitaraman[1], Matthew Reese[2], Sean Garner[3], Scott Jones[4], Doojin Vak[5]

[1]Georgia Institute of Technology, [2]National Renewable Energy Laboratory; [3]Corning, Inc., [4]3M, Inc., [5]CSIRO-Monash; Australia

DURAMAT Project:
Scalable Packaging Materials for Roll-To-Roll Processed Thin Films Solar Cells

DuraMAT
Durable Module Materials Consortium

Outline

- Introduction
- Materials for PV Packaging
- Optical Calcium Testing
- Mechanical Adhesion Testing
- Conclusions and Future work

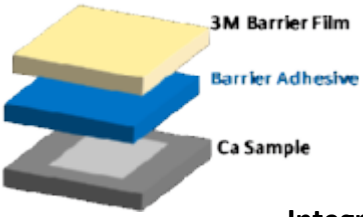
Project Summary

DuraMAT
Durable Module Materials Consortium

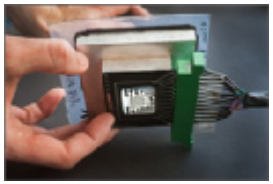
Innovation

This work will determine barrier and adhesive materials that are compatible with R2R processing of solar cells while also providing long term stable performance.

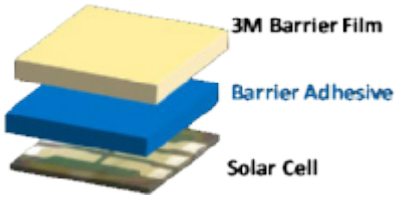
Barrier Film and Adhesive Development



High Throughput Testing



Integration with Thin Film PV



Technology Summary & Impact

The goal of this research is to characterize classes of materials that are flexible, mechanically reliable, and have low permeability for use in packaging thin film solar cells in a R2R process.

Expected Outcome:
We will provide critical data on permeation and mechanical performance of encapsulants and edge seals for thin film PV processed on polymer substrates.

Key Milestones

Date	Key Milestones & Deliverables
8/2018	• Characterize permeation through Barrier Films and Adhesives using Ca Testing • Perform baseline adhesive testing of all materials.
8/2019	• Modify and characterize Barrier Adhesives • Integrate Best Barriers Films and Adhesives with PV Cells Produced By R2R. • Characterize cell stability.

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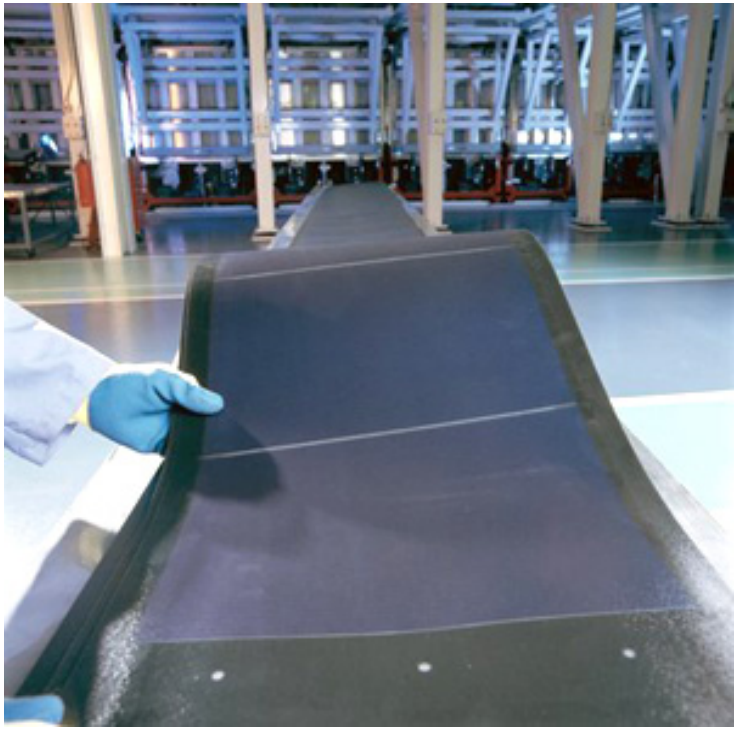
Flexible Photovoltaics

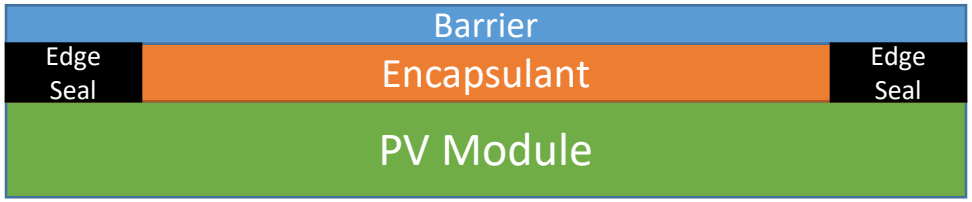
- Differences from rigid PV technologies
  - Materials – thin films and polymers
  - Manufacturing – Roll to Roll processes
  - Heightened sensitivity to environmental factors



NREL

Thin-Film Photovoltaics

- Construction



- Encapsulants and Edge Seals must provide:
  - Mechanical support
  - Environmental protection
- Many commercial options are available
  - Designed for rigid PVs

Are the commercial options applicable for flexible PVs?

Can we make something better?

Objectives

- Understand the permeation and adhesive properties of adhesives that can be used to package solar cells via roll-to-roll processing.
- Use Ca corrosion testing with glass slides to isolate side permeation behavior. Screen commercial materials and materials developed at GT.
- Perform mechanical adhesion testing using PET based substrates

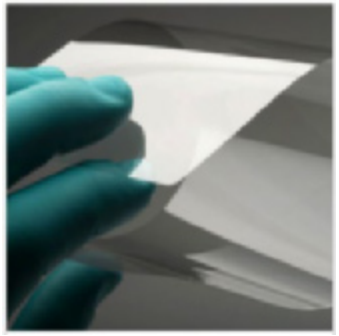
Materials for Flexible PV Packaging

DuraMAT
Durable Module Materials Consortium

Barrier Materials:

3M

3M Ultra Barrier



Corning

Corning Willow Glass

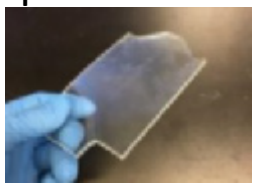
Adhesive/Encapsulant Materials:

- Polyisobutylene Rubber (PIB)
  - Established edge seal for PVs
  - Flexible
  - Highly modifiable
  - ADCO PVS101

PIB Edge Seal

- Polydimethylsiloxane (PDMS)
  - Highly modifiable
  - Flexible
  - Transparent

- Ethylene Vinyl Acetate (EVA)
  - Most common PV encapsulant
  - Transparent
  - UV stability issues
  - Moisture reaction



- Ionomer and Polyolefin
  - No moisture reaction
  - UV stable
  - Strong adhesion

Ionomer Encapsulant

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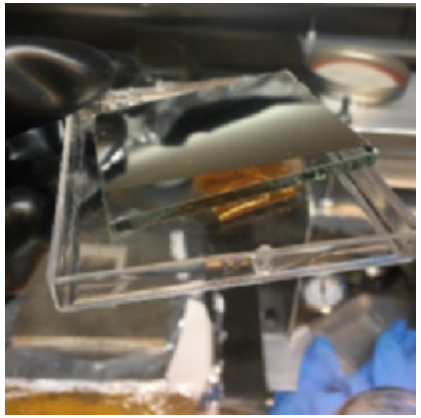
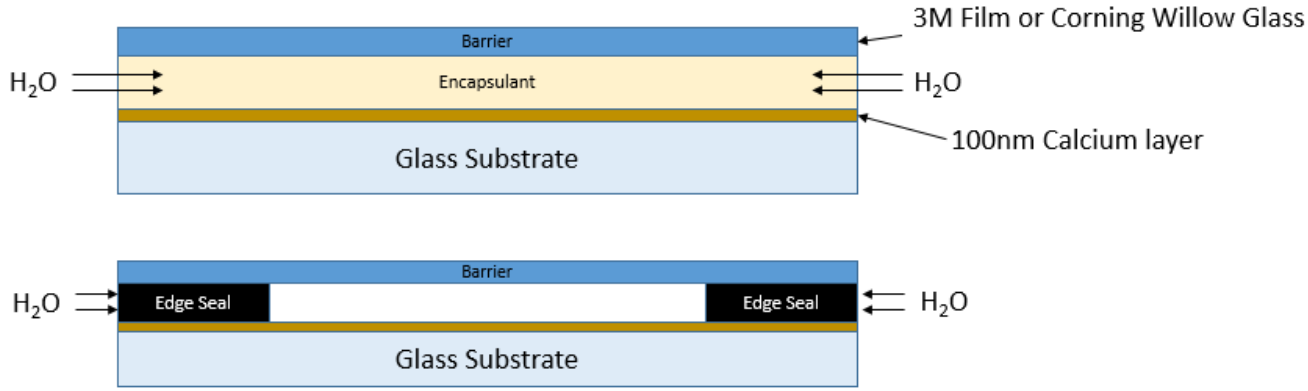
Durable Module Materials Consortium

Calcium Test Specimens

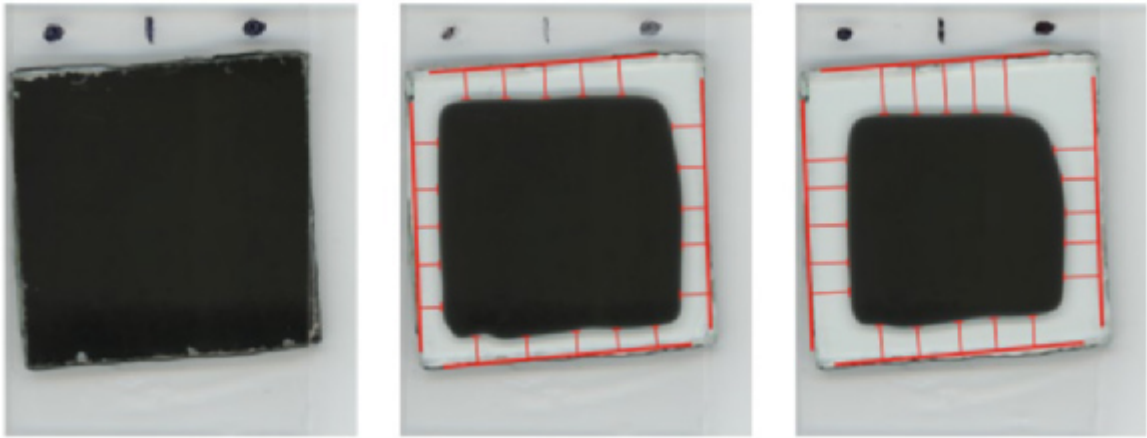




$$Ca(s) + 2H_2O(g) \rightarrow Ca(OH)_2(aq) + H_2(g)$$

*Glass barrier isolates side permeation

Epson Photo Scanner



→ Exposure time →

Degradation distance from average of 16 measurements (4 per side)

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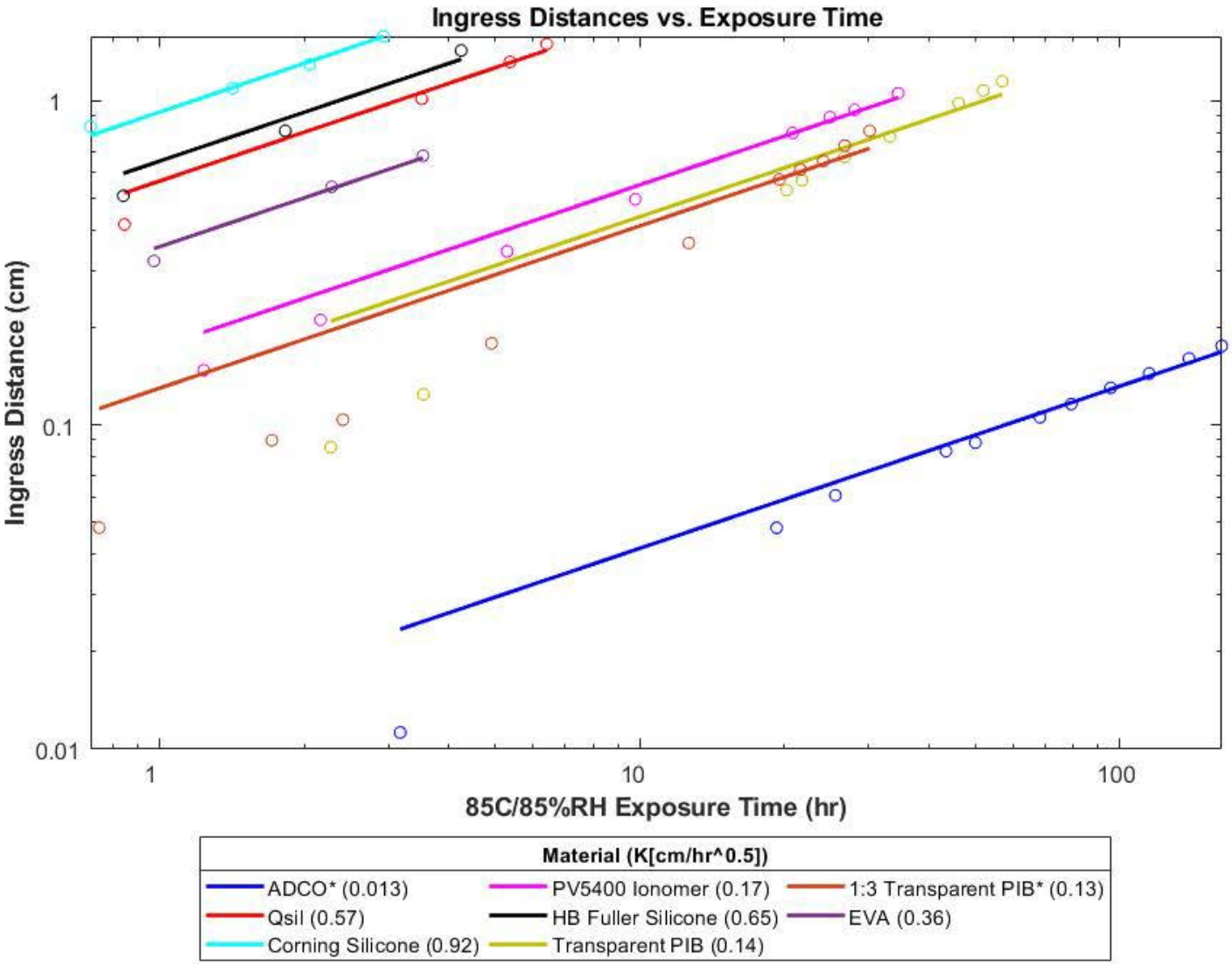
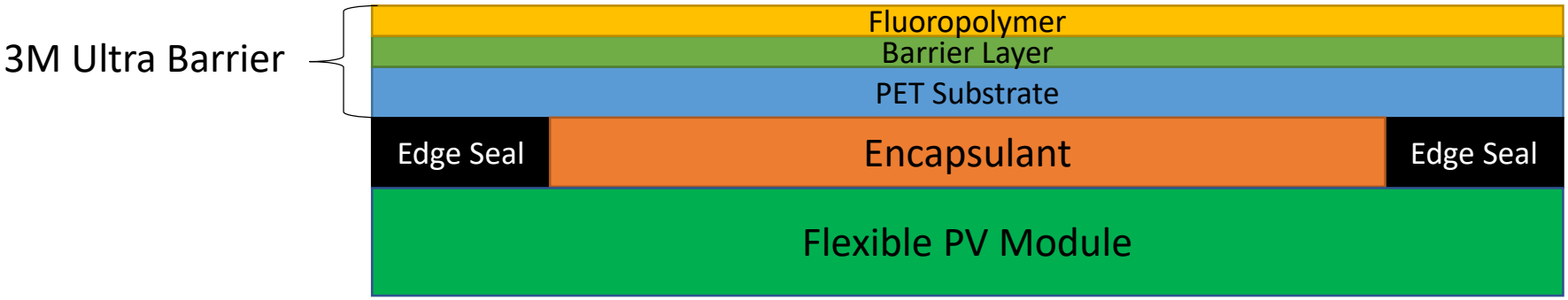
Calcium Screening Results



Mechanical Characterization

Adhesion is the most important parameter.

Flexible top sheets and modules introduce new adhesive interfaces.



Understanding the mechanical performance of encapsulants and edge seals bonded to flexible materials is critical.

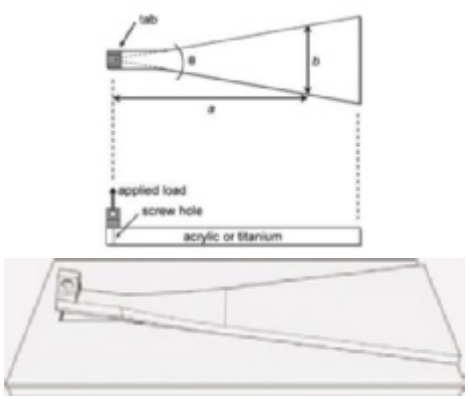
Mechanical Testing

Methods

- Single or Double Cantilever beam
- Width-Tapered Cantilever Beam
- Peel Tests

Width-Tapered Cantilever Beam Experiment (NREL)

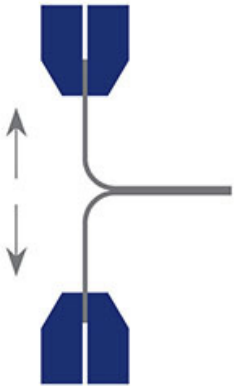
- Capable of evaluating adhesion energy G_c
- Applicable for coupon-level and full module tests



Peel Testing

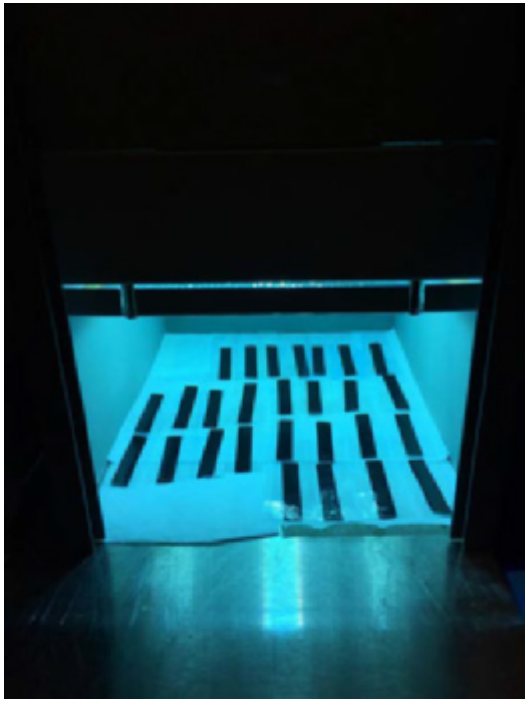
- More compatible with flexible materials
- High-throughput

Testresources.net

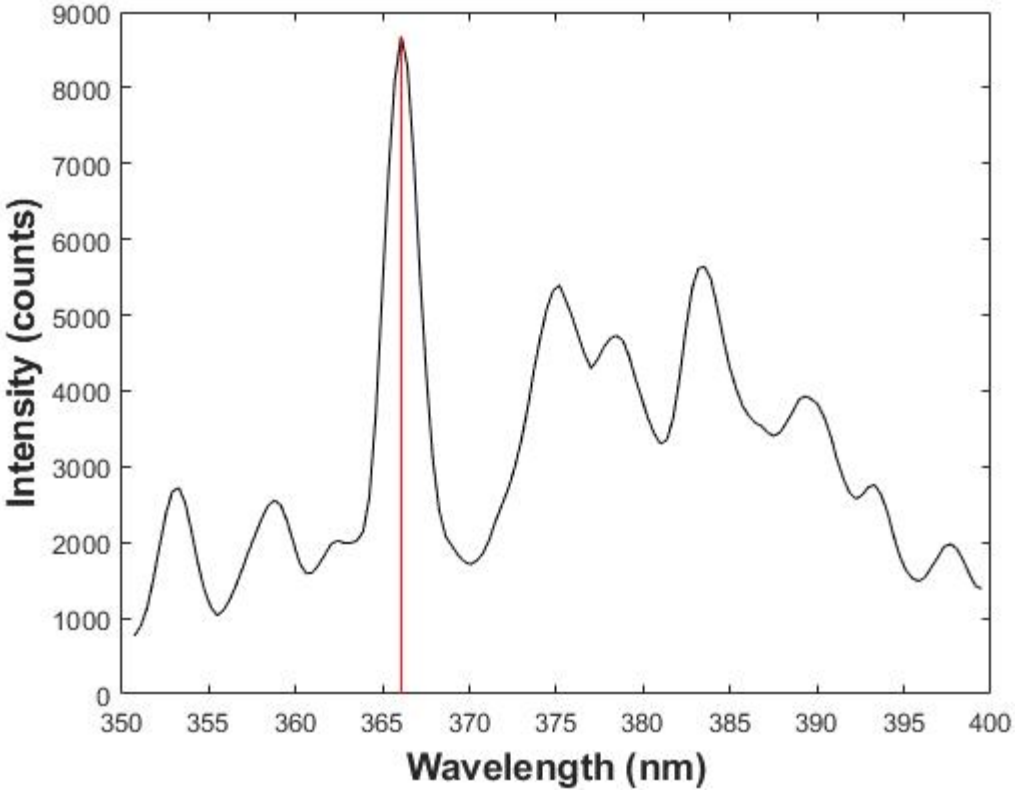


Mecmesin.com

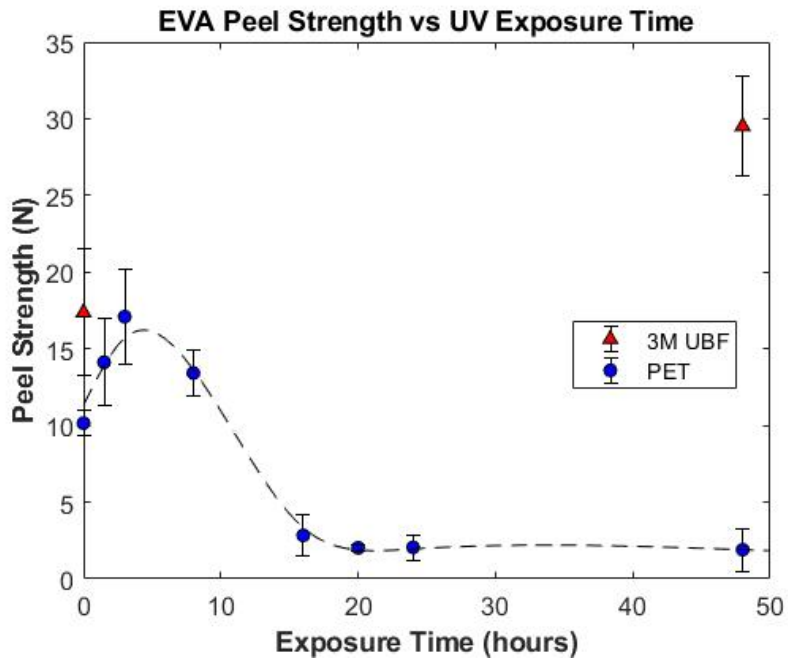
UV Aging of Peel Specimens

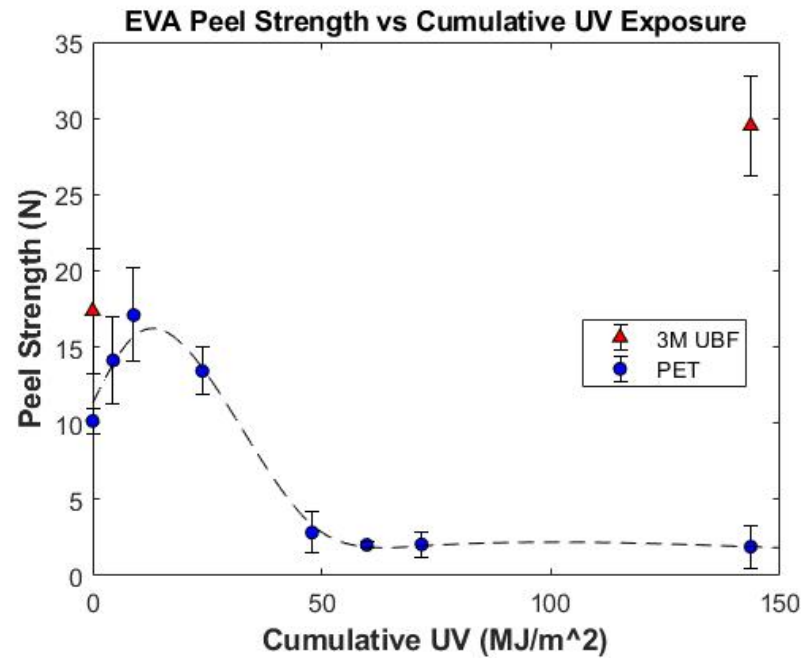


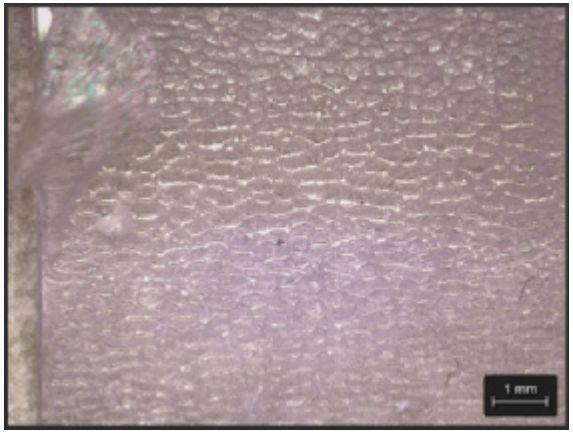
365nm Lamp @ 831 W/m^2



Peel Testing Results – EVA

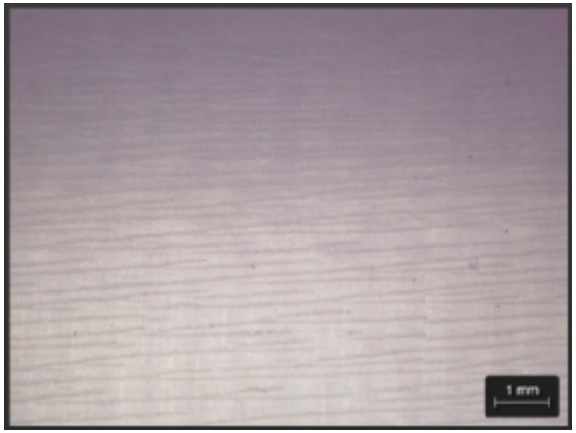






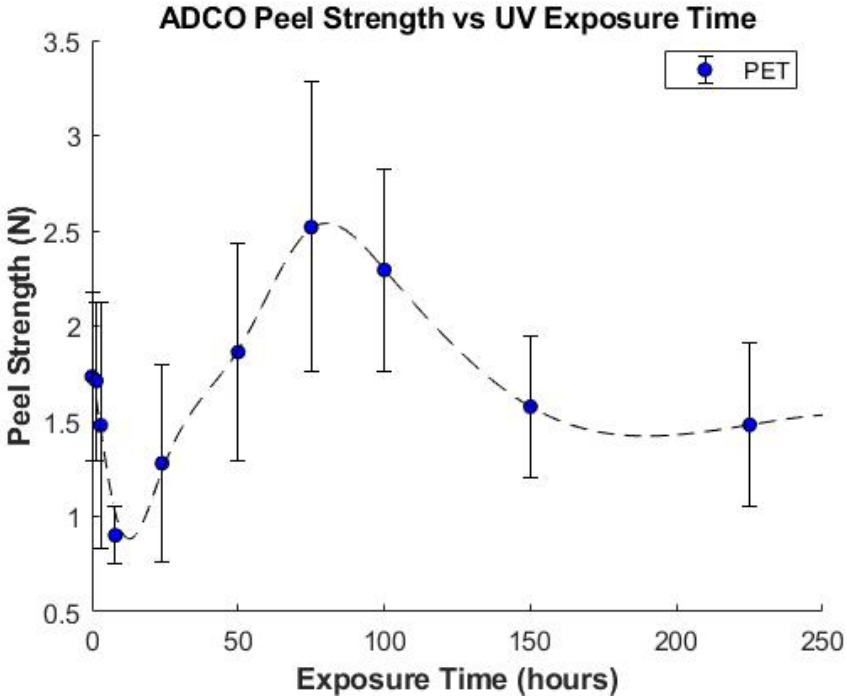
Delamination with cavitation

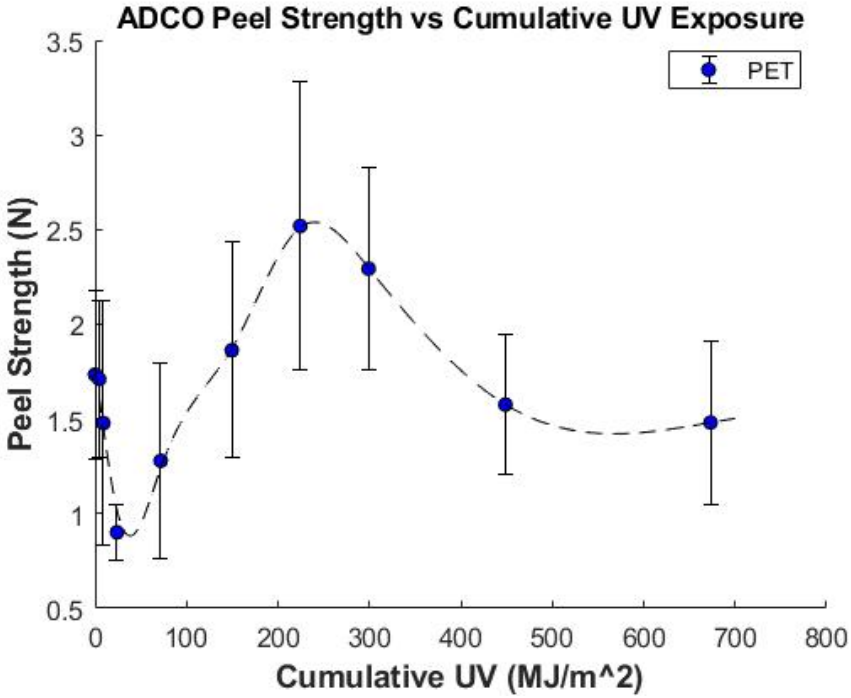
UV

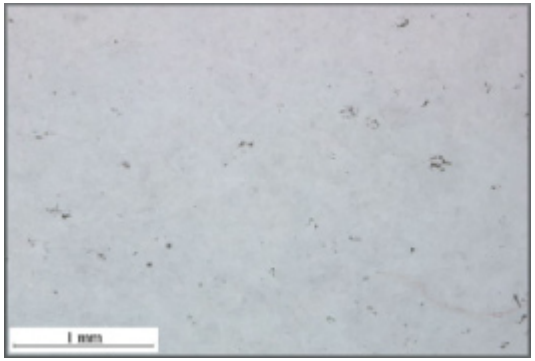


Delamination with no cavitation

Peel Testing Results – ADCO (PIB)

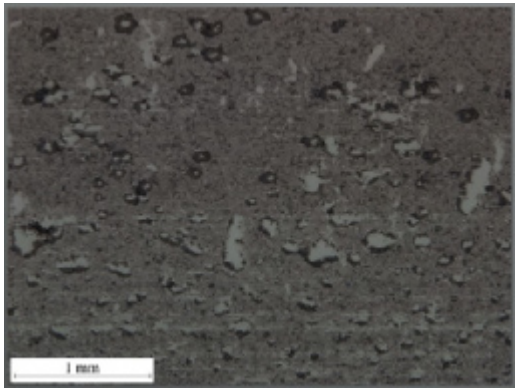






Clean Delamination

UV



Residue on UV side

Peel Testing Results – Other Materials

Can an inorganic adhesion layer improve the peel strength of low adhesion materials?

Adhesive	Substrate	Peel Strength (N)
PV5400 Ionomer	PET	0.21 ± 0.02
Qsil (PDMS)	PET	0.22 ± 0.03
PV5400 Ionomer	ITO/PET	0.54 ± 0.07
Qsil (PDMS)	ITO/PET	0.46 ± 0.02

→ Yes, but performance is still poor

Other layers to try: SiO_2, Si_3N_4

Conclusions

- Desiccant filled edge seals provide by far the best moisture protection
- Encapsulant materials are poor moisture barriers; adhesion performance is more critical to device lifetime

- EVA exhibits strong adhesion to PET, but other encapsulants perform poorly
  - Performance degrades significantly under UV exposure, but can be mitigated using UV blocking films
- UV exposure of PIB edge seals increases adhesion, resulting in cohesive failure

Future Work

- Calcium Screening
  - Test at multiple temperature/humidity conditions
  - High performing materials will be selected for high throughput testing at NREL
- Mechanical Testing
  - Study the effects of damp heat aging on adhesion strength
  - Perform chemical analysis on peeled surfaces to determine degradation mechanisms
  - Improve the performance of low adhesion materials using inorganic adhesion layers and surface treatments
  - Environmental aging at NREL

Questions?

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

DuraMAT
Durable Module Materials Consortium

A Unified Constitutive Model for the Degradation of Electrically Conductive Adhesives (ECA)

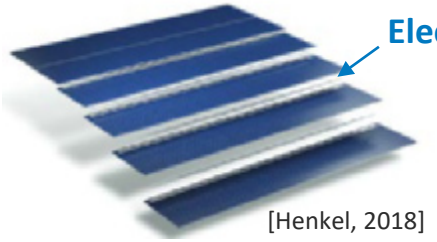
Martin Springer and Nick Bosco ***NREL***

Motivation

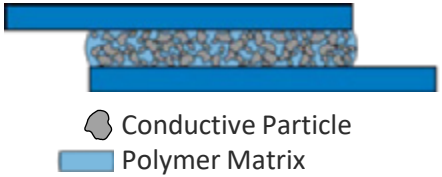
Current state: ECA is being incorporated into PV modules

Cell Interconnect Ribbon Bonding

Shingled Solar Modules



Electrically Conductive Adhesive (ECA)



Problem: Thermal cycling solder ≠ Thermal cycling ECA

- Significant material change from metallic solders to ECA's
- Reliability of ECA modules is still assessed by accelerated tests developed for solders
- Reliability test results may not represent the long-term performance of ECA modules

Goal: Predict degradation and failure of ECA PV module interconnects

- Develop a physical damage model that predicts mechanical and electrical degradation of ECA
- Create the materials characterization and modeling workflow

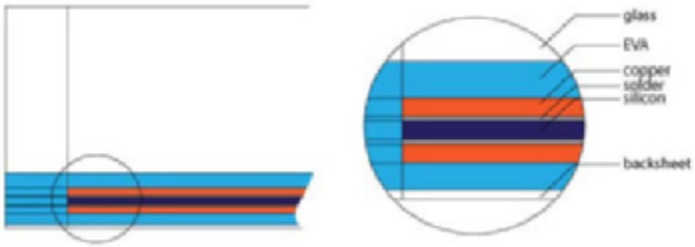
Introduction - Predictive Simulation

Finite Element Method (FEM)

Predictive Simulation (FEM)

PV module - boundary value problem

- partial differential equations
- FEM helps to find an approximate solution



2D cross-sectional model of generic PV module

Input parameters

- Boundary conditions – Geometry, Loading,…
- **Constitutive equations** – Hooke's law, Ohm's law, Fourier's law,…

Constitutive equations for ECA?

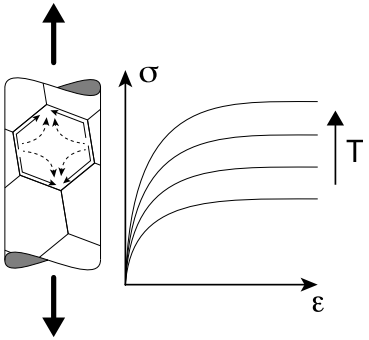
Formulation of constitutive models requires materials characterization

- Mechanical behavior: correlation between stress – strain
- Rate and temperature dependence
- Damage, Failure, and Fatigue
- Environmental aspects (Humidity,...)
- ….

Example – Solder

Materials behavior

- strain rate
- temperature



Constitutive model

- Anand model
- unified plasticity model

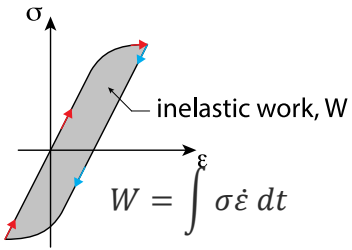
$$\dot{\varepsilon}_p = A exp\left(-\frac{Q}{RT}\right)\left[sinh\xi\frac{\sigma^*}{s^*}\right]^{\frac{1}{m}}$$

$$\dot{s} = \left\{h_0\left|1-\frac{s}{s^*}\right|^a sign\left(1-\frac{s}{s^*}\right)\right\}\dot{\varepsilon}_p$$

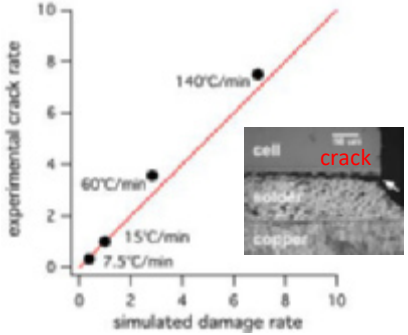
$$s^* = \hat{s}\left[\frac{\dot{\varepsilon}_p}{A} exp\left(\frac{Q}{RT}\right)\right]^n$$

Damage metric

- inelastic strain energy density

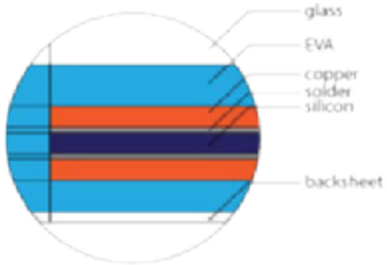


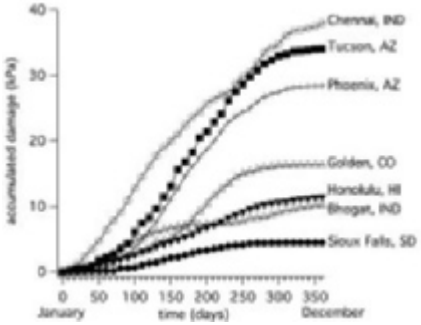
$$W = \int \sigma\dot{\varepsilon}\, dt$$



Predictive simulations*

- Finite Element Method





*N. Bosco, T. J. Silverman, and S. Kurtz. "Climate specific thermo-mechanical fatigue of flat plate photovoltaic module solder joints." *Microelectronics Reliability* 62 (2016): 124-129.

Materials Characterization

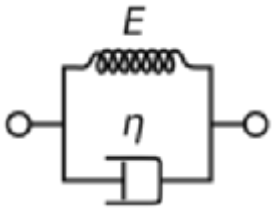
Linear Viscoelasticity

Materials Characterization - Viscoelasticity

ECA matrix = polymer material

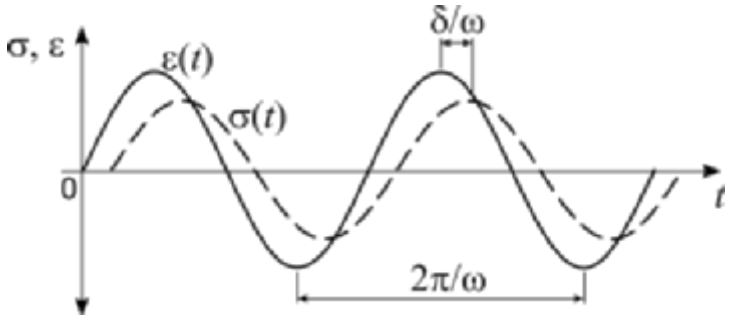
- Viscoelastic material response is expected
- Influence of particles = ?

Stress – Strain Curve



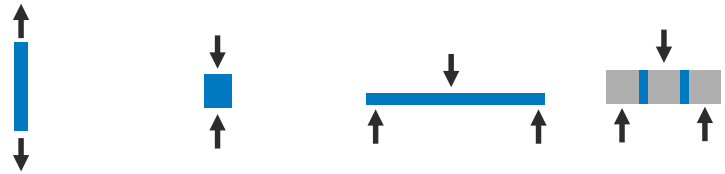
Kelvin-Voigt Model

Dynamic Mechanical Analysis (DMA)



$$\varepsilon = \varepsilon_0 \sin(\omega t) \qquad \sigma = \sigma_0 \sin(\omega t + \delta)$$

Load type examples



Tension Compression Bending Shear

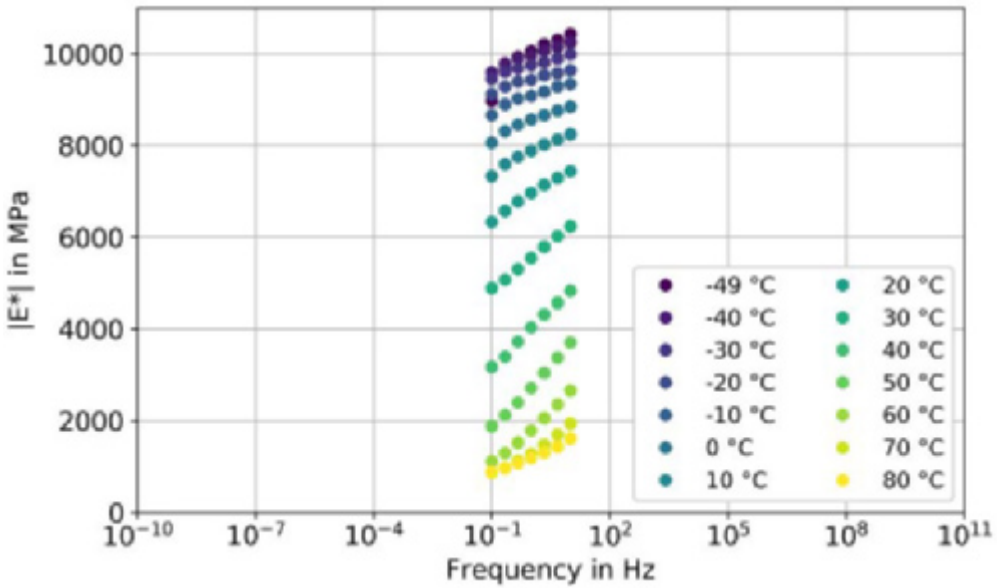
Material parameters obtained from DMA

- Storage modulus $E' = \frac{\sigma_0}{\varepsilon_0} \cos\delta$
- Loss modulus $E'' = \frac{\sigma_0}{\varepsilon_0} \sin\delta$
- Complex modulus $E^* = E' + iE''$
- Phase angle $\tan\delta = \frac{E''}{E'}$

DMA - Measurement Results

Temperature – Frequency Sweep of Epoxy ECA

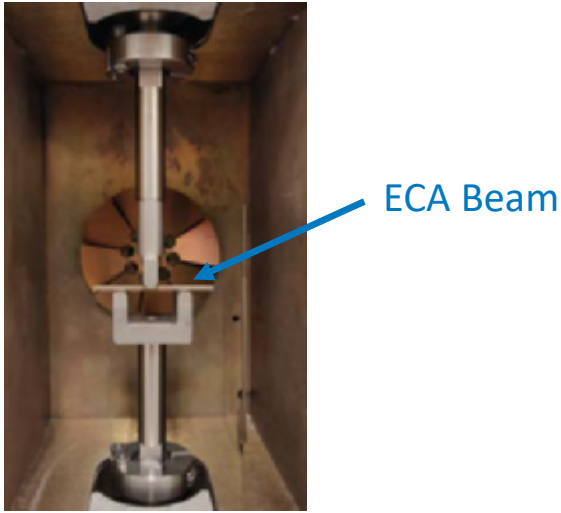
- Temperature range -50°C to 80°C
- Frequency range 0.1Hz to 100Hz



ECA Beam

(30mm x 3mm x 1mm)

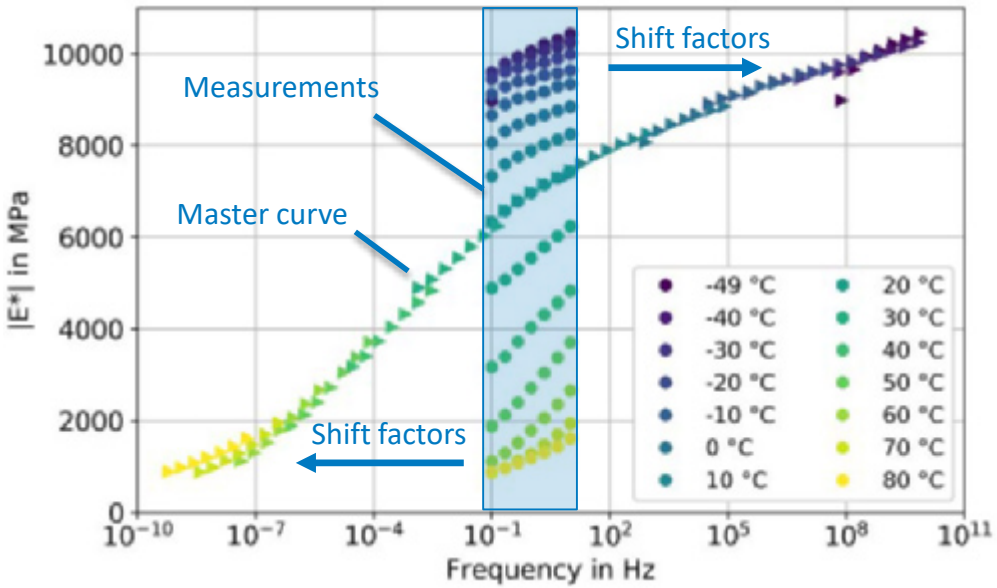
3 Point Bending Test



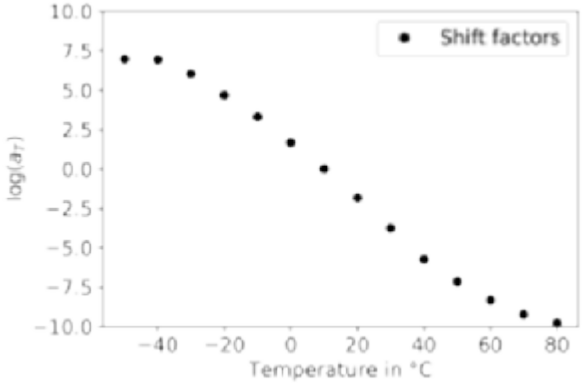
DMA - Master Curve Generation

Time – Temperature Superposition

- used to determine the material properties over broad range of times and temperatures
- linear viscoelastic response of high frequencies corresponds to lower temperatures and vice versa



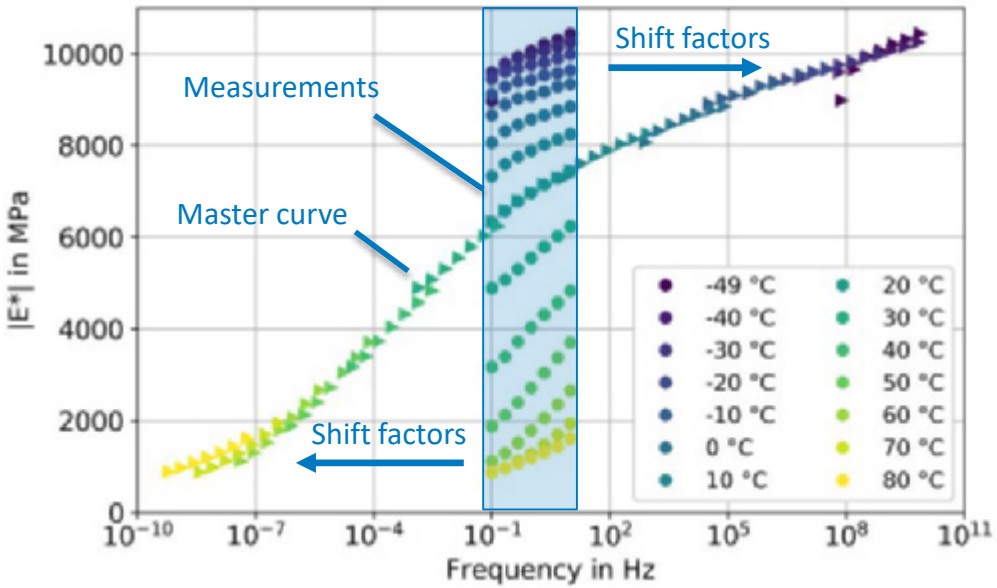
Shift factors
$\log(a_T)$



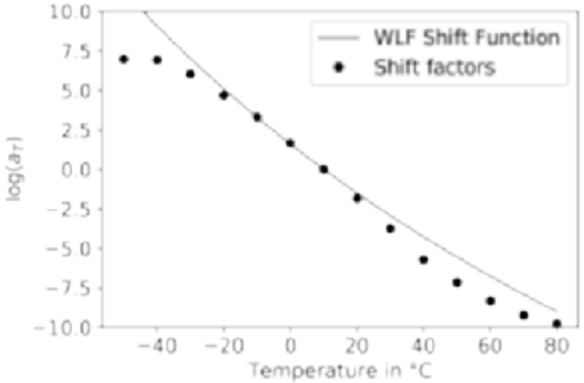
DMA - WLF Shift Function

Time – Temperature Superposition

- used to determine the material properties over broad range of times and temperatures
- linear viscoelastic response of high frequencies corresponds to lower temperatures and vice versa



Shift factors
$\log(a_T)$



WLF shift function

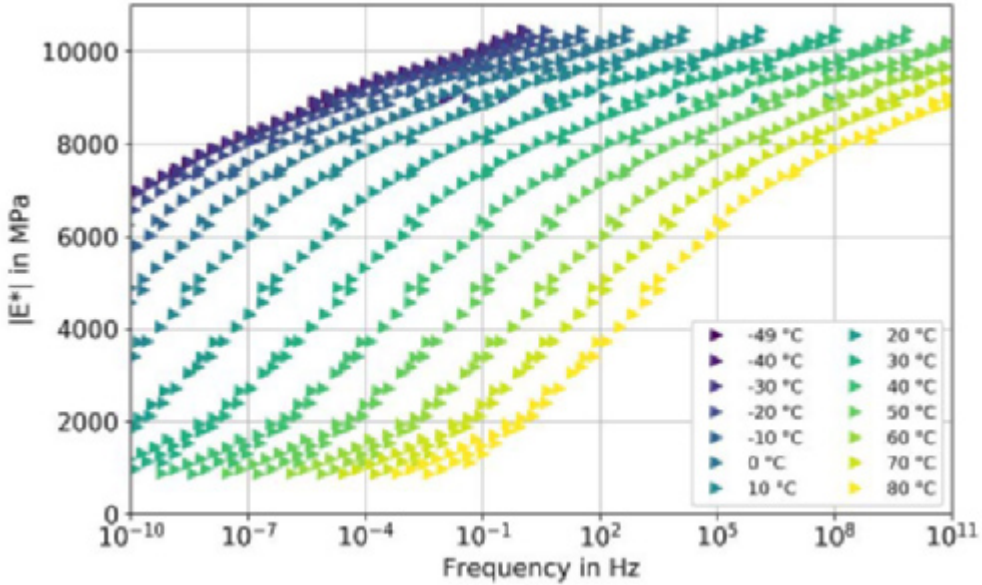
$$\log_{10}(a_T) = -\frac{C_1(T-T_r)}{C_2+(T-T_r)}$$

a_T … shift factor
T … temperature
T_r … reference temperature
C_1, C_2 … material parameters

DMA - Temperature Dependent Master Curve

Time – Temperature Superposition

- used to determine the material properties over broad range of times and temperatures
- linear viscoelastic response of high frequencies corresponds to lower temperatures and vice versa



Shift Master Curve

WLF shift function

$$\log_{10}(a_T) = -\frac{C_1(T-T_r)}{C_2+(T-T_r)}$$

a_T … shift factor
T … temperature
T_r … reference temperature
C_1, C_2 … material parameters

- broad range of frequencies and
- temperatures captured

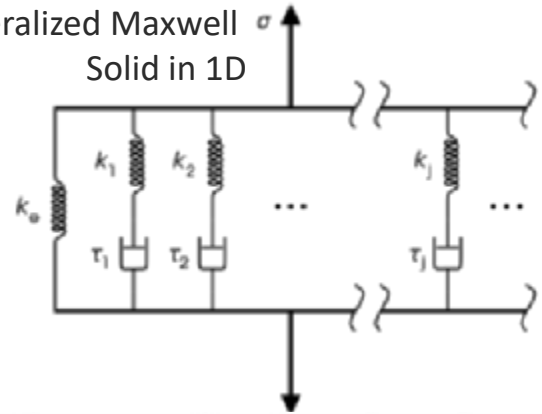
Constitutive Model - Generalized Maxwell Solid

Generalized Maxwell Solid in 3D

$$\boldsymbol{\sigma} = \int_0^t 2G(t-\tau)\frac{\mathrm{d}\mathbf{e}}{\mathrm{d}\tau}\mathrm{d}\tau + \mathbf{I}\int_0^t K(t-\tau)\frac{\mathrm{d}\Delta}{\mathrm{d}\tau}\mathrm{d}\tau$$

$\boldsymbol{\sigma}$ … Cauchy stress tensor
$\mathbf{e}$ … deviatoric strain tensor
Δ … volumetric strain
τ … past time
$\boldsymbol{I}$ … identity tensor

Generalized Maxwell Solid in 1D

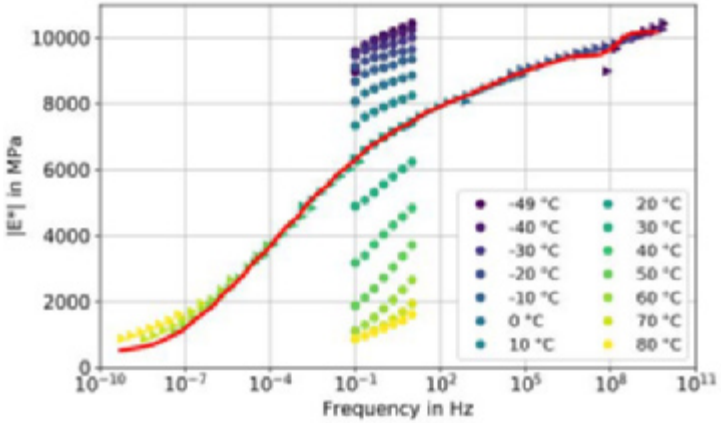


Prony Series

- obtained from curve fitting of master curve

$$G(t) = G_0\left[\alpha_\infty^G + \sum_{i=1}^{n_G}\alpha_i^G \exp\left(-\frac{t}{\tau_i^G}\right)\right]$$

G_0 … relaxation moduli at t=0
n_G … number of Prony terms
α_i^G … relative moduli
τ_i^G … relaxation time

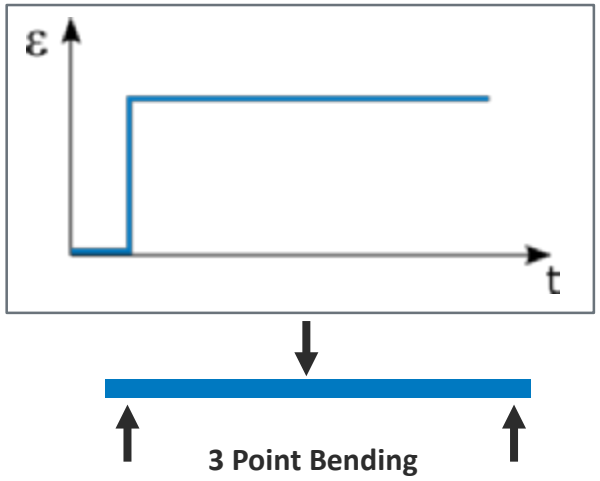


FEM Simulation Results – Relaxation Test

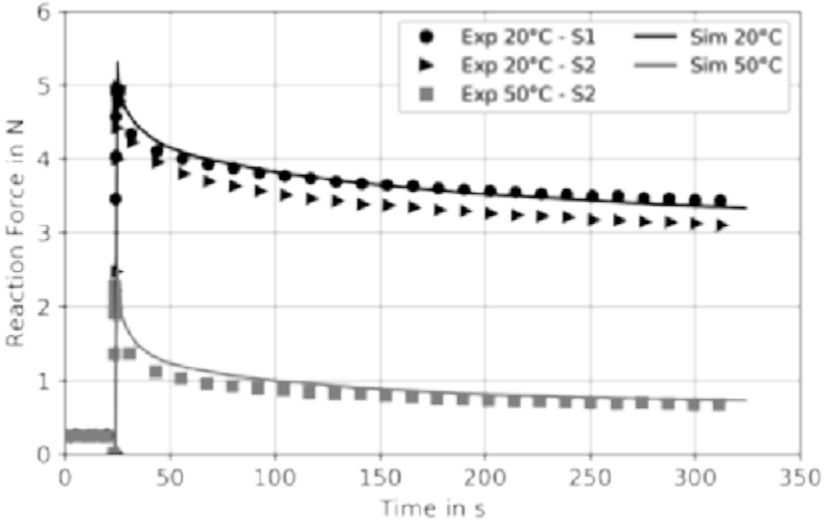
Comparison of experimental results with numerical simulation

- Constitutive Model: Generalized Maxwell with WLF shift function
- Boundary Conditions: 3 Point Bending
- Time Dependence: Relaxation Test

Displacement Loading



Reaction Force



Work in Progress - Preliminary Results!

ECA Characterization Matrix

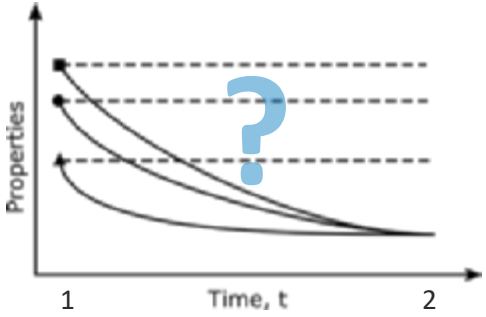
Characterization of a variety of ECA's

- different ECA types (acrylic, epoxy, silicone)
- different manufacturers

Looking for differences, similarities, trends…

Evolution of material properties over time

- varying cure conditions
  fast vs. slow cure profiles
- preconditioning of samples
  Temperature 85°C / Rel. Humidity <10%
  Temperature 85°C / Rel. Humidity 85%



1) How are the initial ECA properties affected?
2) If so, will the effect vanish or remain over time?

Identification of Damage Mechanisms

Thermal Cycling Test

Damage Mechanisms

What are the damage driving forces?

- physical quantities related to degradation
- (solder: inelastic strain energy density)

What does ECA degradation look like?

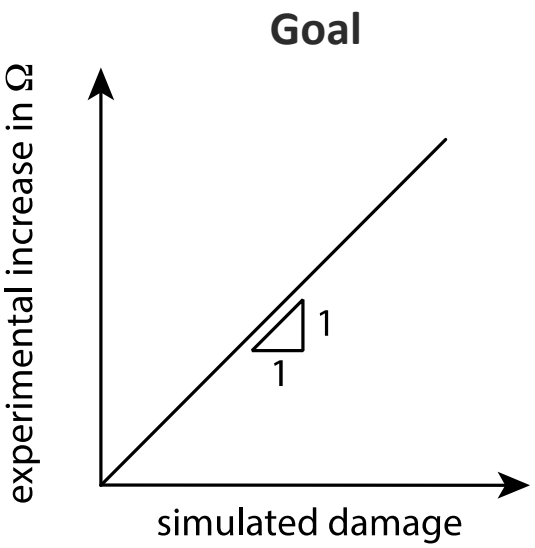
- cracking, voids, delamination, microstructure….

Degradation of mechanical vs. electrical properties?

- differences degradation rate, time point of failure…

Differences in loading conditions?

- mechanical vs. thermal cyclic loading
- tensile, bending, **shear**…

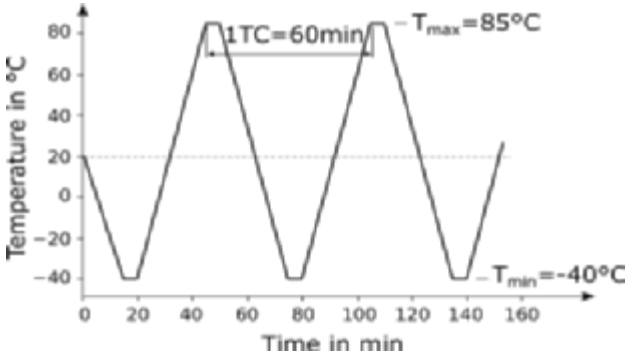


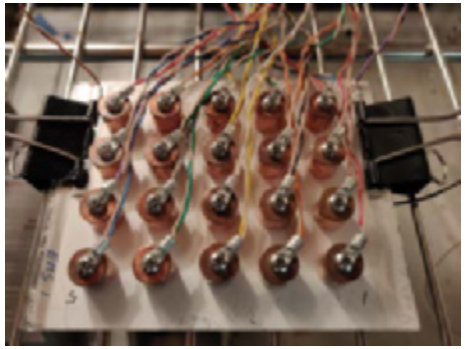
Thermal Cycling Tests

AIM of the test setup: Cause mechanical and electrical ECA degradation

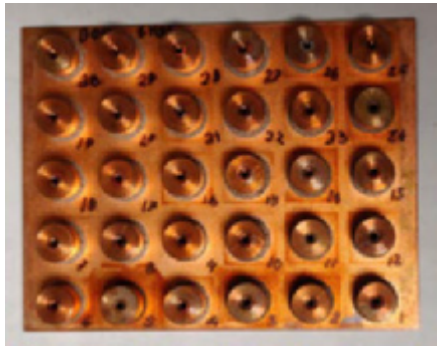
- loading conditions similar to a real module
  - thermal cycling from -40°C to 85°C
- accelerated testing (1h/Load Cycle)
  - high stresses and strains at ECA interface
  - materials with significant differences in CTE
- measurement of degradation
  - monitor electrical resistance
  - measure changes in the interface area

Thermal cycle

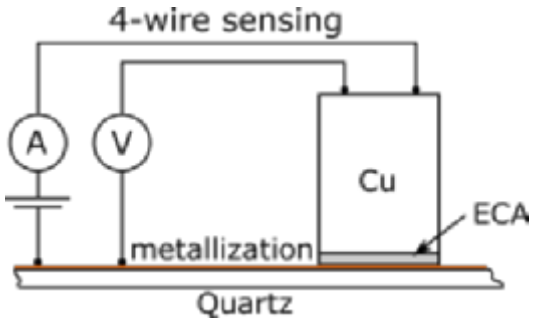




Quartz Board



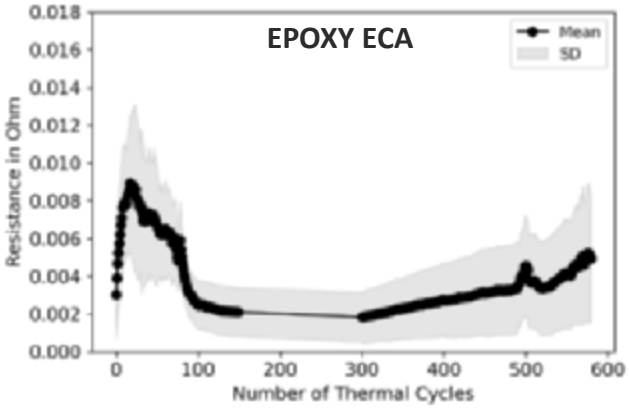
Double Bond Copper (DBC)

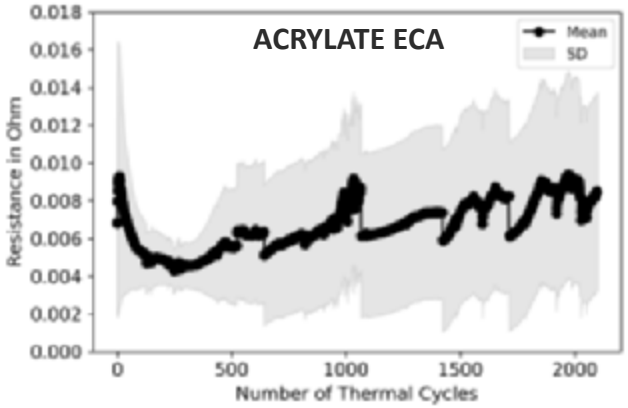


Schematic of the test setup

Measurement of degradation

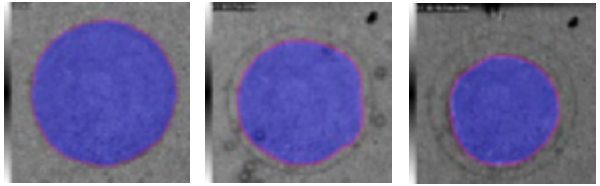
Monitoring of Resistance





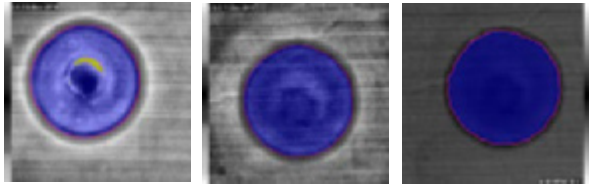
Interface Area (Confocal Scanning Acoustic Microscopy)

EPOXY ECA (S28)

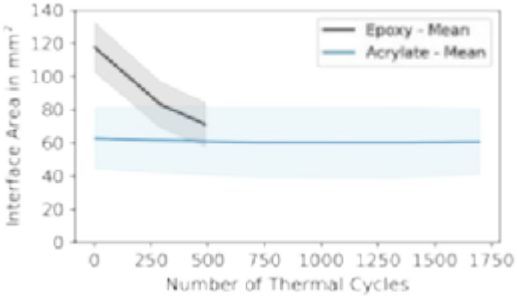


N = 0 N = 293 N = 490

ACRYLATE ECA (S6)



N = 0 N = 721 N = 1701



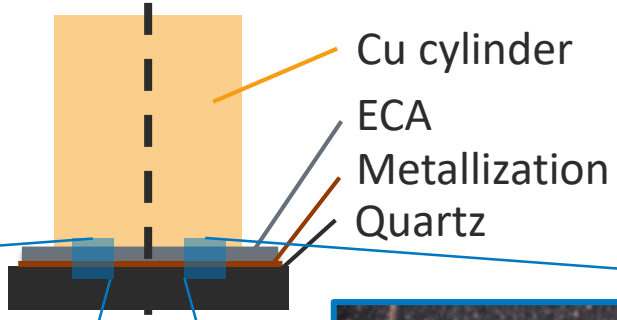
Work in Progress - Preliminary Results!

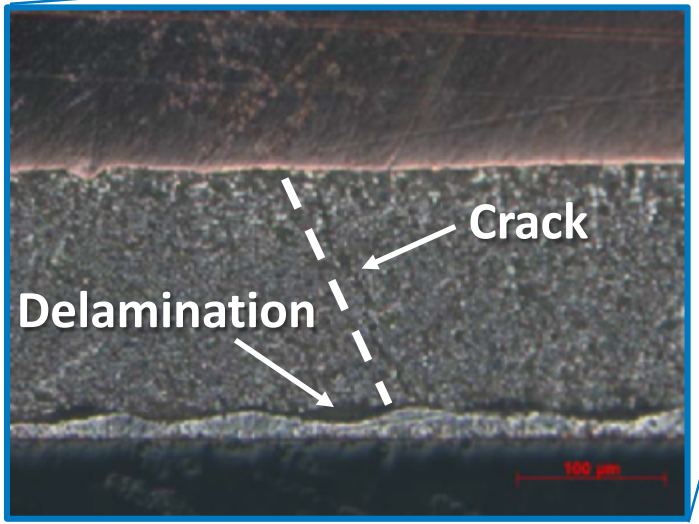
Damage - Light Microscopy

Cross Section of Cu Cylinder

- Acrylate ECA
- 1651 thermal cycles

Cracks & Delamination found



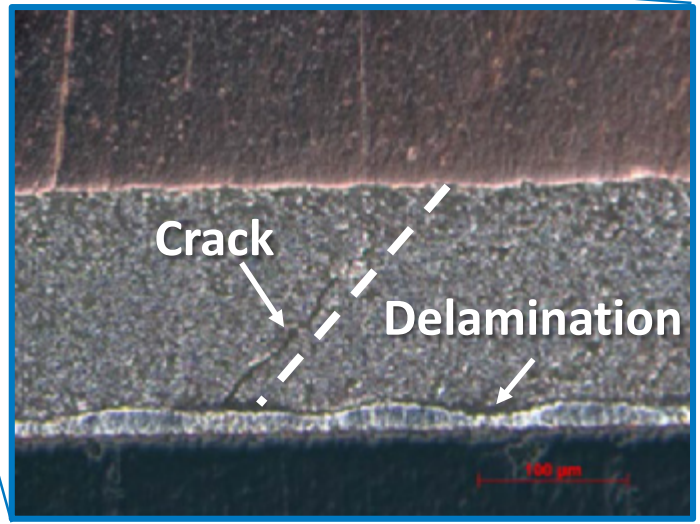


Cu

ECA

Metallization

Quartz



Summary & Next Steps

Materials Characterization

- Dynamic Mechanical Analysis to characterize the viscoelastic behavior of ECA's
- Next: Establish a materials characterization matrix

Constitutive Modelling

- Linear Viscoelasticity – Generalized Maxwell Model & WLF Shift Function
- Preliminary relaxation tests show good agreements between test results and FEM simulations
- Next: Model validation

Identification of damage mechanisms

- Thermal cyclic test vehicle designed to cause ECA degradation
- Monitor: Changes in the electric conductivity and changes in the interface area
- Cracks and Delamination are detected at the ECA interface
- Next: Fatigue Tests of ECA shear samples under mechanical cyclic loading

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

Low-Cost Advanced Metallization to Reduce Cell-Crack-Induced Degradation for Increased Module Reliability

Omar K. Abudayyeh[1], Andre Chavez[1,2], John Chavez[1], and Sang M. Han[1,2*]

Brian Rounsaville[3], Vijaykumar Upadhyaya[3], and Ajeet Rohatgi[3]

Byron McDonald[4], Timothy Silverman[4], and Nick Bosco[4]

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Acknowledgements:

Department of Energy DuraMAT (RGJ-7-70325 and RGJ-8-8224)

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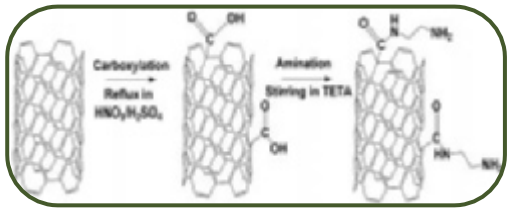
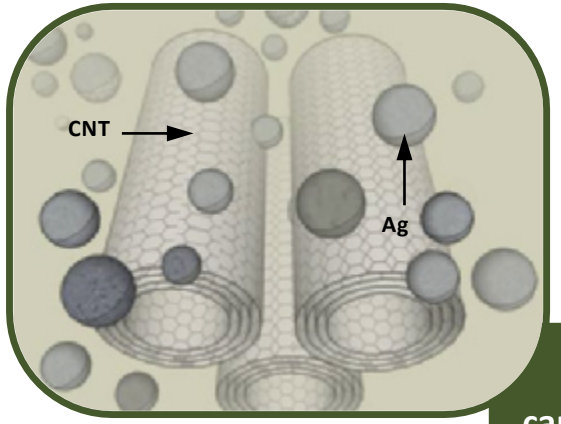
OSAZDA'S APPROACH TO CRACK-INDUCED PV DEGRADATION





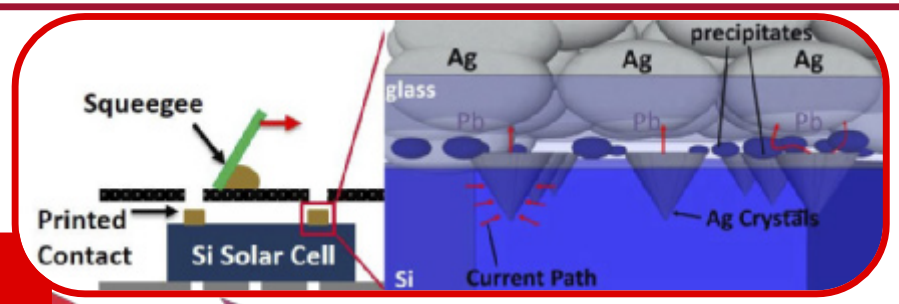
Goal 1: Commercial MMC Paste Product

Step 1: Materials Engineering
- MMC Paste Formulation

carboxylation vs. amination, μ, wt.%, etc.

Step 2: Processing
- Screen Printing & Firing

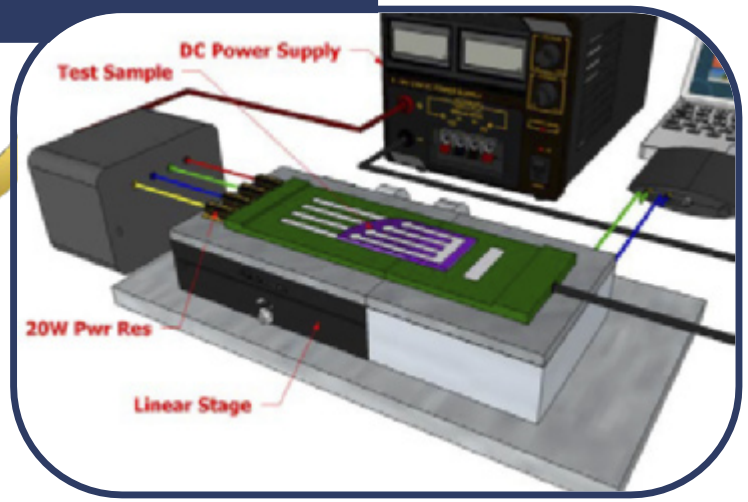
σ_C, R_{sq}, r_c, etc.



Goal 2: Proprietary Integration Processing Recipes

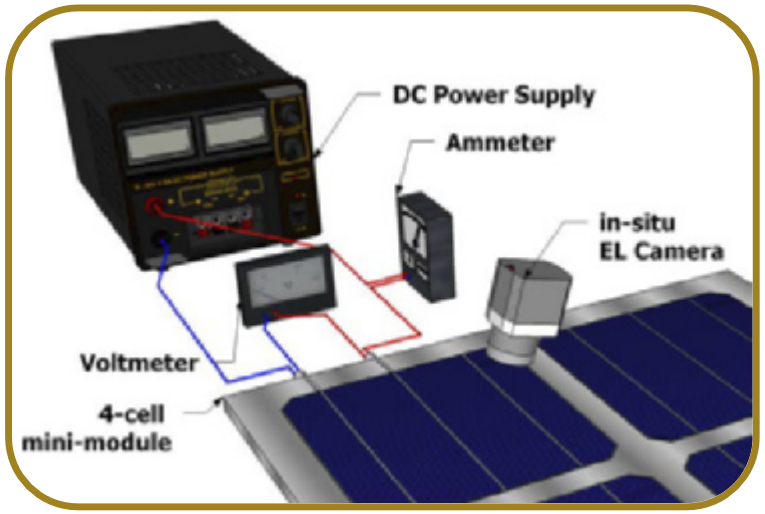
Step 3: Materials Characterization
- RACK & DMA

E, σ_{YS}, ρ_ε, S-N, etc.



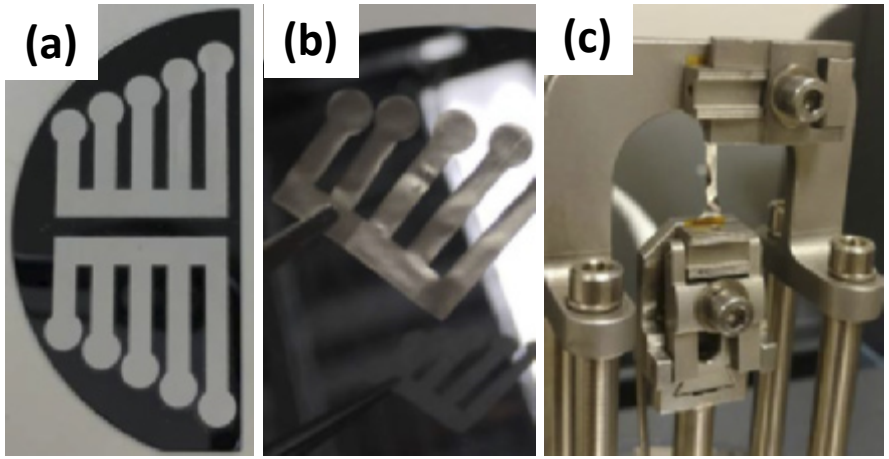
Step 4: Integration
- Cell and Mini-Module Testing

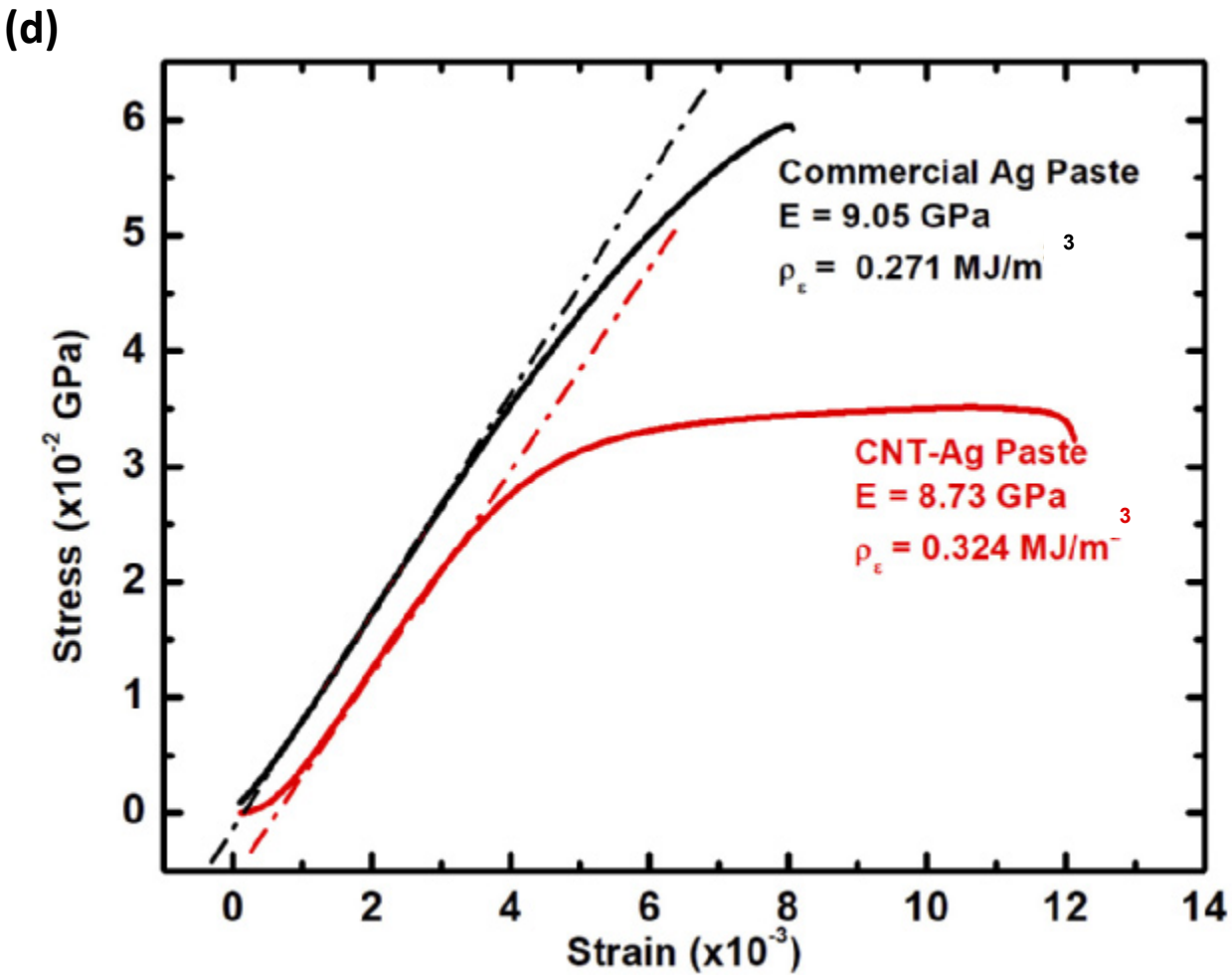
V_{oc}, J_{sc}, FF, η, accumulated damage, equivalent year thermal cycles, etc.



Goal 3: Predictable Module Performance & Degradation

Dynamic Mechanical Analysis

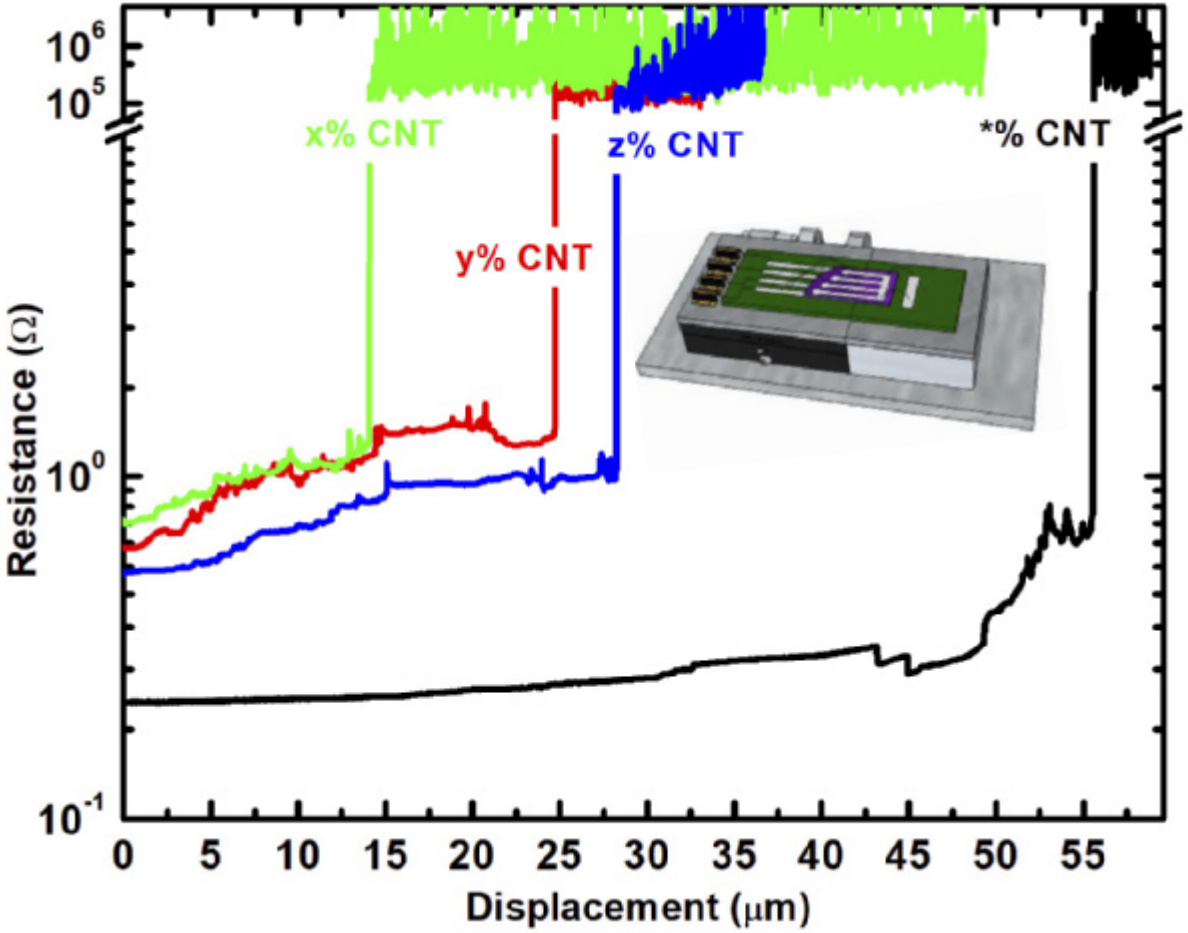


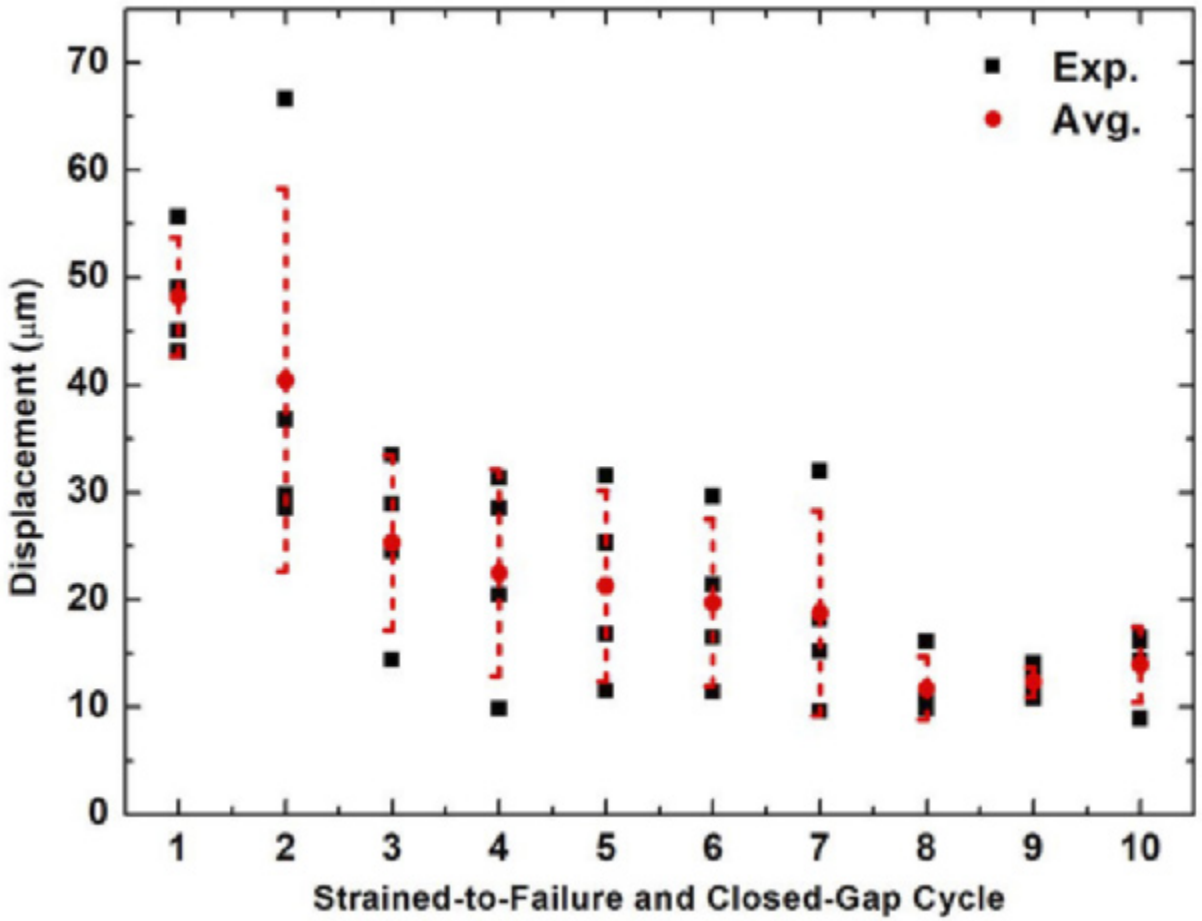


With MMC incorporation:

- 4% decrease in elastic modulus
- 16% increase in strain energy density
- Increase in ductility

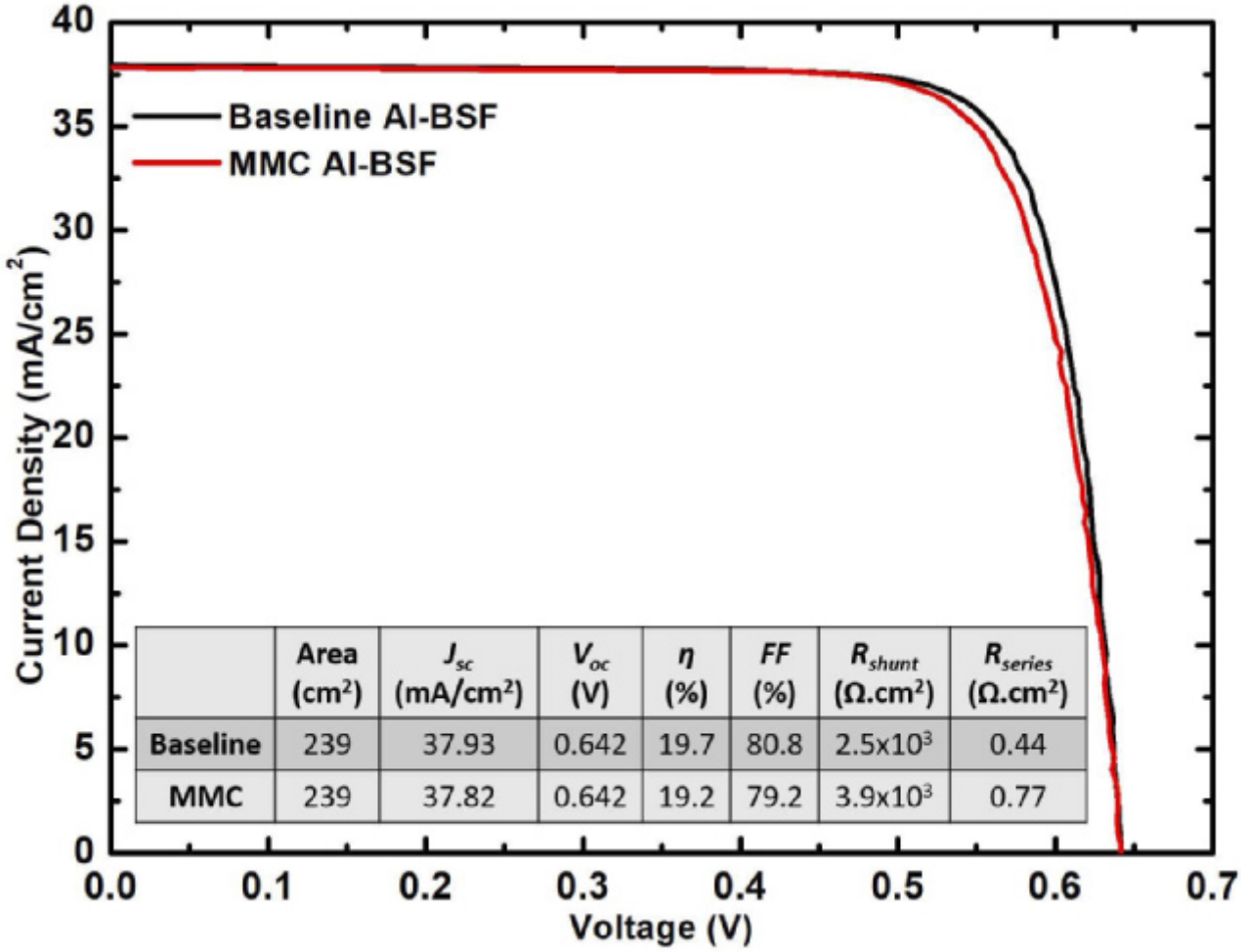
RACK (RESISTANCE ACROSS CLEAVES & CRACKS) – CNT BRIDGING





- **>50 μm** maximum bridgeable gap with optimum CNT loading
- "Self-healing" to bridge ~20 μm gaps repeatably

CELL PERFORMANCE – SILVER PASTE MMC



	Area (cm^2)	J_{sc} (mA/cm^2)	V_{oc} (V)	η (%)	FF (%)	R_{shunt} ($\Omega.cm^2$)	R_{series} ($\Omega.cm^2$)
Baseline	239	37.93	0.642	19.7	80.8	2.5×10^3	0.44
MMC	239	37.82	0.642	19.2	79.2	3.9×10^3	0.77

✓ Similar cell performance with CNT incorporation

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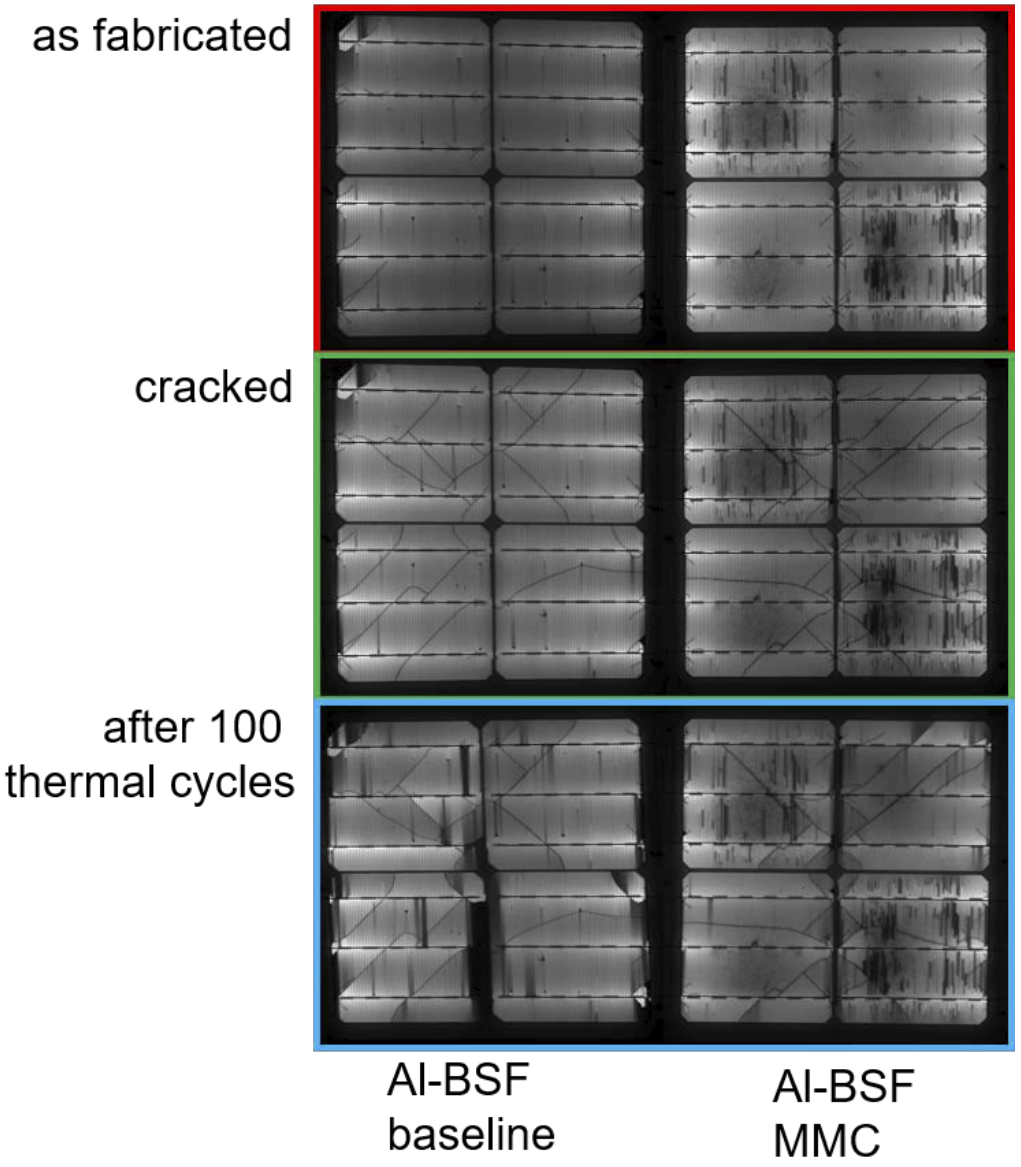
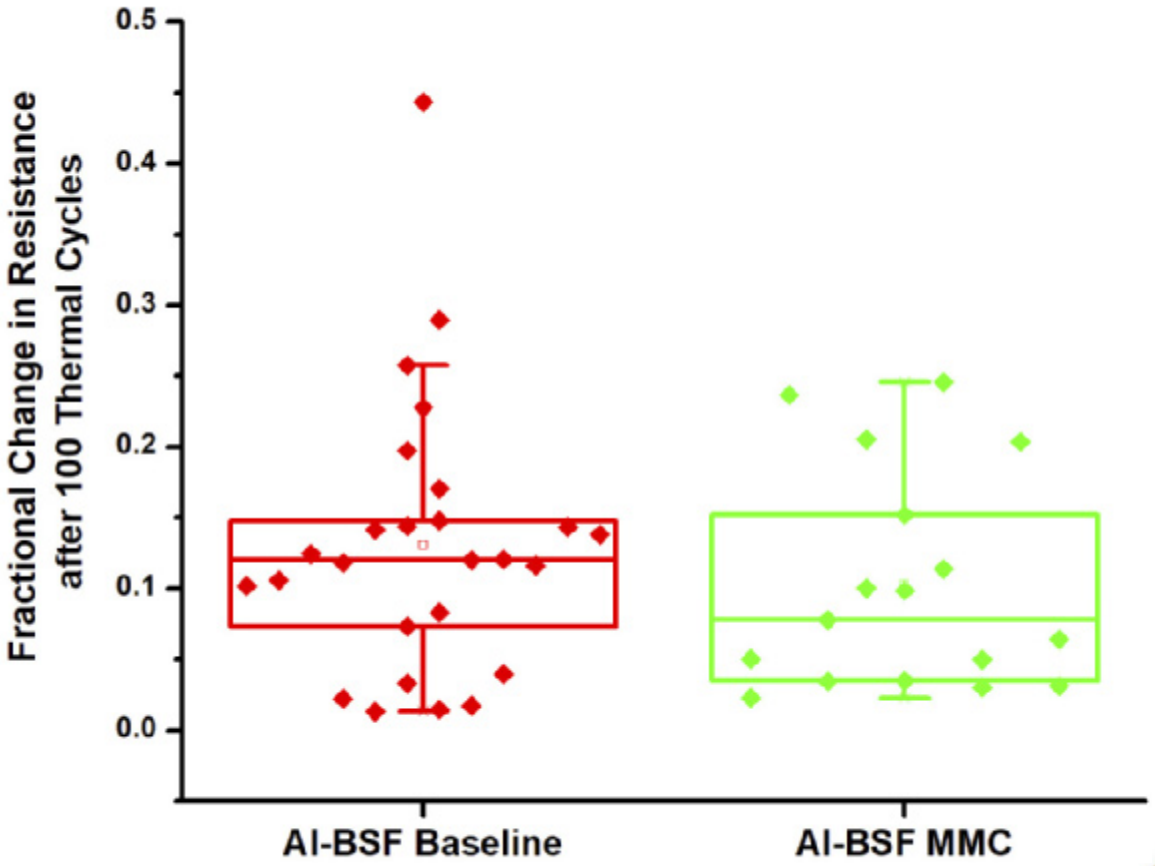
Module Integration – Accelerated Testing





- Commercial Ag paste as baseline
- MMC shows slower degradation
- Future testing with PERC

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CONCLUSIONS

- Fracture toughness increases with CNT incorporation.
- MMC-enhanced metallization can provide > **50 µm** gap bridging capability.
- “Self-healing” occurs when the fractured composite gridlines are brought together.
- “Self-healing” is repeatable and settles at **10 to 20 µm**.
- Beginning-of-life cell performance is approximately the same with and without the MMC integration.
- MMC-enhanced Al-BSF modules degrade at a slower rate compared to baseline modules.
- Accelerated testing will be conducted on PERC modules.

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Poster Session I (Tuesday) Poster Awards

1st Place: #25 M. Springer, K. Han, and N. Bosco, "A unified constitutive model for the degradation of electrically-conductive adhesives"

2nd Place: #43 Y. Zhu, C. Taubert, K. Chen, B.D. Vogt, and H. Fan, "Low percolation threshold in electrically-conductive adhesives using complex dimensional fillers"

3rd Place: #61 D. Sulas, "Fill factor loss in fielded photovoltaic modules due to metallization failures, characterized by luminescence and thermal imaging"

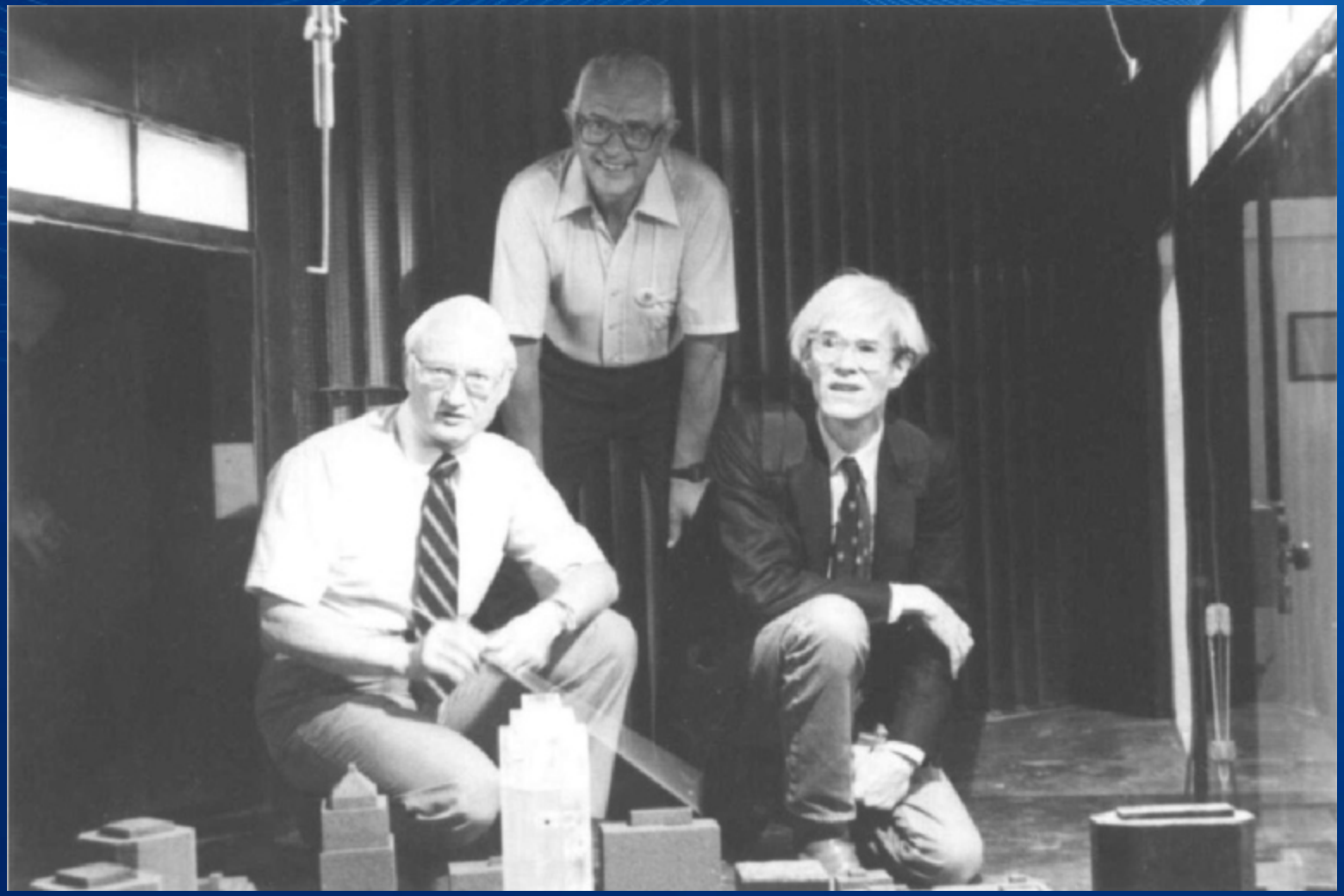
CERMAK
PETERKA
PETERSEN

Dynamic wind loading on ground-mounted solar

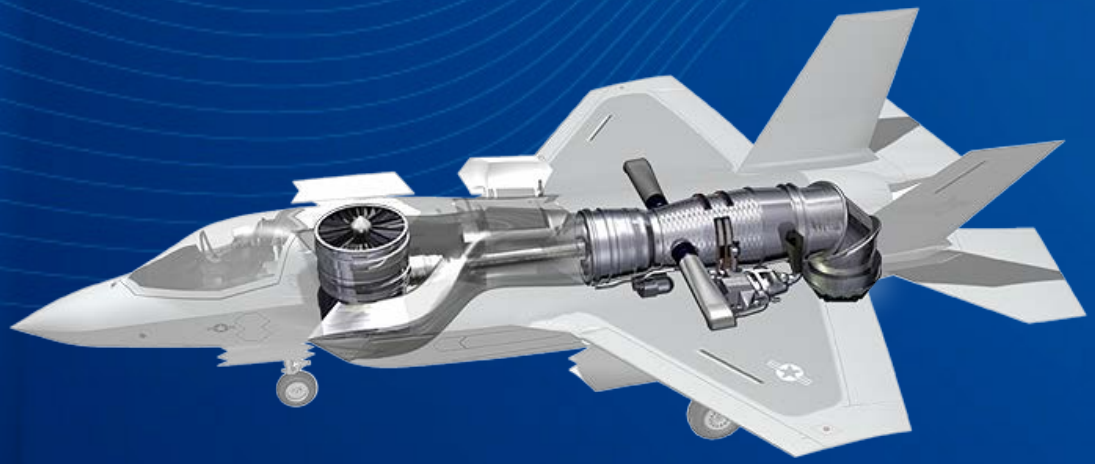
Dr. David Banks

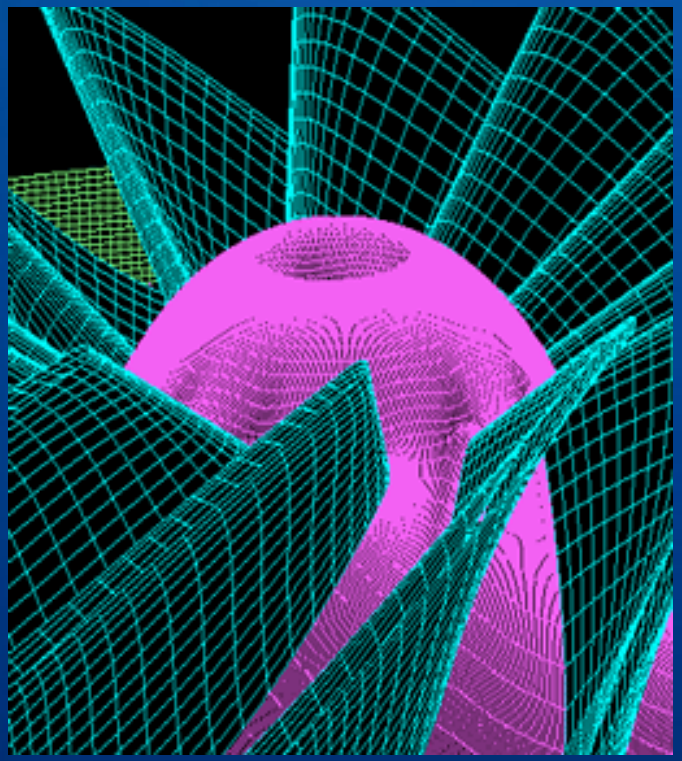
Wind tunnel testing

Dr. Jack Cermak



Joint Strike Fighter



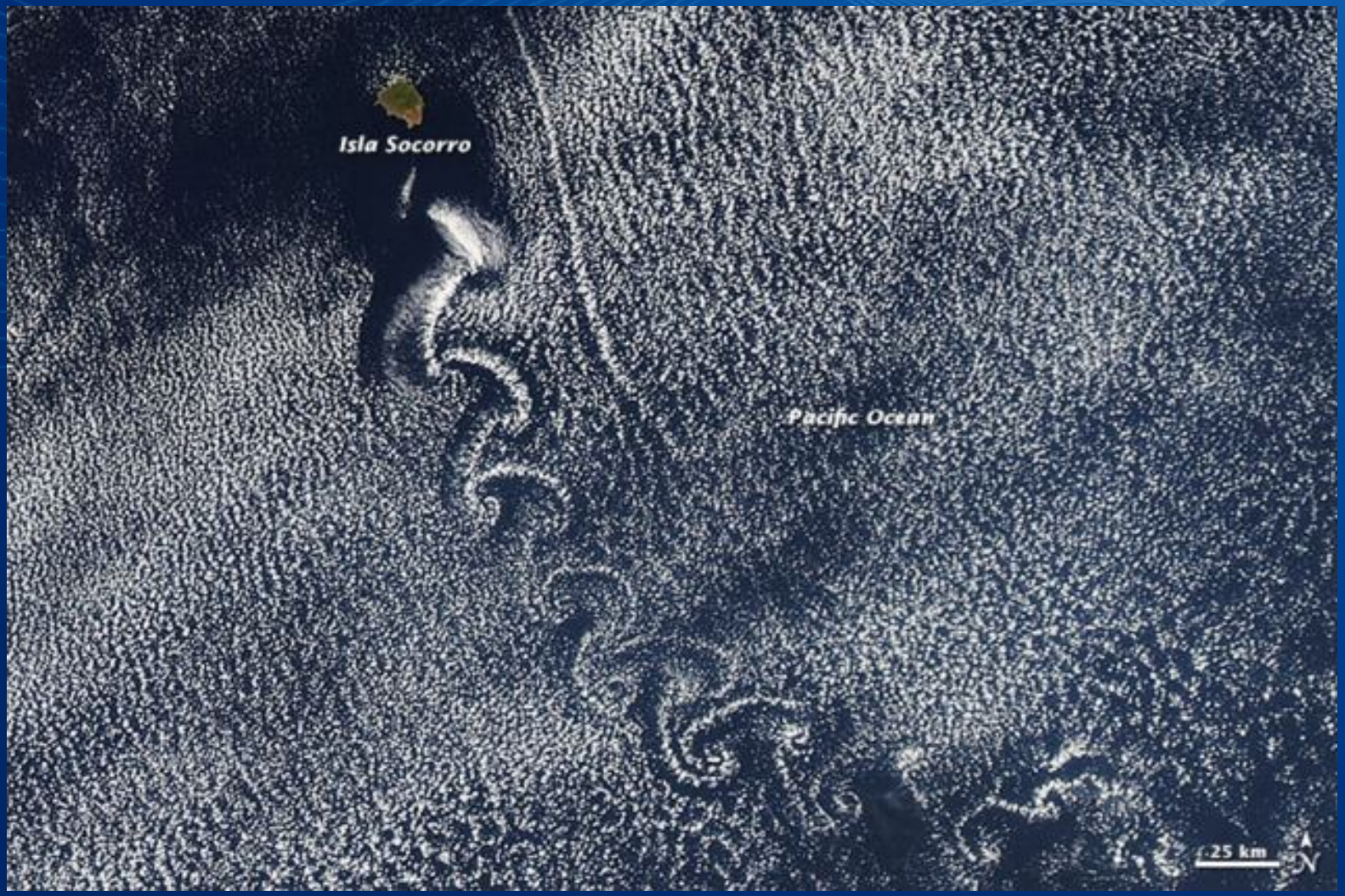


Topics

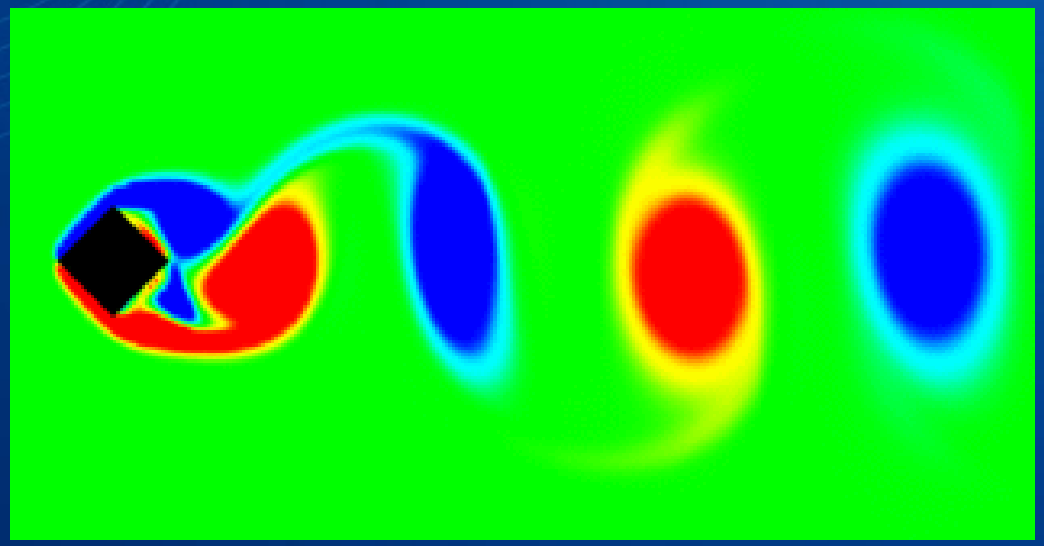
- Vortex shedding
- Tracker instability
- Kind of testing that is needed
- Codes and standards?

Oil train wreck in Quebec.

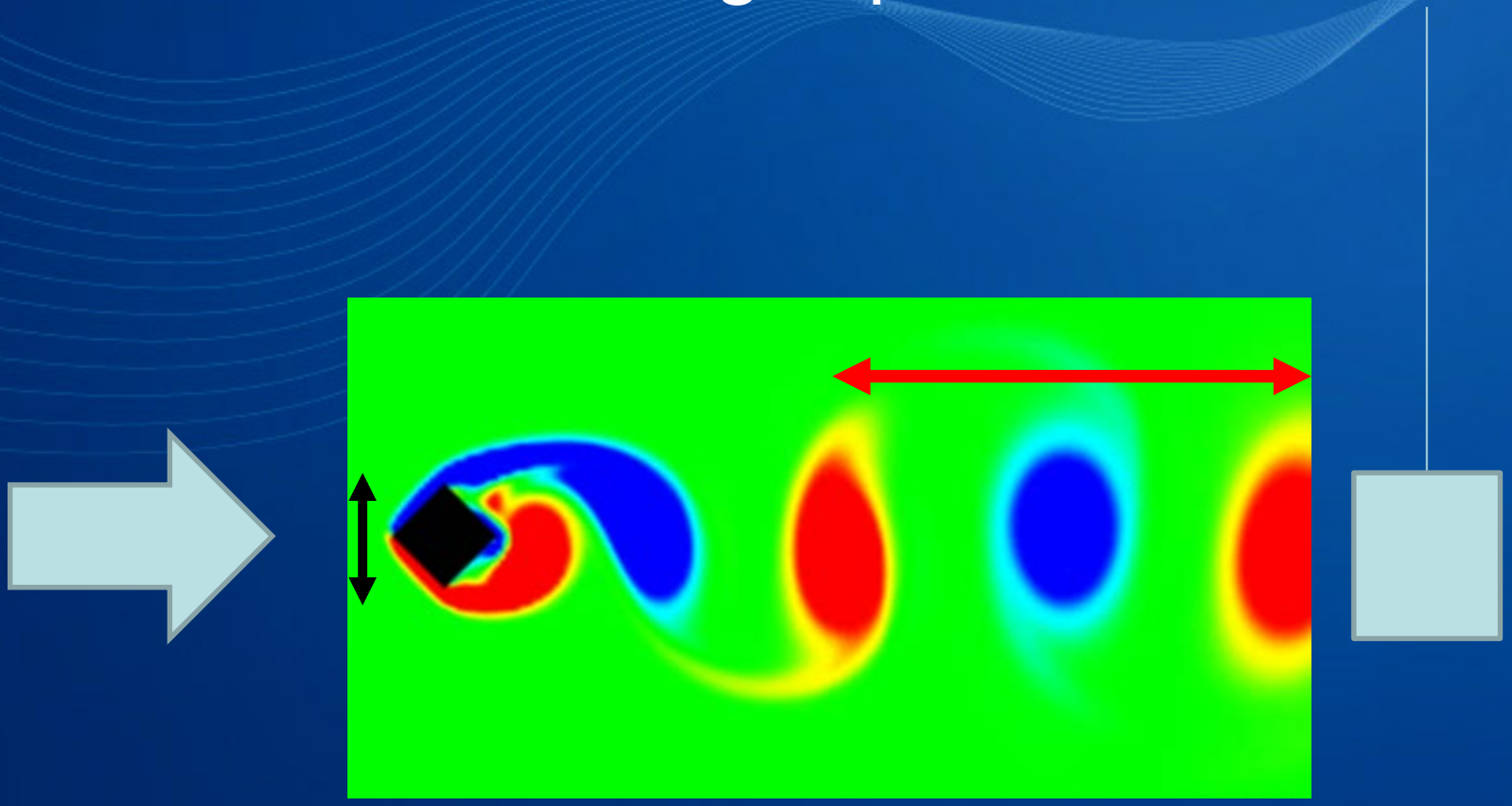
Vortex shedding from an island



Vortex shedding from diamond shape



Vortex shedding is predictable



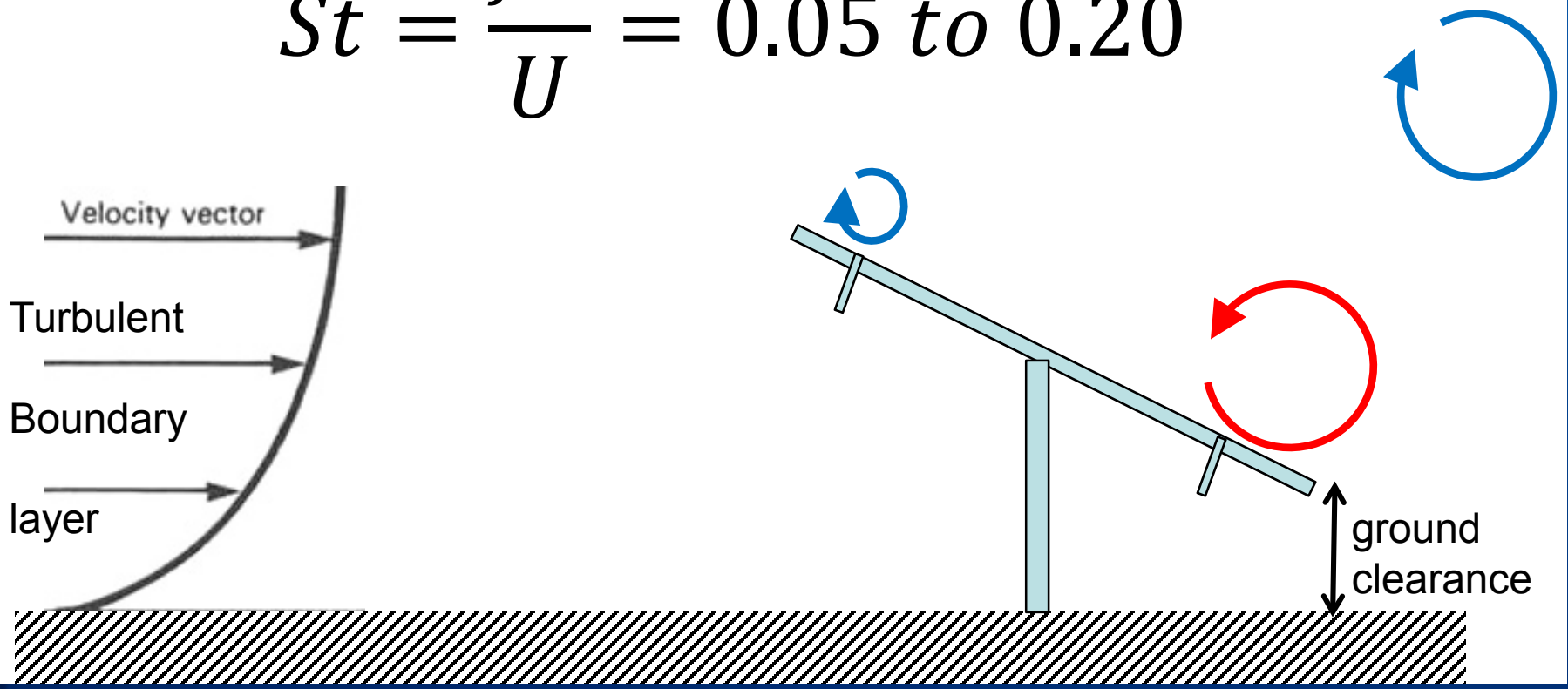
Building code requirements not enough

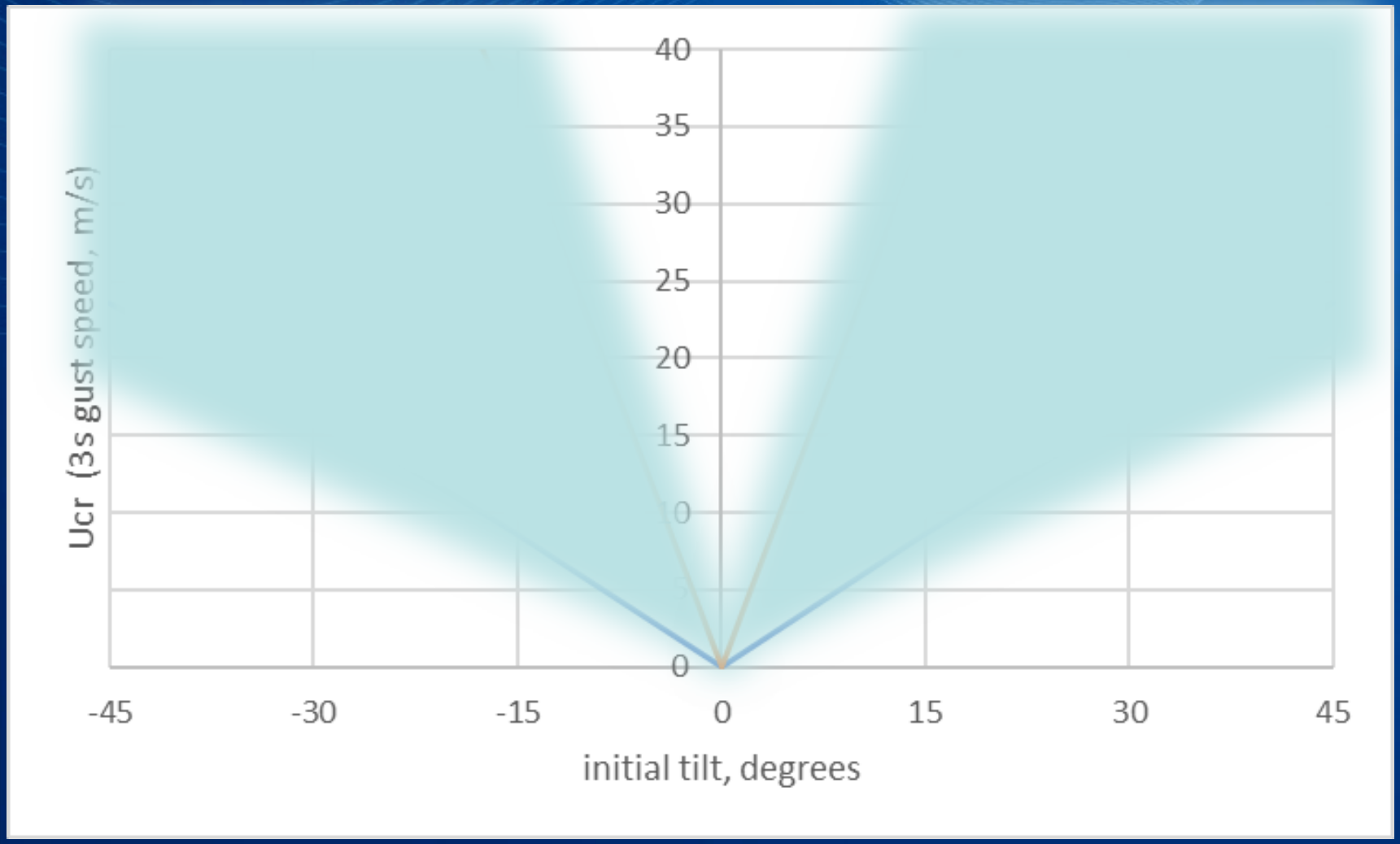
Single Axis Trackers

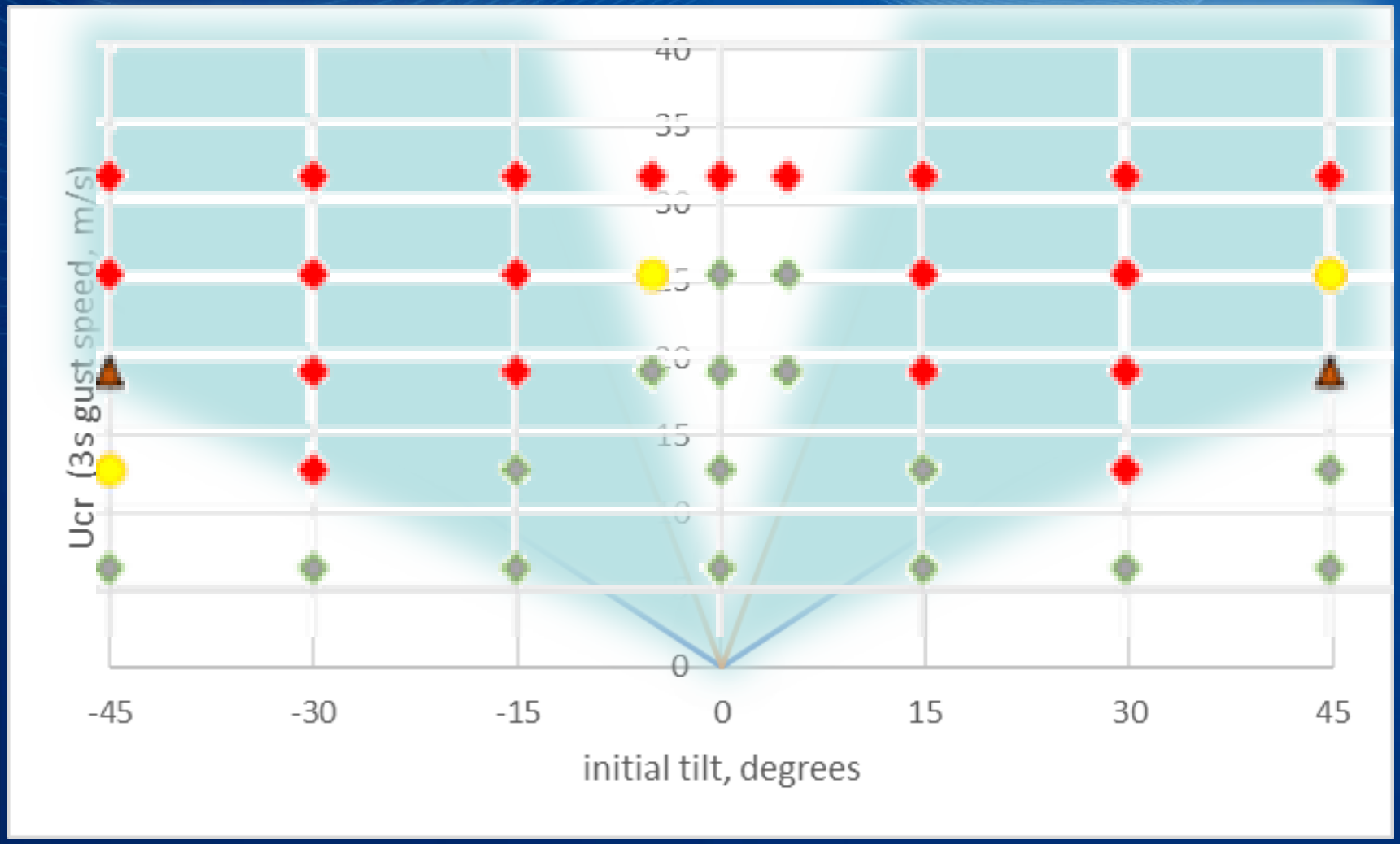
Helical strakes to prevent vortex shedding and subsequent vortex lock-in

What is the Frequency of Vortex Shedding?

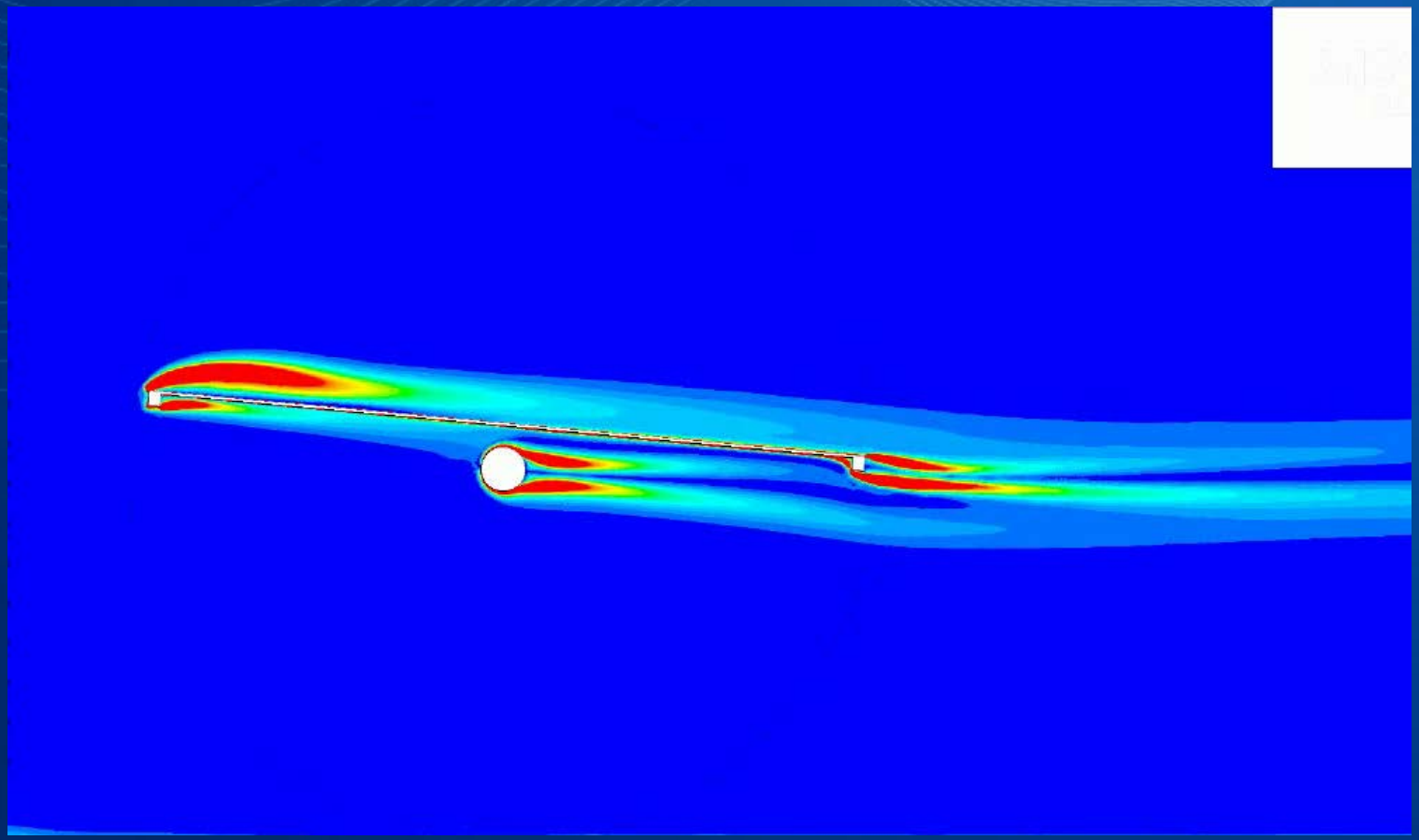
$$St = \frac{fL}{U} = 0.05\ to\ 0.20$$



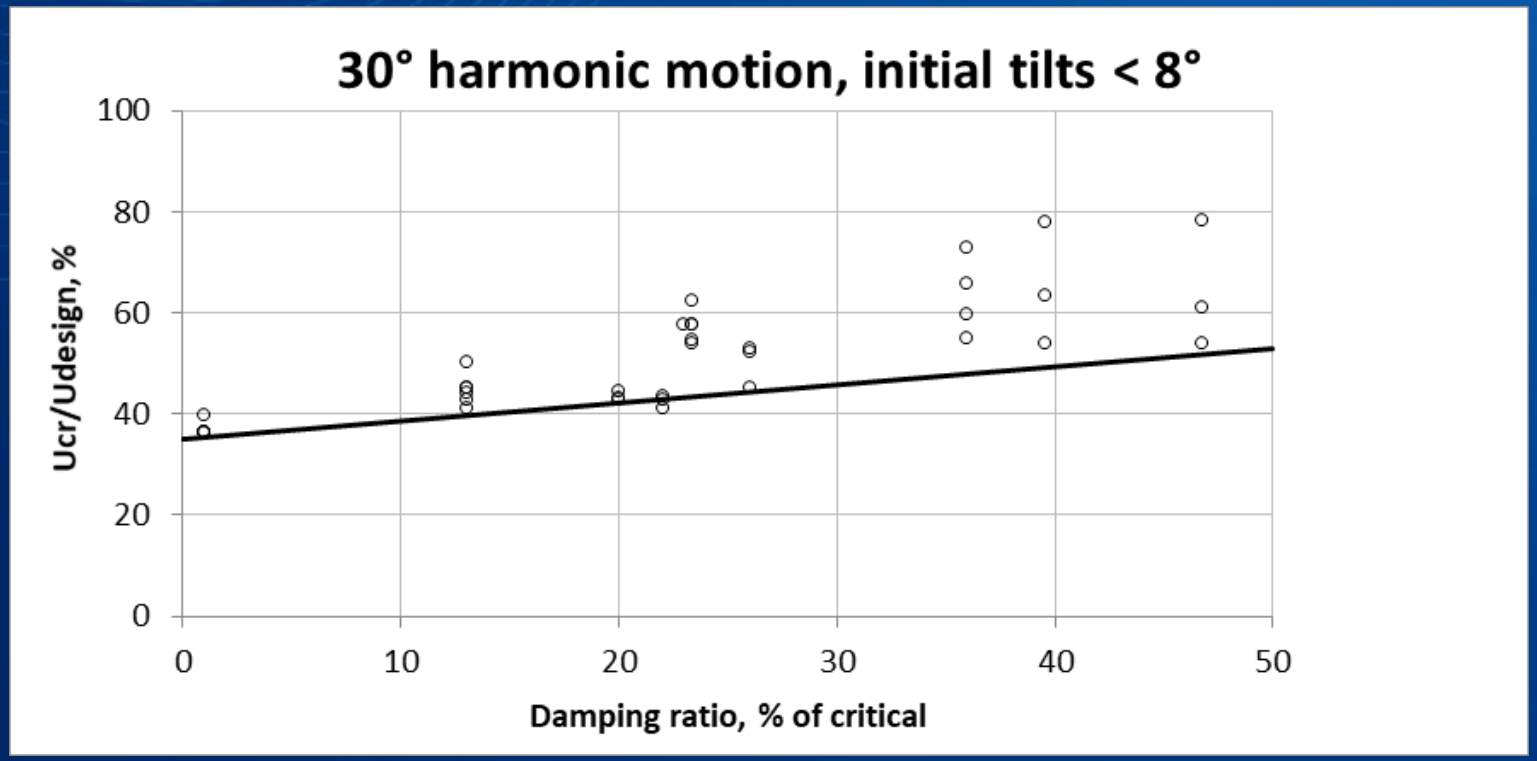

40
35
30
25
20
15
10
5
0
Ucr (3s gust speed, m/s)
-45
-30
-15
0
15
30
45
initial tilt, degrees


Ucr (3s gust speed, m/s)
40
35
30
25
20
15
10
5
0
-45
-30
-15
0
15
30
45
initial tilt, degrees

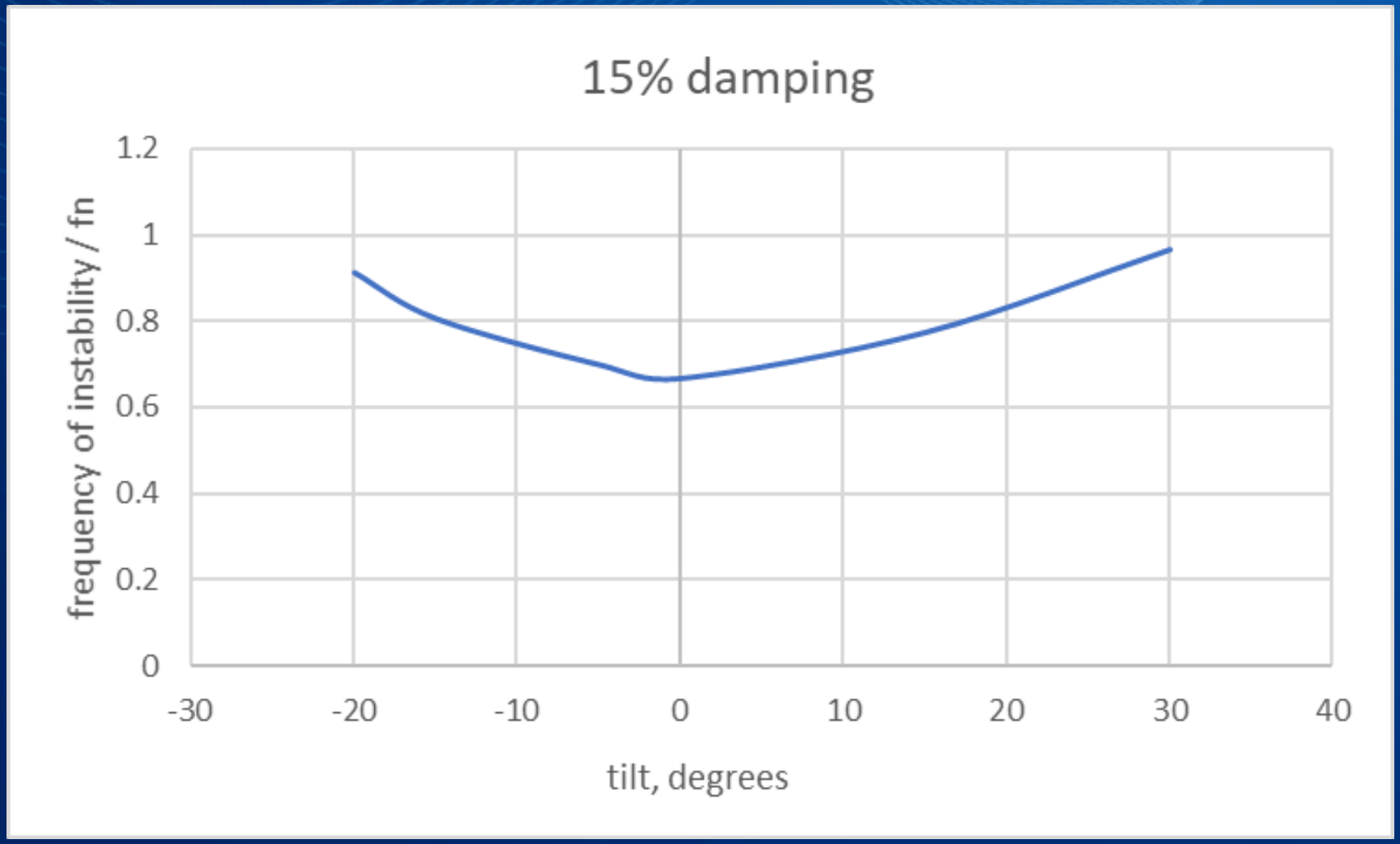
Low tilts: Cyclical Torsional Divergence



Damping has little at low tilts effect



Natural frequency shift

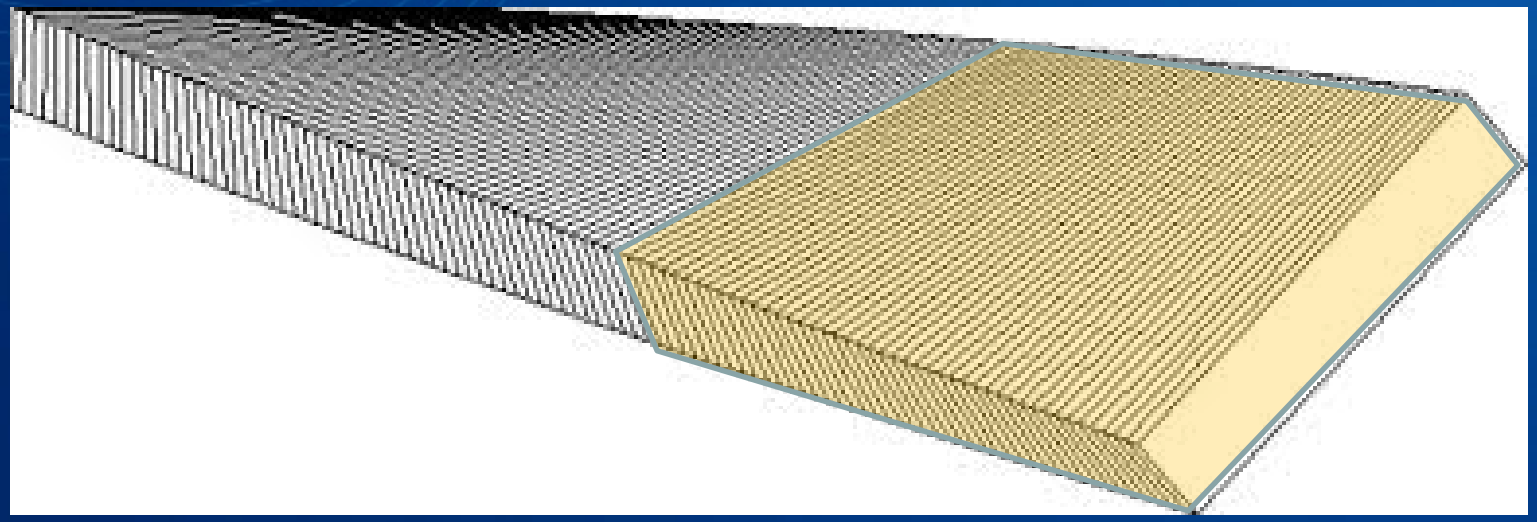


Instabilities

- ~~Flutter~~
- Torsional divergence
- ~~Galloping~~
- ~~Torsional galloping~~
- Vortex lock-in
- ~~Stall flutter~~

Multi row testing

- Participation fraction captured



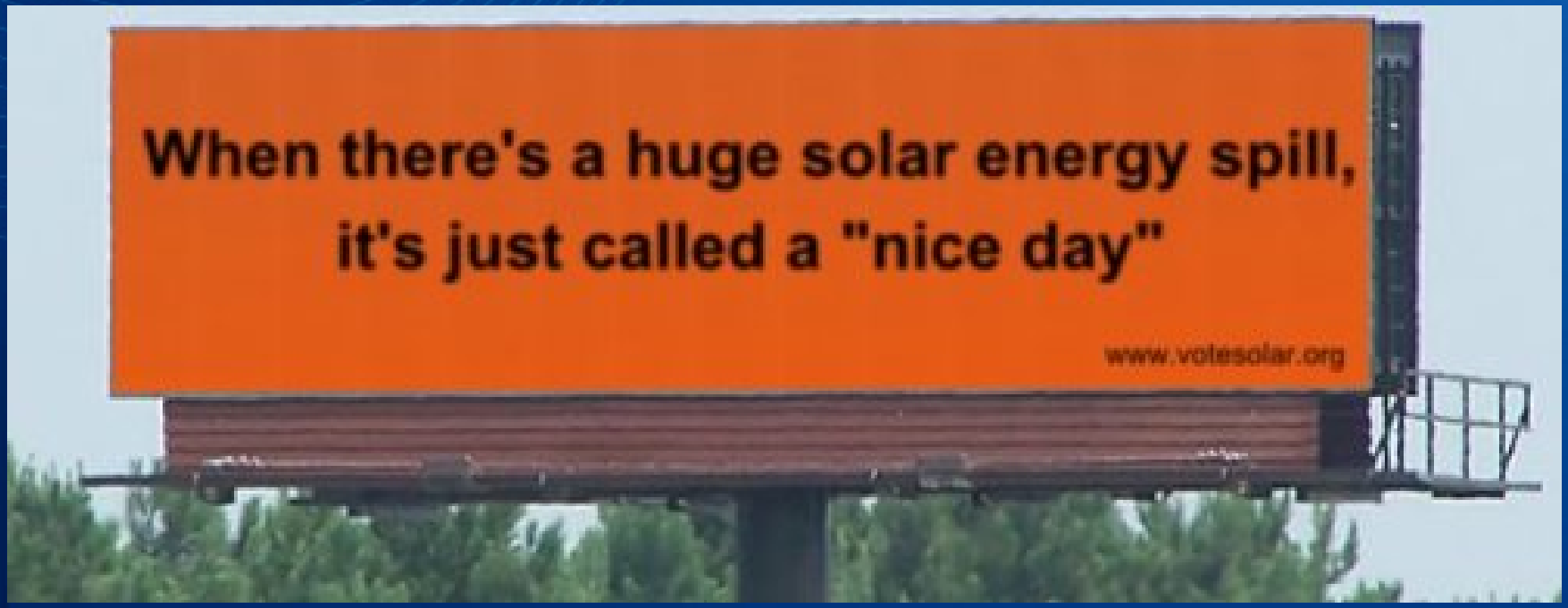
Multi row testing only (not section model)

- Participation fraction captured
- Interior rows go unstable first
- Row edge effects for cornering winds

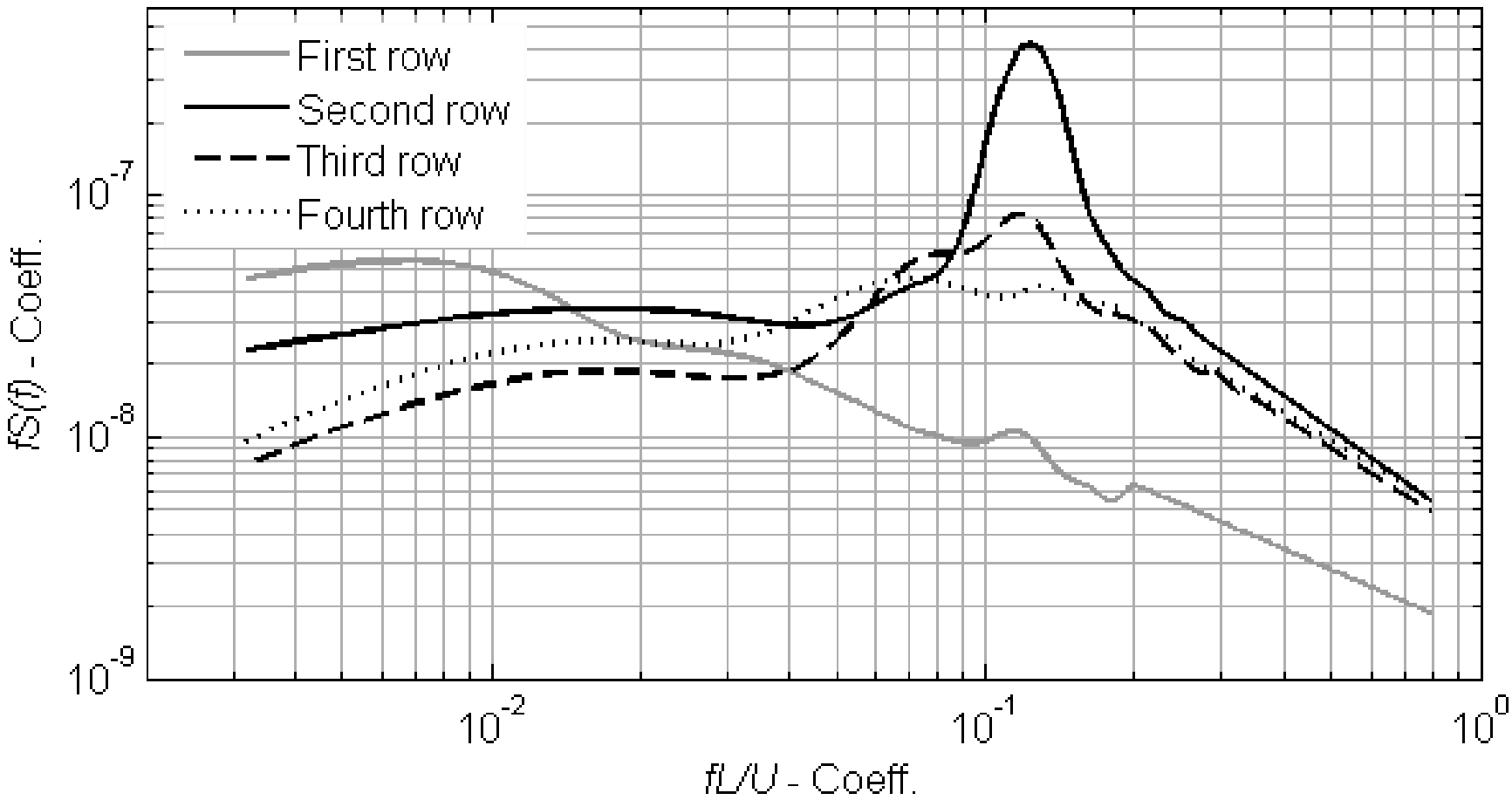
Multi row testing advantages

- Participation fraction captured
- Interior rows go unstable first
- Row edge effects
- Ucr lower in turbulent approach flow
  - Turbulence length scale (eddy size) matters

Solar wind loading standard
Reliability vs. compliance
Performance-based


When there's a huge solar energy spill,
it's just called a "nice day"
www.votesolar.org

Vortex Shedding Energy Spectrumv



Soil Side Pile Corrosion

PROJECT X
CORROSION
ENGINEERING
Corrosion Control – Soil, Water, Metallurgy Lab

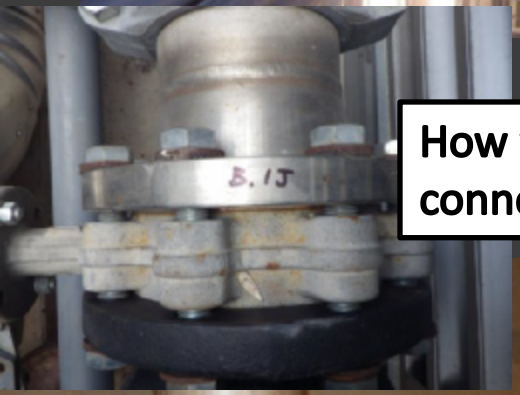
Ed Hernandez, PE
NREL PV Reliability Workshop
2019

Corrosion Study- Doing your Homework
If you have all four, BEWARE!

Questions to ask

Begins with a piece of the problem.

But what was it connected to?



How was it connected?

Is the material what was specified by design?

What was it installed in?

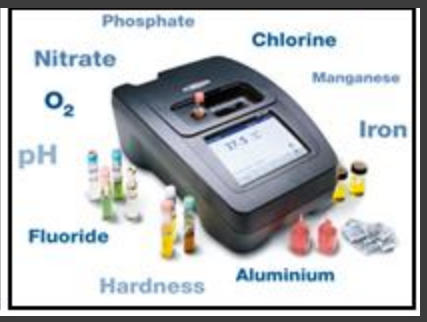
What is the maintenance program if any?

Are materials good in some states, but not in stricter states?

Soil Factors that Contribute to Corrosion

Certain factors affect certain metals

- Ferrous (pH, Cl, SO4, and Resistivity)
- Copper (pH, sulfides, ammonia, nitrates)
- Cementitious (pH, Langelier, Cl, & SO4)
- MIC Probability (Sulfides, REDOX)



Challenge: Convincing people that Soil corrosivity tests are important homework. Do you drink a cup of hot coffee without checking how hot it is?

Recommended Soil Tests

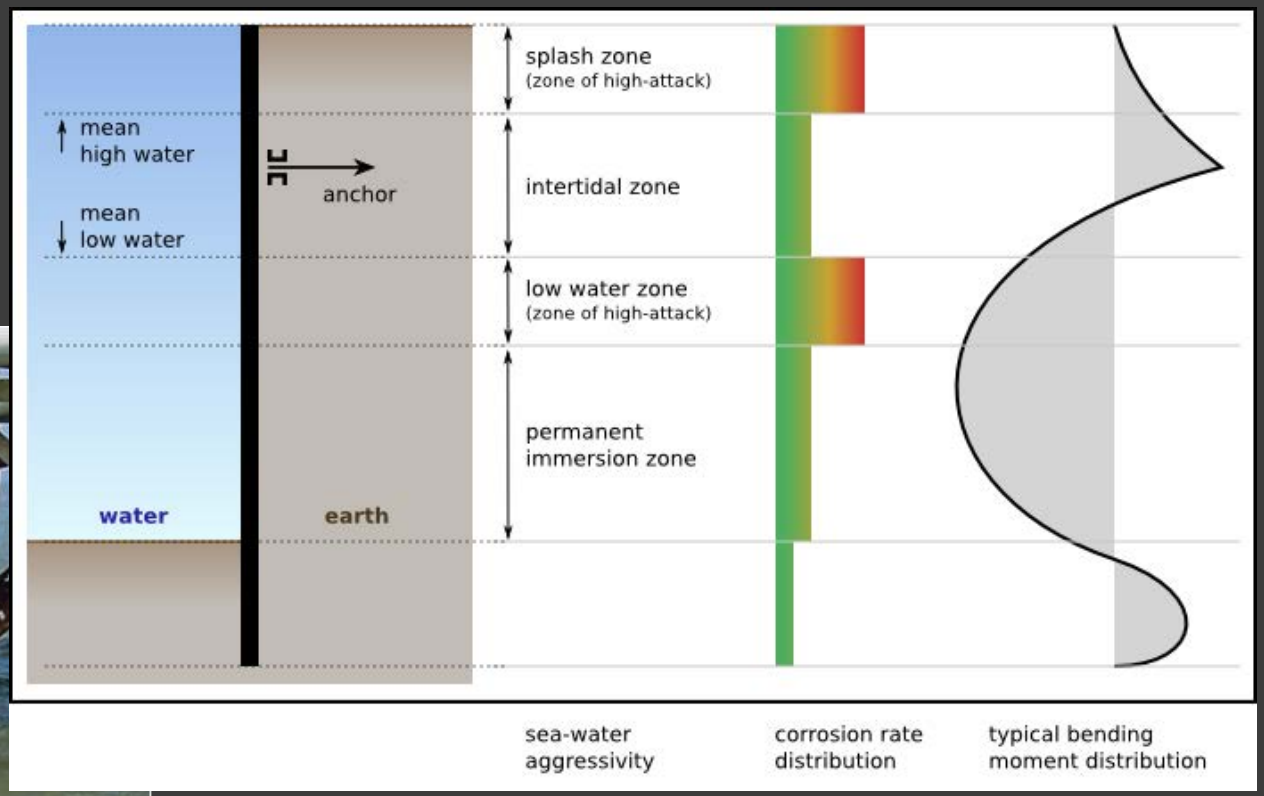
If putting things underground, Collect 300g of soil sample from depth of structure and test for the following:

1. Soil Resistivity (ohm-cm)
2. pH
3. Oxidation-Reduction (Redox) Potential
4. Sulfates
5. Chlorides
6. Ammonia
7. Nitrates
8. Sulfides

Essential data for a Soil Corrosivity Report

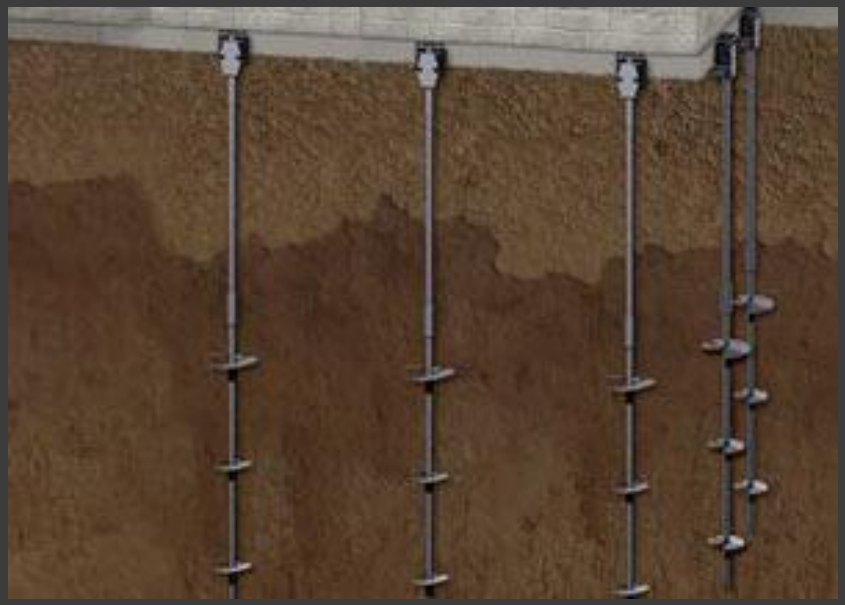
Splash Zones

- Very corrosive environment because of wetting then drying and re-exposure to oxygen.
- Expansive soils can increase oxygen content in soils
- Water table
- Sprinklers



Corrosion of Piles

- Disturbed soil or non-disturbed is key.

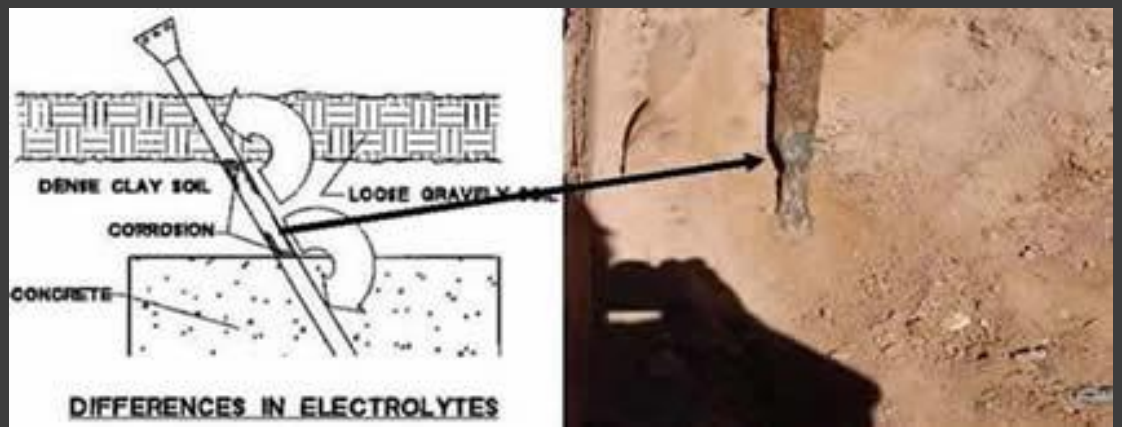


Helical Anchors disturb soil

Driven Piles do not disturb soil

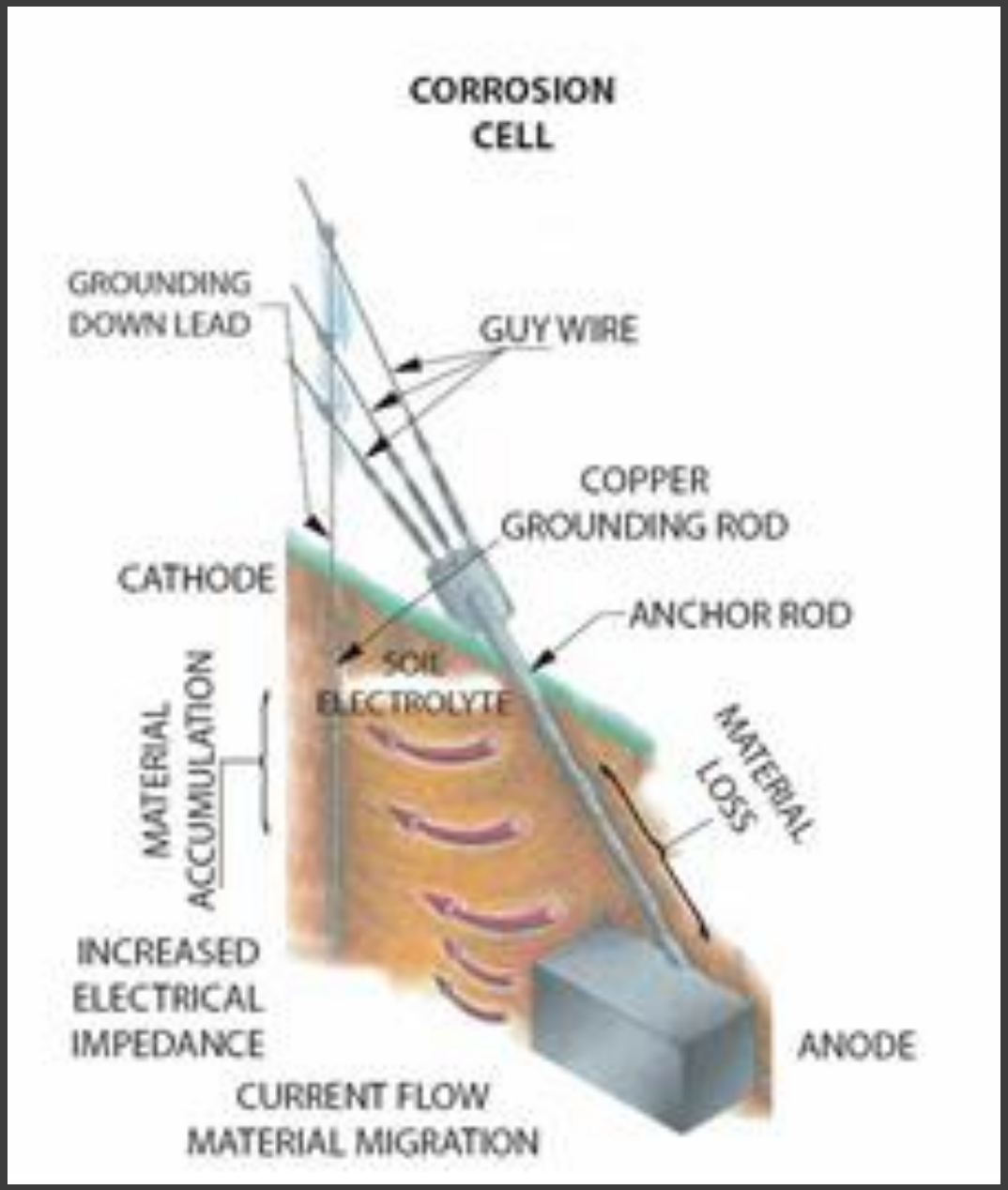
Corrosion of Piles

- In most soils, Corrosion is typically focused like a pinhole
- A pinhole in a pile won't affect integrity too much and there is nothing to leak
- Extremely corrosive soil of differing compaction, or high groundwater or high salts can lead to shallow and uniform corrosion of pile cross section. More significant.



Corrosion of Piles and Anchors

- Connections to dissimilar metals such as copper grounding will also cause corrosion
- Can a sacrificial anode be used for grounding?



Galvanizing?

- Galvanizing is usually great for atmospheric corrosion or low soluble salts soils.
- You don’t know until you test chemistry of your soil. In-Situ field test only provides resistivity information. Truly for CP design. Putting the cart before the horse.

http://www.nacleanenergy.com/articles/30361/pv-system-math-fewer-available-sites-poor-planning-money-down-the-drain

Why do things Corrode?

- Because Mother Nature wants her things back
- She sends her four horsemen of corrosion to get them for her in the form of the Corrosion Cell.

4 factors of Corrosion Cell

ANODE

METALLIC PATH

ELECTROLYTE

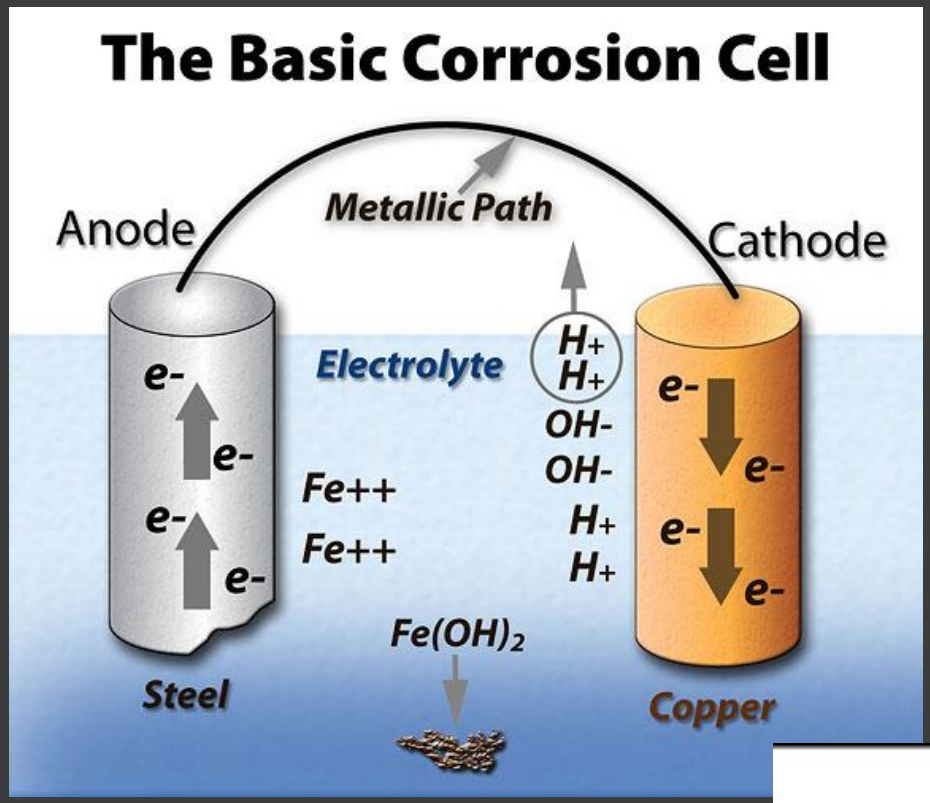
CATHODE

Everything You Need to Know About Corrosion

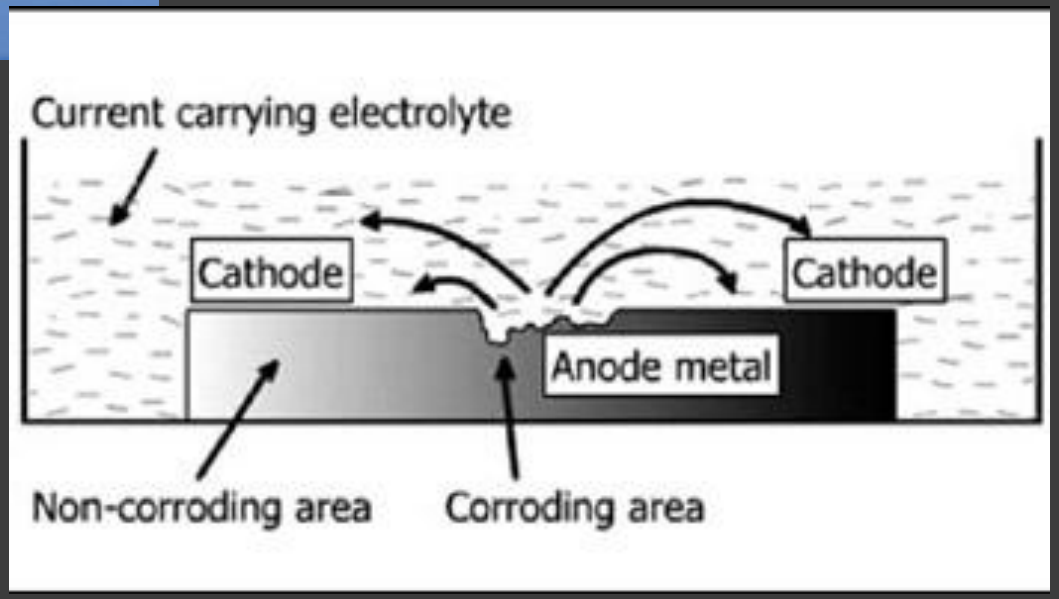
<u>4 Parts of a Corrosion Cell</u>

- Anode (location where corrosion takes place)
  - Oxidation Half-Reaction
- Cathode (no corrosion but generates hydrogen)
  - Reduction Half-Reaction
- Electrolyte (Soil, Water, Moisture, etc.)
- Electrical Connection between anode and cathode (wire, metal wall, carbon fiber, etc.)

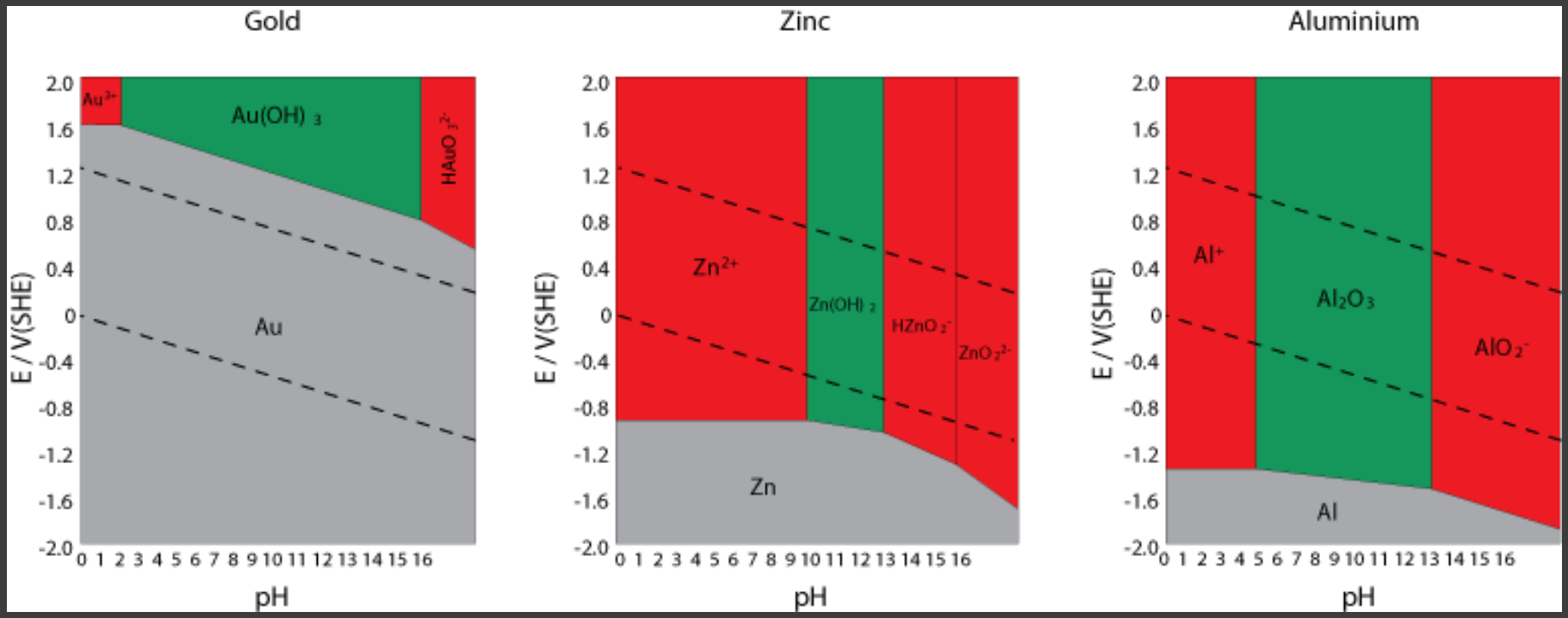
Electrochemical corrosion can be stopped by eliminating any one of the 4 components



You can have an anode and cathode on the same piece of metal.

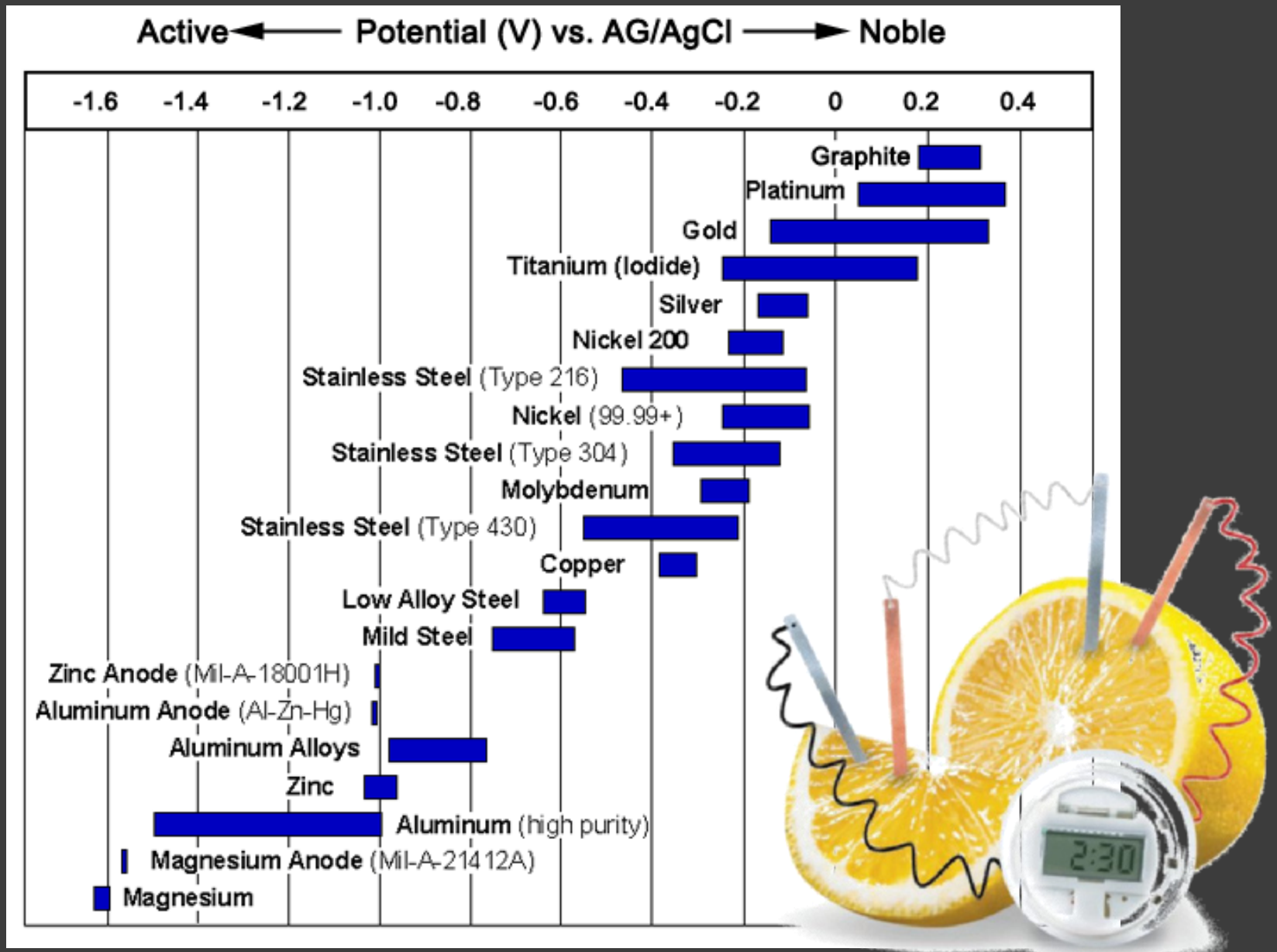


Pourbaix Diagrams

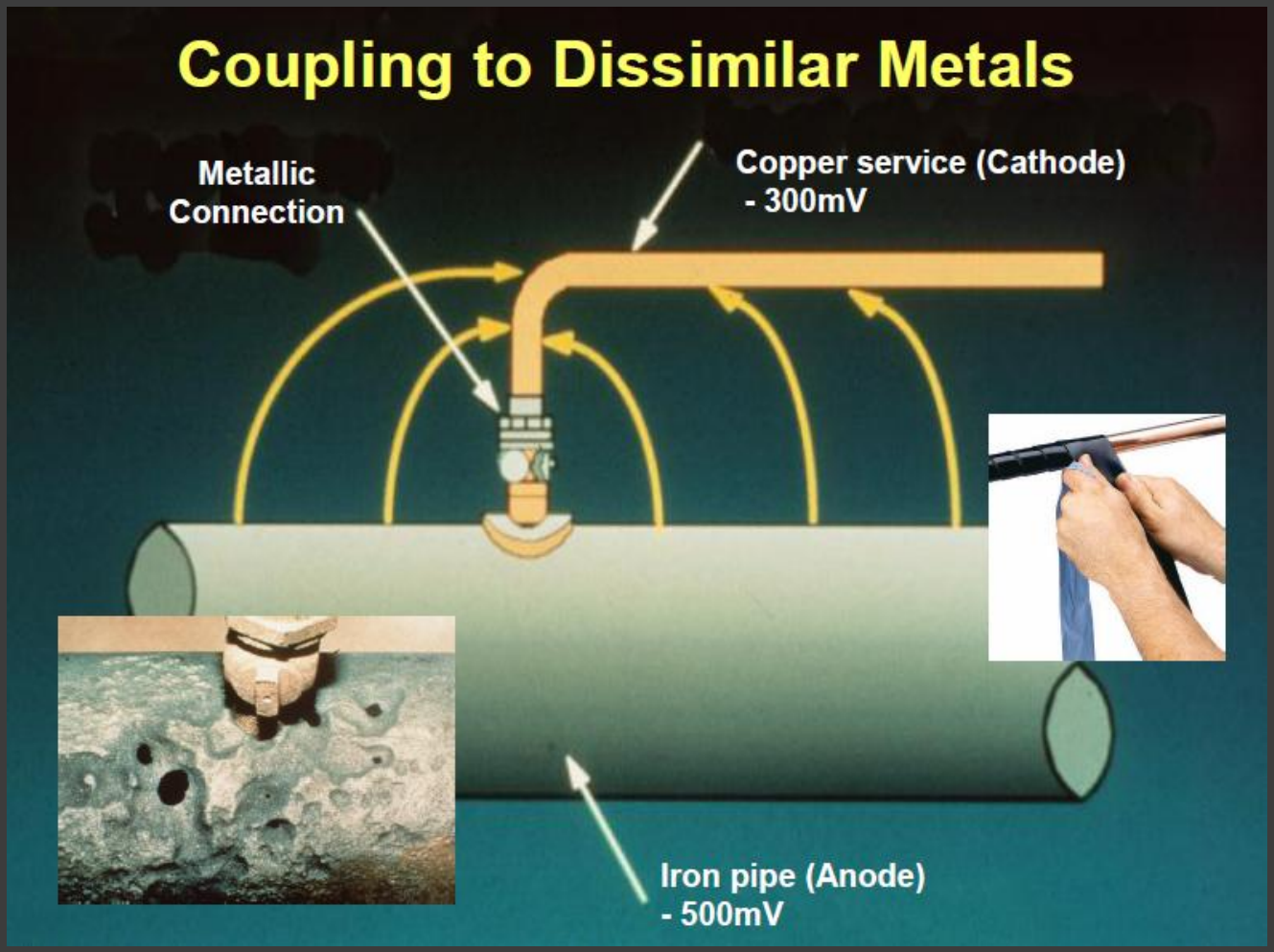


Material Properties: Every Material has its comfort and discomfort zone. What is corrosive to one metal is not always corrosive to another.

Galvanic Series



Material Selection to avoid creating Anodes and Cathodes



Challenge: Economics, If unavoidable, coat the large cathode, installation precautions.

Material Compatibility

	Zinc	Galvanized Steel	Aluminum	Cast Iron	Lead	Mild Steel	Tin	Copper	Stainless Steel
Zinc	None	Low	Medium	High	High	High	High	High	High
Galvanized Steel	Low	None	Medium	Medium	Medium	High	High	High	High
Aluminum	Medium	Medium	None	Medium	Medium	Medium	Medium	High	High
Cast Iron	High	Medium	Medium	None	Low	Low	Low	Medium	Medium
Lead	High	Medium	Medium	Low	None	Low	Low	Medium	Medium
Mild Steel	High	High	Medium	Low	Low	None	Low	Medium	Medium
Tin	High	High	Medium	Low	Low	Low	None	Medium	Medium
Copper	High	High	High	Medium	Medium	Medium	Medium	None	Low
Stainless Steel	High	High	High	Medium	Medium	Medium	Medium	Low	None

Anode : Cathode Ratios

Small Anode

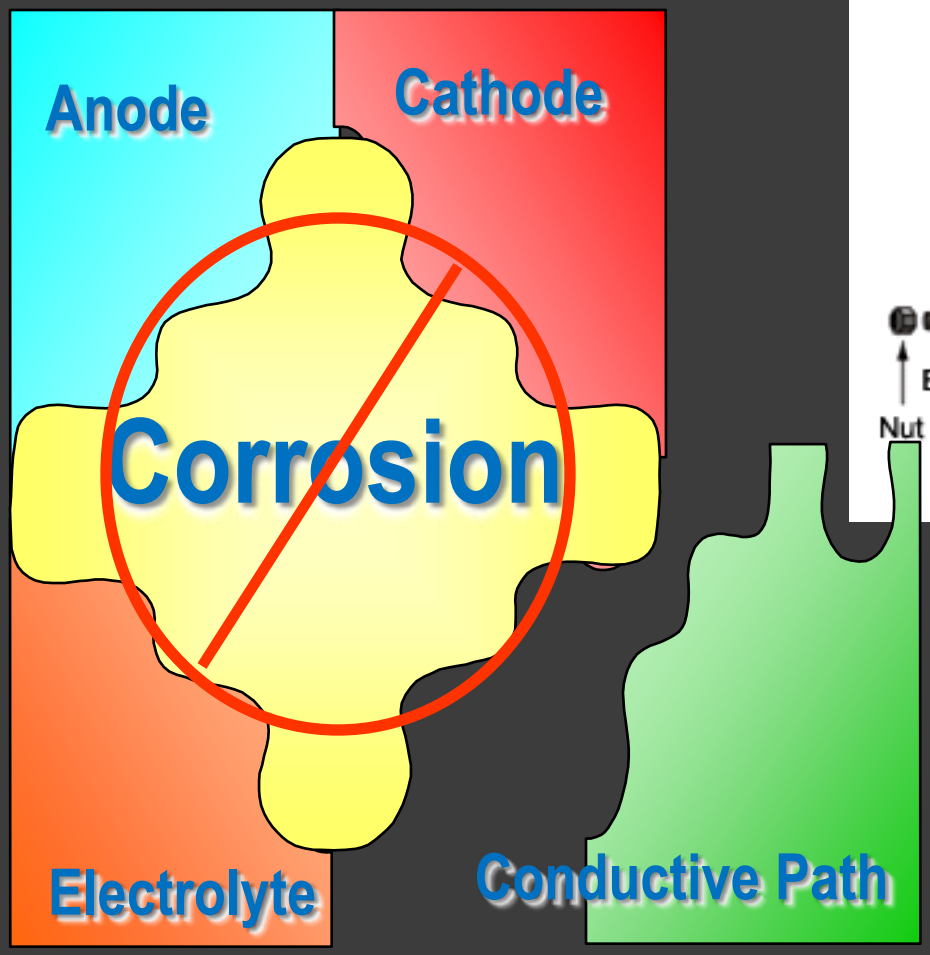
Large CATHODE

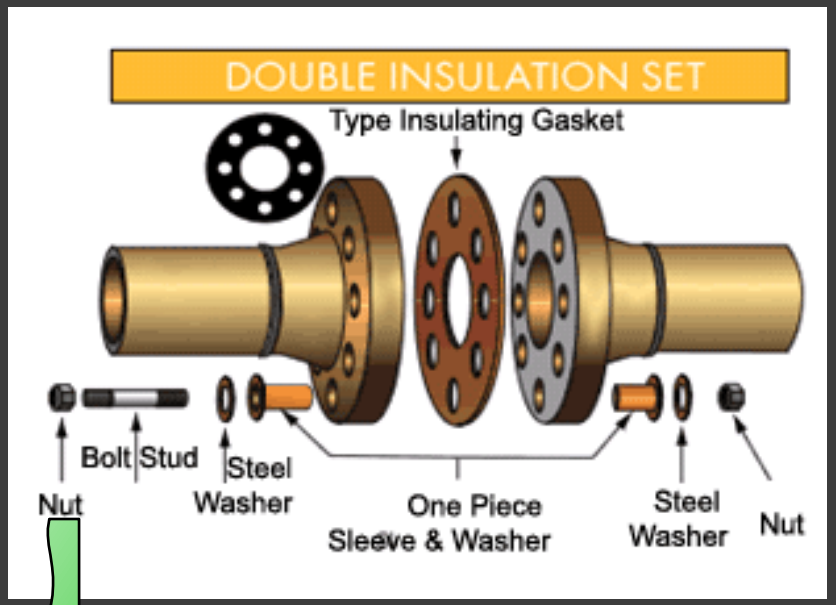
Small Cathode

Large ANODE

If the surface area of the anode is much larger than that of the cathode, the corrosion rate will be very very slow.

Interrupt Conductive paths using Isolation Kits



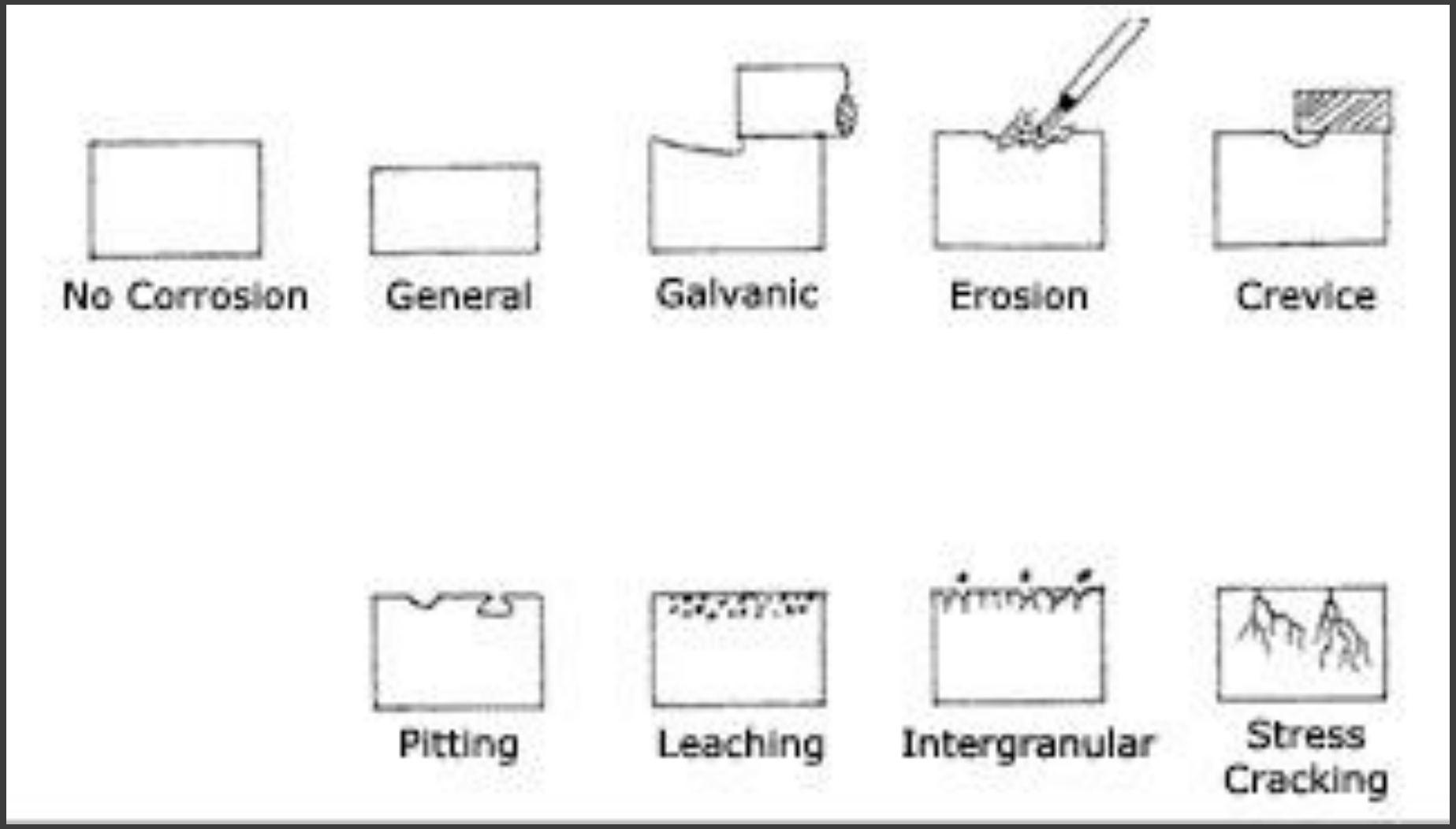


Common misconception:

Brass is not a “Di-Electric” or an insulator.
It is a metallic conductive path.
Aluminum and Stainless don’t mix.

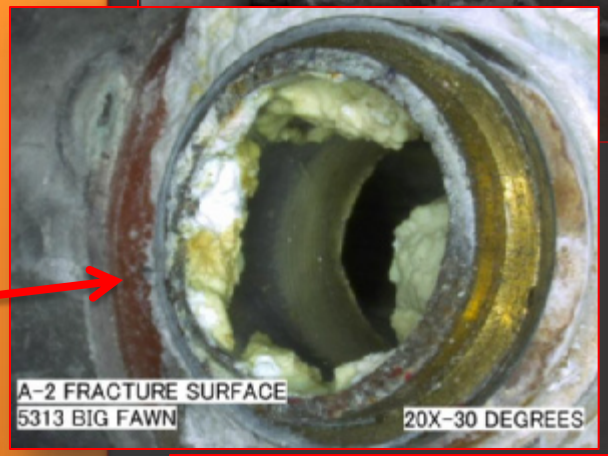
Challenge: GROUNDING SYSTEMS ATTACHING TO PIPES CAN CREATE EARTH BATTERIES

8 Forms of Corrosion

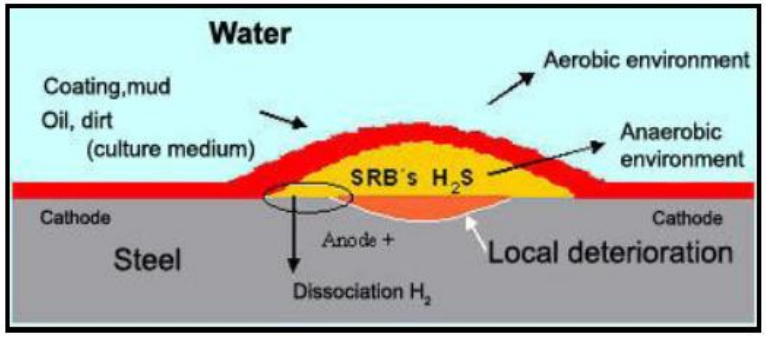


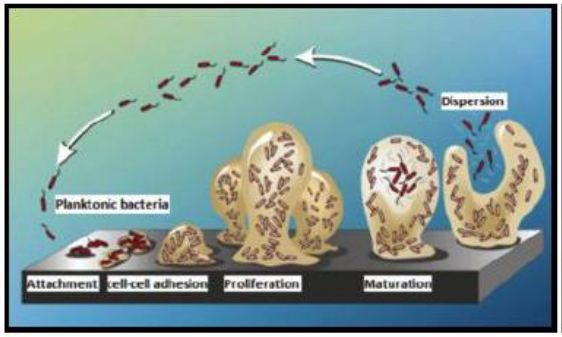
8 FORMS OF CORROSION

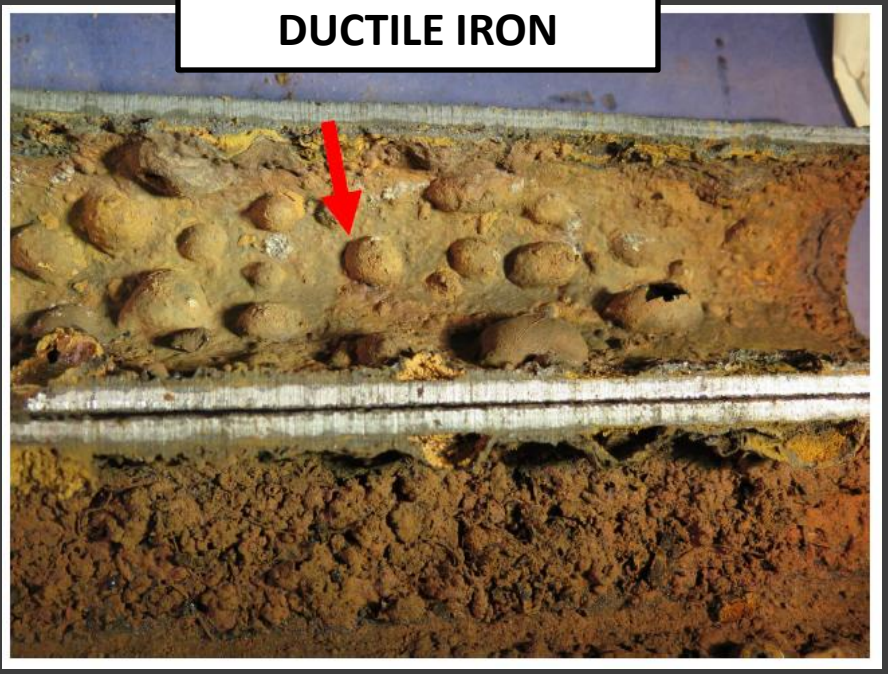
- Uniform Corrosion
- Galvanic Corrosion
- Crevice Corrosion
- Pitting
- Intergranular Corrosion
- Selective Leeching
- Erosion Corrosion
- Stress Corrosion Cracking



Corrosive Bacteria Analysis a.k.a. Microbiologically Induced Corrosion (MIC)

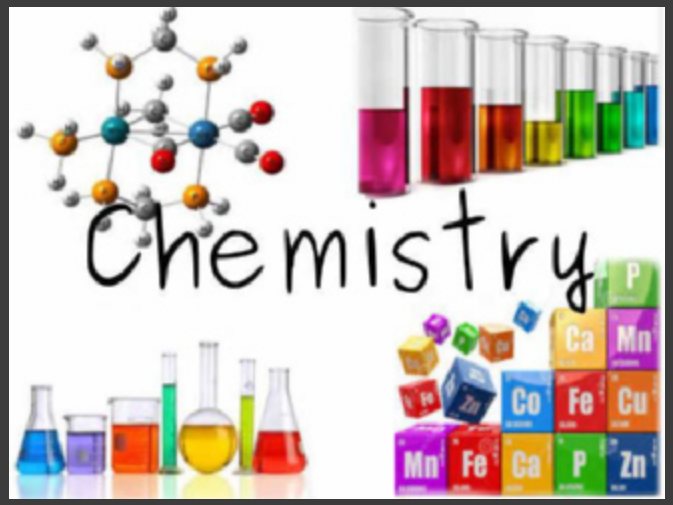






Controlling Corrosion

1. Electrical Isolation of dissimilar systems
2. Coatings to prevent contact to electrolyte
3. Inhibitors to change surface chemistry
4. Cathodic / Anodic Protection



ICCP –Rectifiers

Photo 2 – Typical Cathodic Protection Rectifier

Photo 4 – Typical Anode Hole Being Loaded With Anodes

Photo 5 – Typical Mixed Metal Oxide Anodes

GACP- Sacrificial Anodes

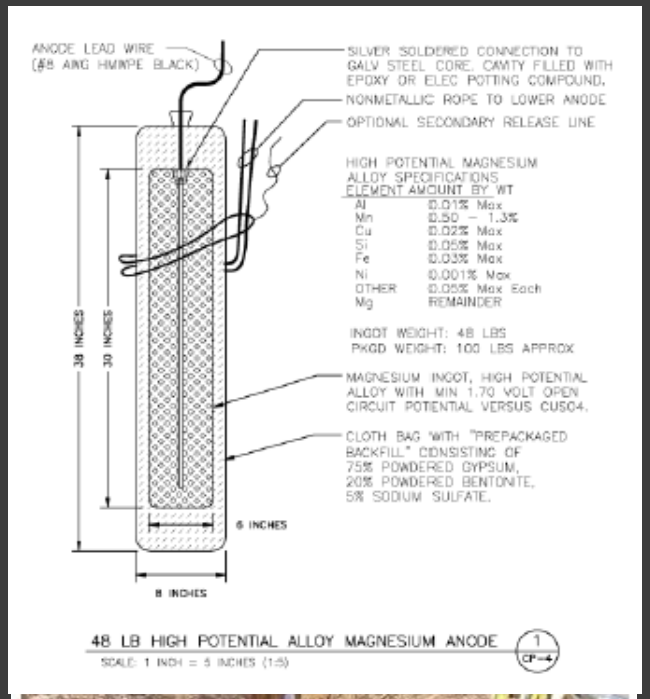


Photo 2 – Example of Magnesium Anodes Installed Horizontally in a Trench

1st line of defense – COATINGS

- Coating can be Corrosion Inhibitor (like cement)
- Coating can be a moisture barrier (like epoxy)

Challenge: Pretty paint job, but will installers ruin it? Nice baggy, here's some sharp gravel.

2nd Line of Defense – Cathodic Protection

Perfect coatings are almost impossible. Cathodic Protection will be the little Dutch boy that plugs the holes.

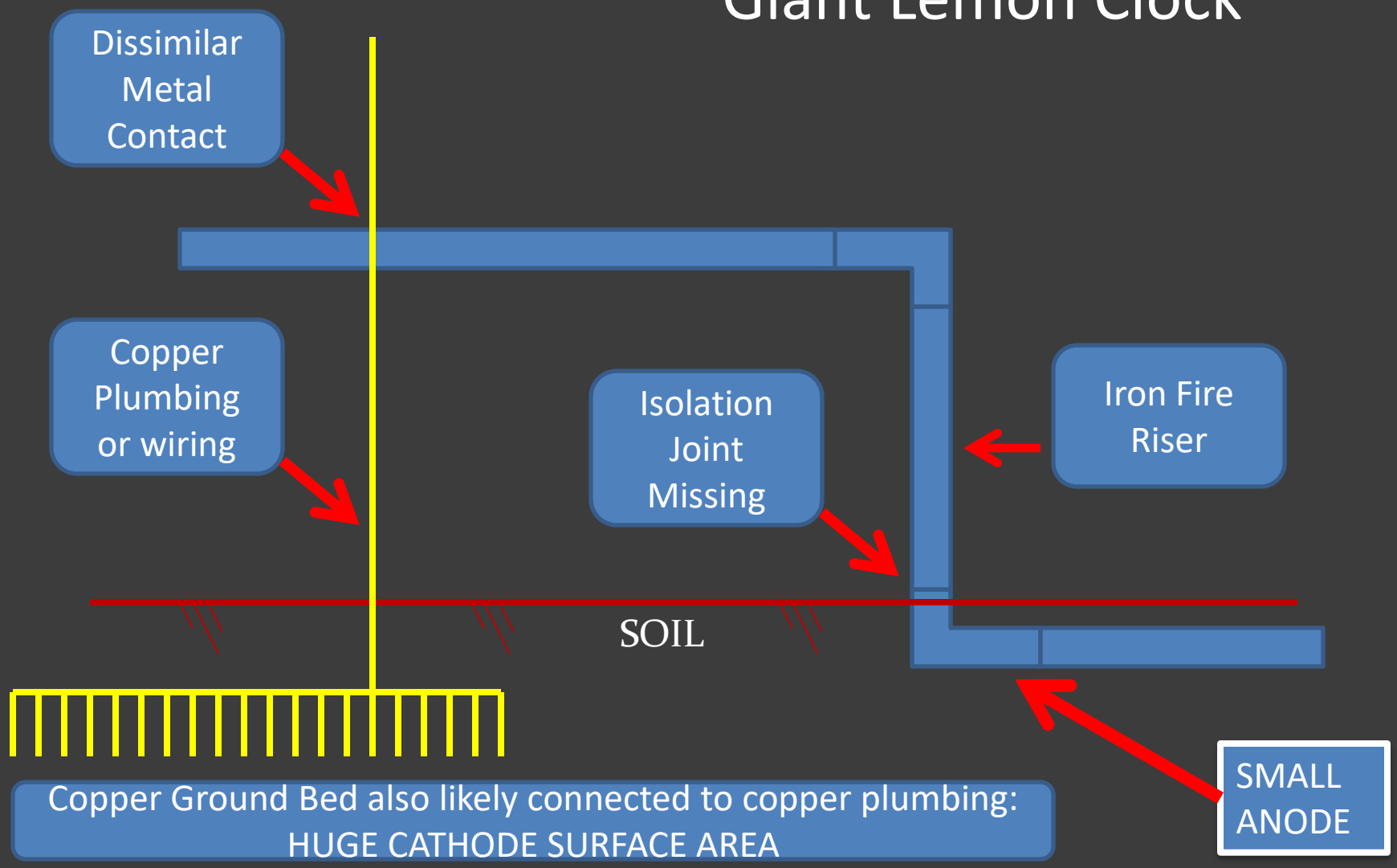
- Structure must be metallic
- Best if installed with intentional electrical continuity
- Coatings or encasement reduce CP need
- Example: Without coating 30 amp DC to CP, With coated pipes:2 amp DC to CP (~10 anodes per amp)

Example of Corrosion Cell Mistake

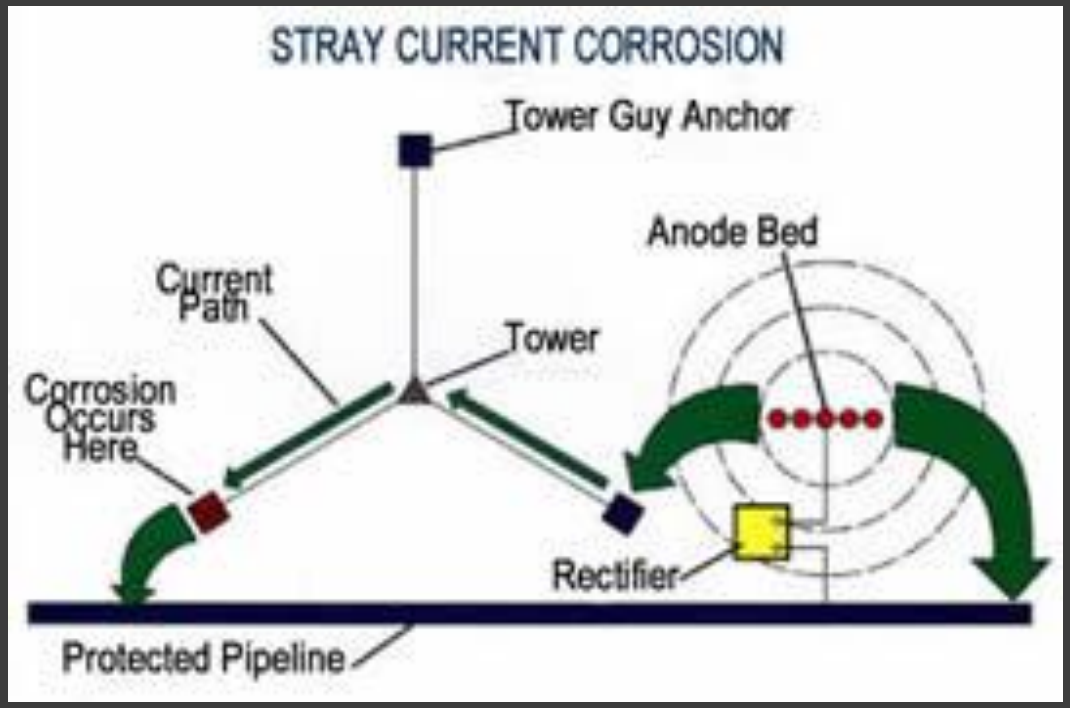
Cast iron pipe Corrosion

Creating Corrosion Cells

Giant Lemon Clock



Stray Current Corrosion



Impressed Current Cathodic Protection Systems near pipelines can create Stray Current Corrosion conditions. Damage occurs when current hops from one structure to the other.

Questions?

Project X Corrosion Engineering
29990 Technology Dr, Suite 13
Murrieta, CA 92563
www.projectxcorrosion.com

Internal/External Corrosion Control

Soil & Forensics Lab

CERTIFIED MBE- DBE - SDB - SBE

NAICS 541330, 237120, 541380

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Joint Relaxation in PV Racking Bolted Joints

MATRIX
ENGINEERING CONSULTANTS

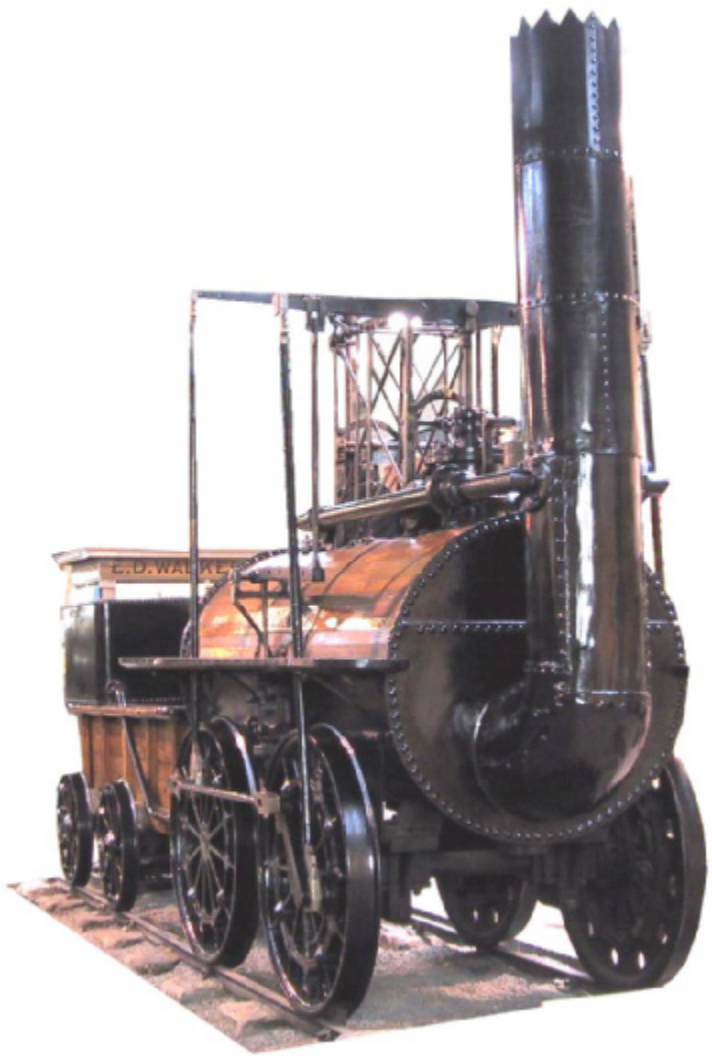
Jon D. Ness, P.E.

Joint Relaxation in PV Racking Bolted Joints

To be Covered

- Typical PV Racking Bolted Joint
- PV Racking Bolted Joints Have Unique Requirements
- Residual Preload is Key to Performance
- ….but, Residual Preload is often Less than Expected.
- Preload Relaxation Due to Embedment
- Current Analytical Model
- Initial Experimental Work
- Preliminary Results/Conclusions
- General Recommendations
- Need for Additional Research

Brief Historical Context



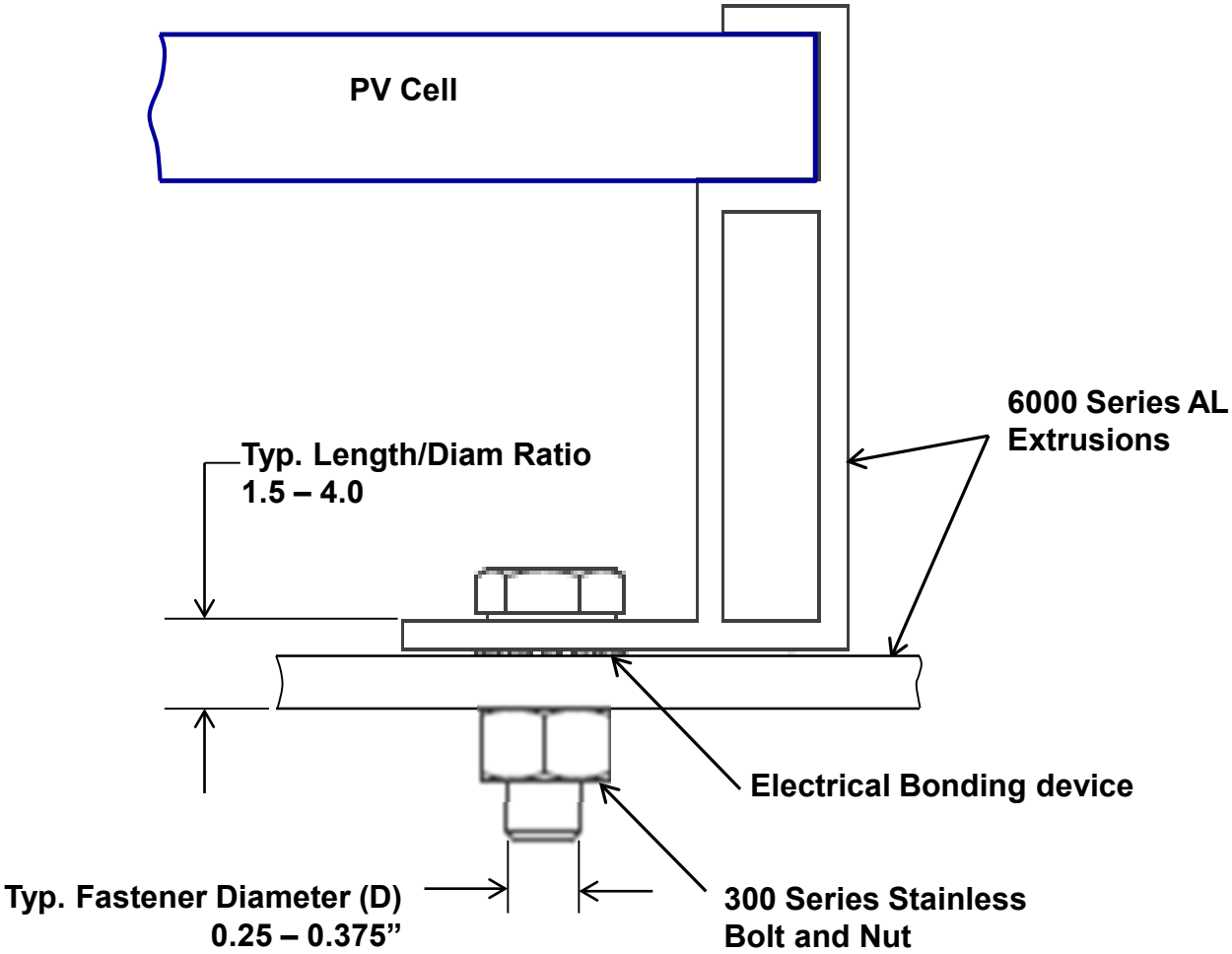
- The Industrial Revolution witnessed a dramatic increase in the usage of threaded fasteners.
- Problems soon became apparent, especially in locomotives where the loading was dynamic.
- The science behind bolted joints has evolved and is generally now well understood.
- The design and assembly of reliable, dynamically loaded joints is now common place.

The typical modern automobile has ≈ 3500 fasteners!

Racking System Bolted Joints

- Bolted joints are prolific in PV racking systems!
- Bolted joints are critical in the **structural integrity** AND **electrical bonding** of the system.
- Typically the weakest link in the racking system!
  - Frequently one of the largest single causes of failure, claims and safety concerns.
- Commonly require preventative maintenance, which is a significant effect on the cost of ownership.
- Often overlooked during the design, integration and assembly of PV racking system.
- Corners are often cut to save cost!

Typical PV Racking System - Bonded Bolted Joint



Common Bolted Joint Application Types

Structural Bolted Joints

- Common Bolts: ASTM A325 / A490
- Standardized joints and grip lengths.
- Typically painted or galvanized structural steel components.
- Bolt Preload Control –Required by code.
- Simple Joint Requirements
  - Bearing – Static Loads
    - The load is transferred between members by bearing on the bolts.
  - Slip-critical – Dynamic Loads
    - The load is transferred between members by friction in the joint.

PV Racking Bolted Joints

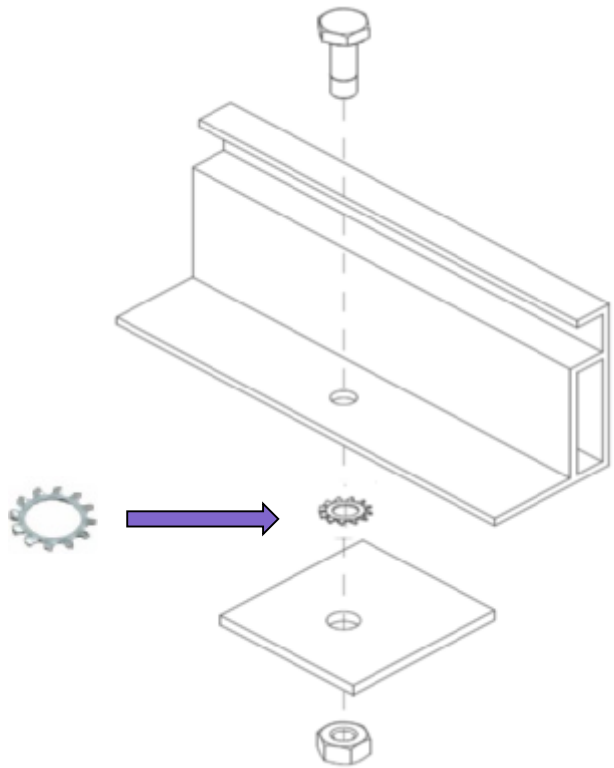
- Common Bolts: Stainless steel
- Non-standardized joints and grip lengths.
- Tend to have many fasteners.
- Anodized Aluminum components.
- Bolt Preload Control
  - Torque control tightening
- Joint Requirements –UL2703
  - Electrical bonding requirements
  - Axial clamp load safety factors
  - Friction grip safety factors
- Applied loads are both static and dynamic.

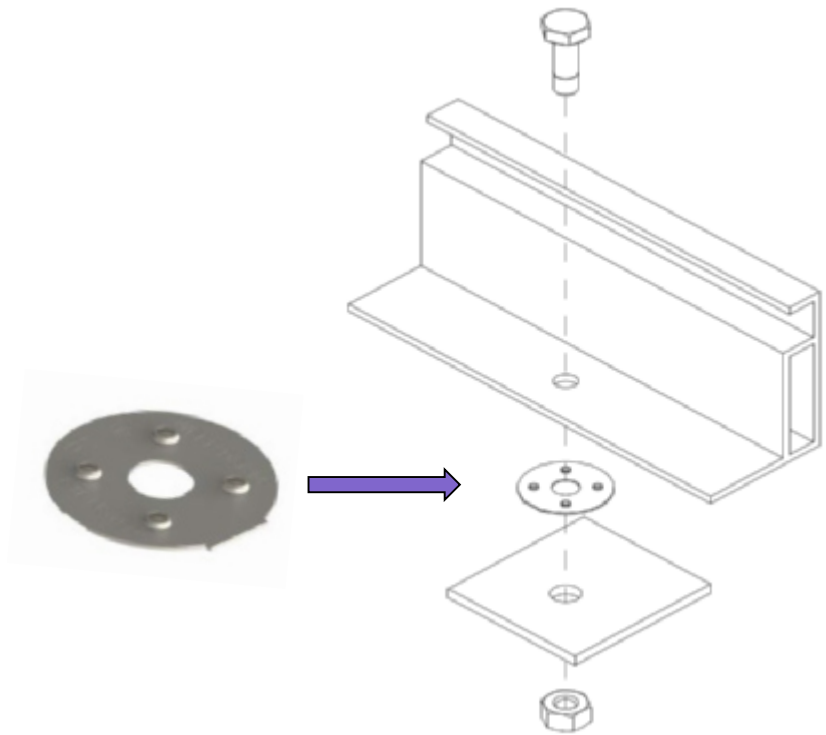
Mechanical Bolted Joints

- Common Bolts: SAE J429 Grade 5, 8
- Non-standardized joints and grip lengths.
- Products tend to have many fasteners
- Non standard joint materials
- Bolt Preload Control
  - Multiple methods dependent on criticality of joint and production environment.
- Complex Joint Requirements
  - Friction grip must be sufficient to carry transverse shear
  - Axial clamp load must be greater than applied load.
  - Embedment Losses
  - Thermal Effects
  - Preload Scatter
  - Serviceability
  - Corrosion

Typical PV Racking System - Bonded Bolted Joint

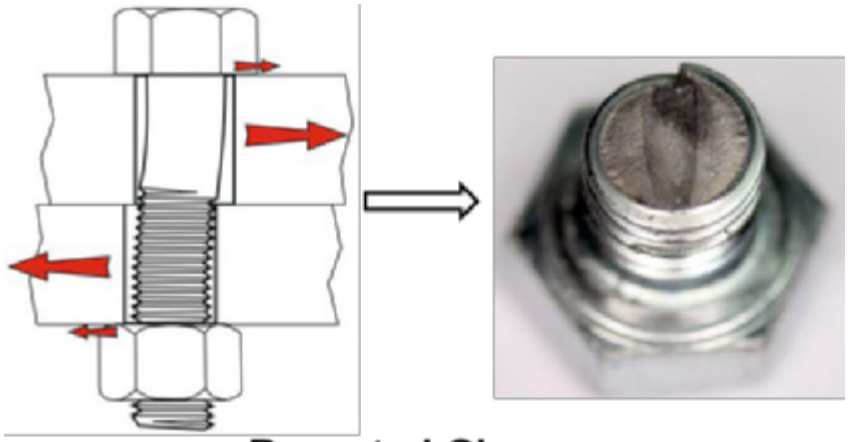
- PV racking bolted joints are unique because of ***"conflicting"*** requirements.
  1. Joints are often provide a reliable, low resistance electrical conduction path.
     - Lower cost electrical bonding method – elimination of separate grounding straps.
     - A bonding device is often placed in the joint interface to pierce the outer non-conductive anodized surfaces and create the electrical conduction path.



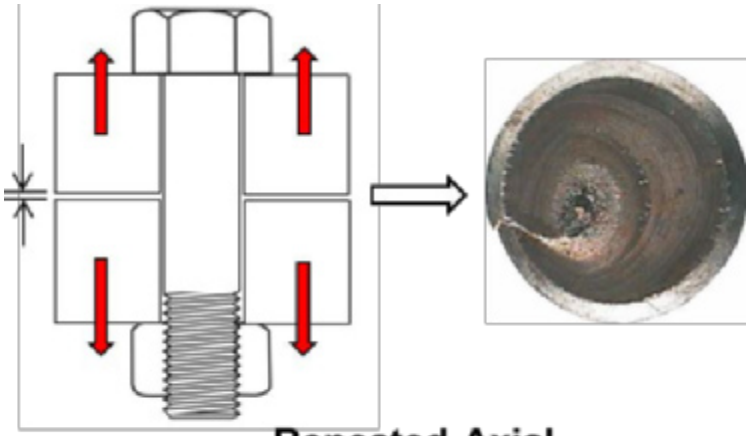


Typical PV Racking System - Bonded Bolted Joint

2. Joints must also reliably carry both static and dynamic loads.
   - It is critical that residual preload in the assembled bolt be high enough to carry the applied dynamic loading without movement.



Repeated Shear Overload



Repeated Axial Overload

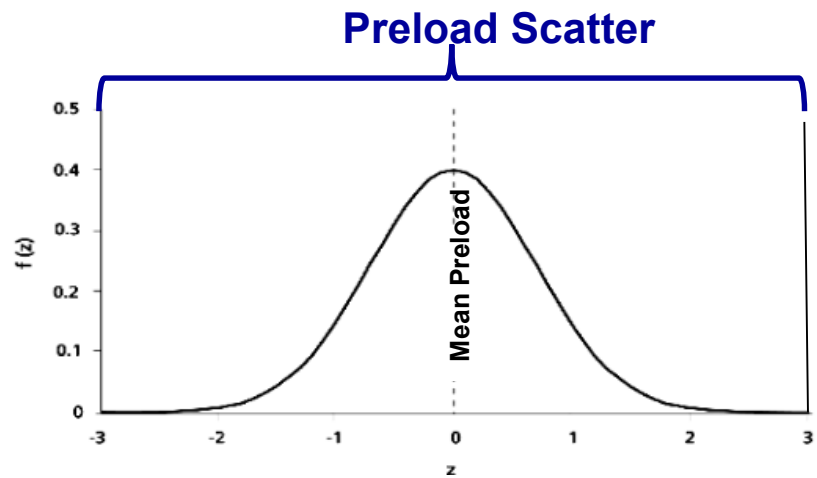
Residual preload is key to the reliability to PV racking system bolted joints!

PV Racking System – Bolted Joint Failures

- **A common problem is the residual preload is often less than what was assumed in the design calculations.**
- It is believed that low residual preload in the bolted joints contributes to many PV racking system failures.

Preload Scatter

- Torque is the least accurate assembly method and produces large scatter in the residual preload.
- Typical preload scatter can range between ± 25% to ±43% scatter in controlled tightening techniques
- Preload scatter is primarily caused by;
  - Variation in torque applied
  - Variation in friction co-efficients in fasteners
    - Stainless steel fasteners are prone to galling
    - Galling generally results a significant increase in thread friction resulting in a relatively low bolt preload.

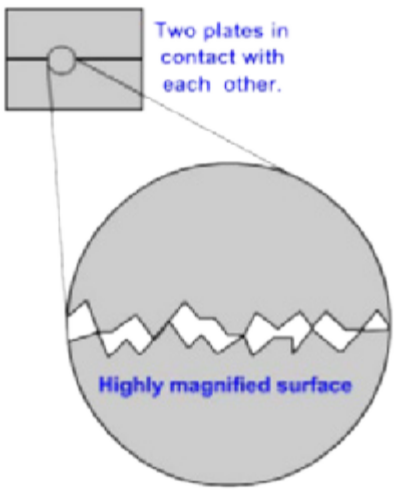


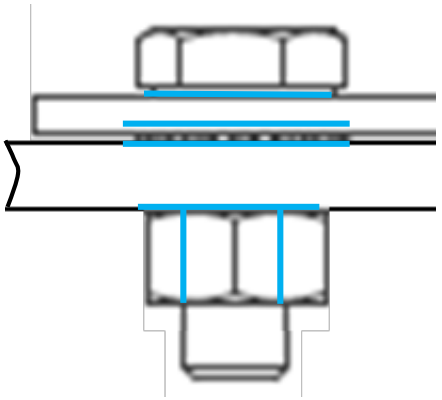
Damaged thread due to localized galling

Untrained Assembler And Uncontrolled Tools

Preload Relaxation due to Embedment

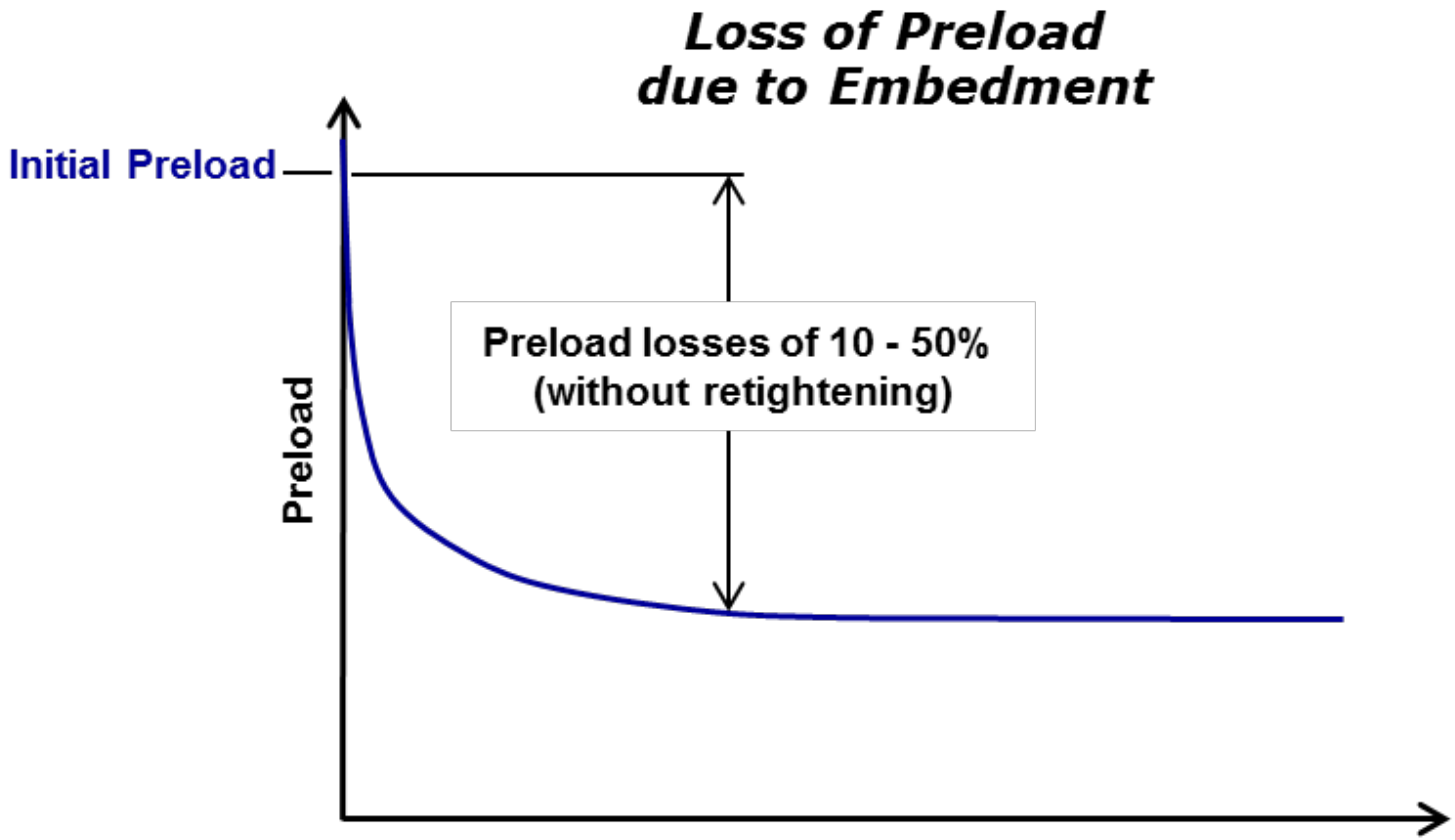
- Embedment is defined as the localized plastic deformation occurring in the mating surfaces within a joint during and after assembly.
  - Normal embedment results in ‘plastic flattening’ of the asperities in load bearing surfaces.
  - Bonding devices plastically deform or pierce the joint interface to create the electrical conduction path.
- Embedment occurs at every interface within the joint.
  - Between the bolt and the PV module.
  - At the two bonding device interfaces.
  - Between the nut and the PV racking.
  - In the threads of the fastener.
- The greatest amount of plastic deformation occurs during the initial tightening.
  - This embedment is compensated for by further tightening.
- Additional embedment occurs after assembly during the initial loading cycles.





Preload Relaxation due to Embedment

- Since many PV bolted joints are not re-tightened after the initial assembly, embedment which occurs when the product is in the field results in a loss of preload.
  - Many PV bolted joints are not accessible.
  - Retightening PV bolted joints is time consuming (i.e. expensive)



Analytical Model of Preload Relaxation

$$F_Z = f_z \frac{k_B k_J}{k_B + k_J}$$

Where:

$F_z = preload\ relaxation\ \ (kN)$

$f_Z = total\ amount\ of\ joint\ embedment\ (\mu m)$

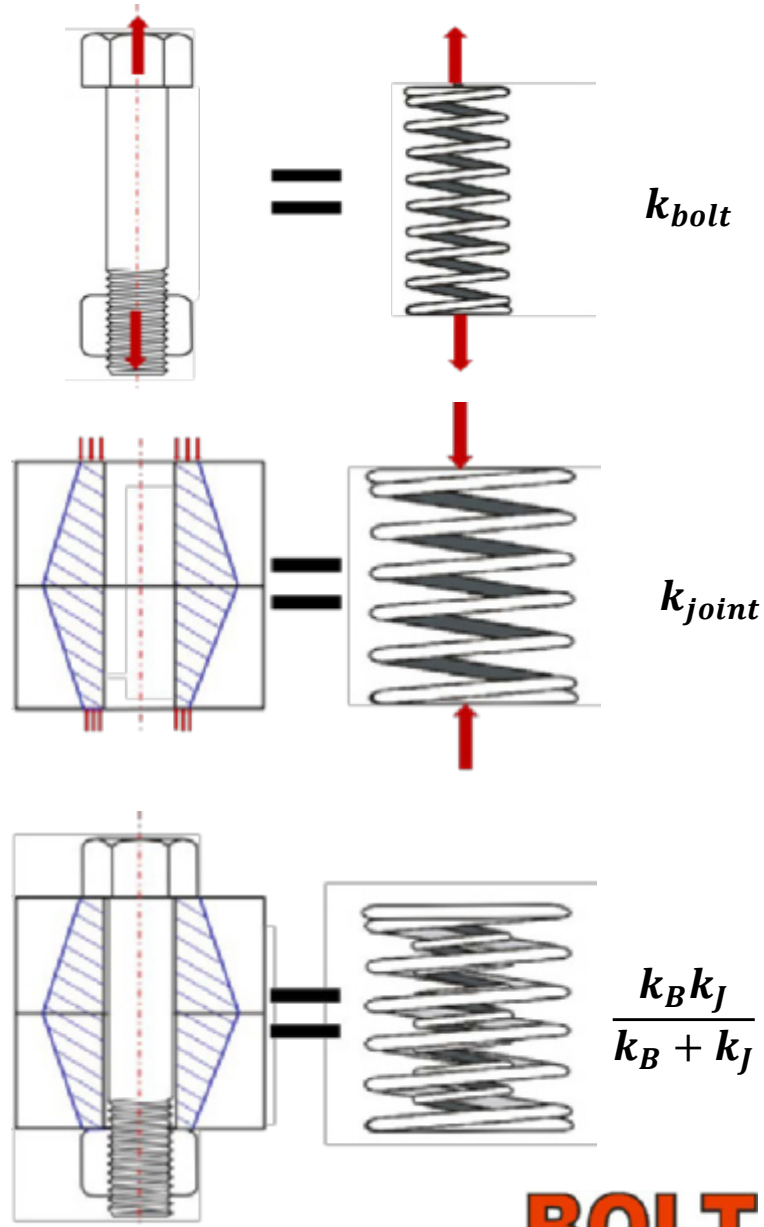
$k_{bolt} = bolt\ spring\ constant\ \left({}^{kN}/_{\mu m}\right)$

$k_{joint} = joint\ spring\ constant \left({}^{kN}/_{\mu m}\right)$

Guide Values for fz**

Average Roughness Height Rz (per DIN 4768)	Main Type of Applied Loading Acting	Guide Values for the Amount of Embedding (in µm)		
		In the thread	Head/nut bearing surface	Interfaces within the joint
<10 µm	Tension/ Compression	3	2.5	1.5
	Shear	3	3	2
10 µm to <40 µm	Tension/ Compression	3	3	2
	Shear	3	4.5	2.5
40 µm to <160 µm	Tension/ Compression	3	4	3
	Shear	3	6.5	3.5

***VDI 2230 Part 1 – Table 5*

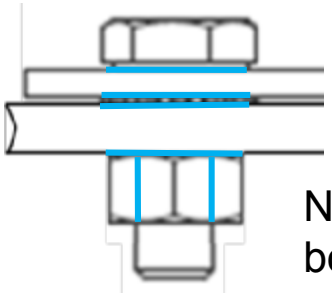


Analytical Model of Preload Relaxation

Guide Values for fz

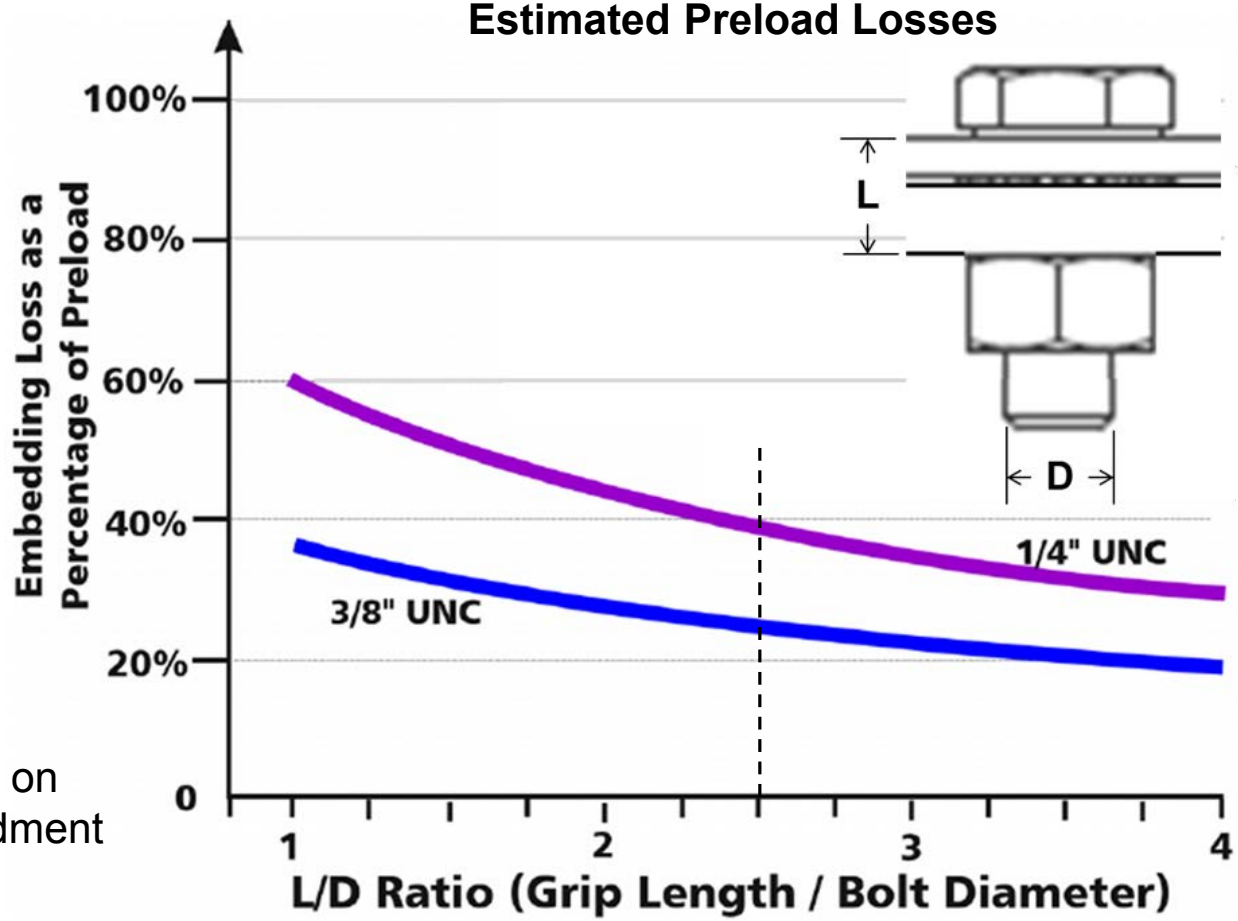
Average Roughness Height Rz (per DIN 4768)	Main Type of Applied Loading Acting	Guide Values for the Amount of Embedding (in µm)		
		In the thread	Head/nut bearing surface	Interfaces within the joint
<10 µm	Tension/ Compression	3	2.5	1.5
	Shear	3	3	2
10 µm to <40 µm	Tension/ Compression	3	3	2
	Shear	3	4.5	2.5
40 µm to <160 µm	Tension/ Compression	3	4	3
	Shear	3	6.5	3.5

***VDI 2230 Part 1 – Table 5*



No guidance available on bonding device embedment

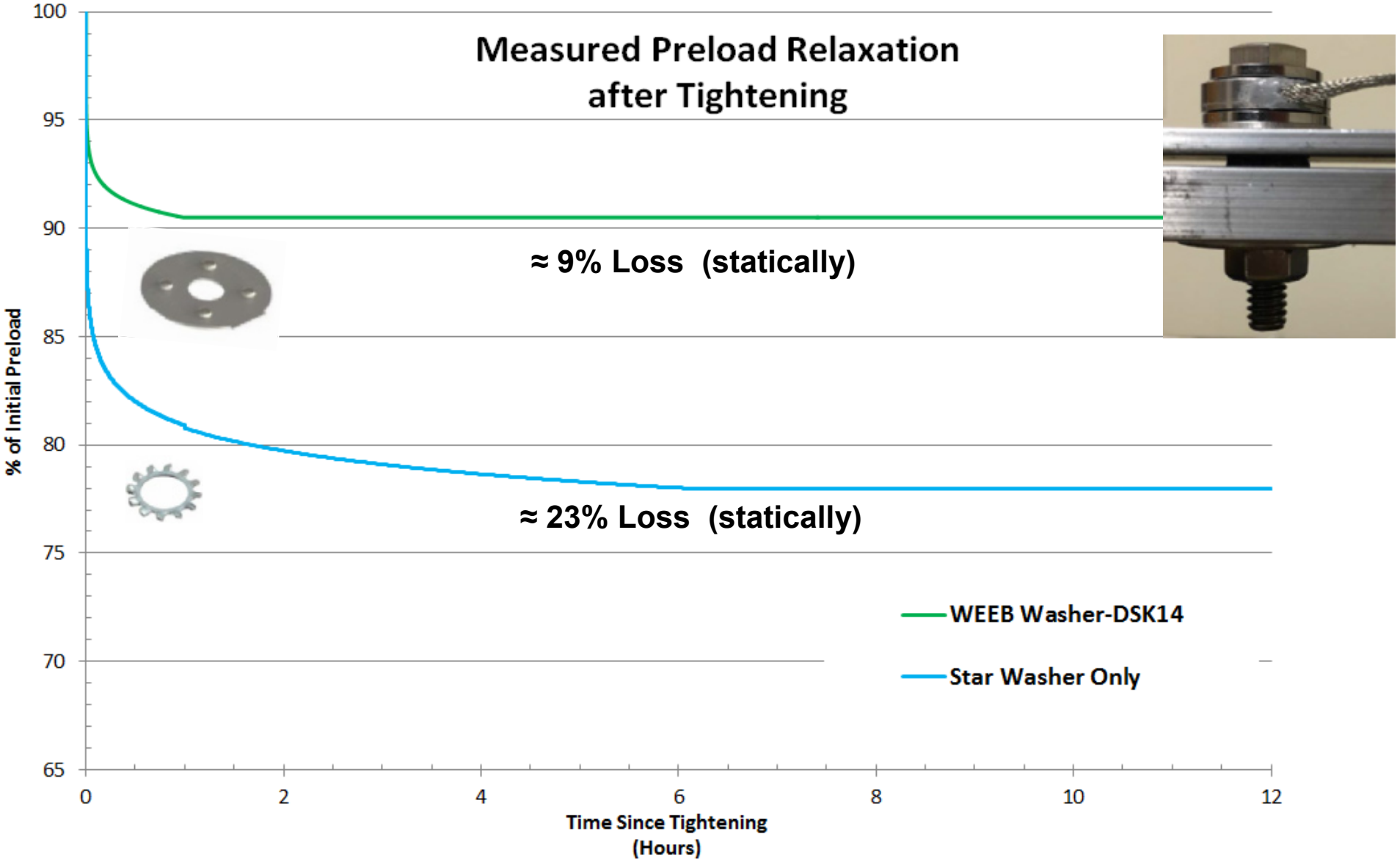
Estimated Preload Losses



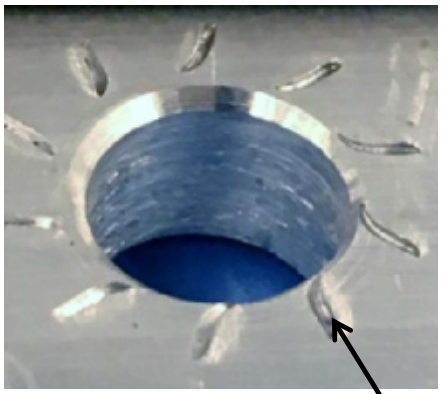
courtesy of Bolt Science

$$f_Z = estimated\ total\ embedment$$
$$= 3+3.5+3.5+3+3 = 16\ \mu m$$

Ongoing - Experimental Work

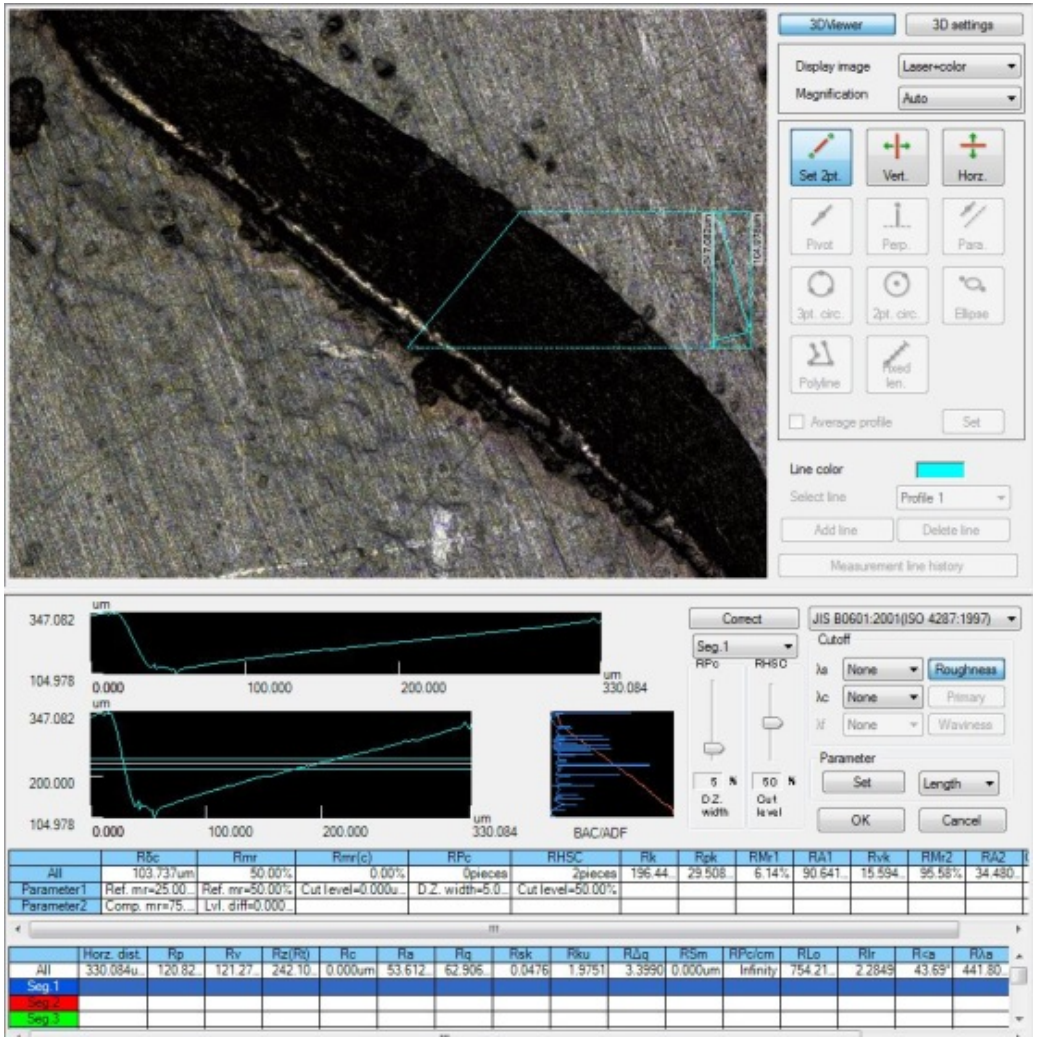


Ongoing - Experimental Work



Piercing Action

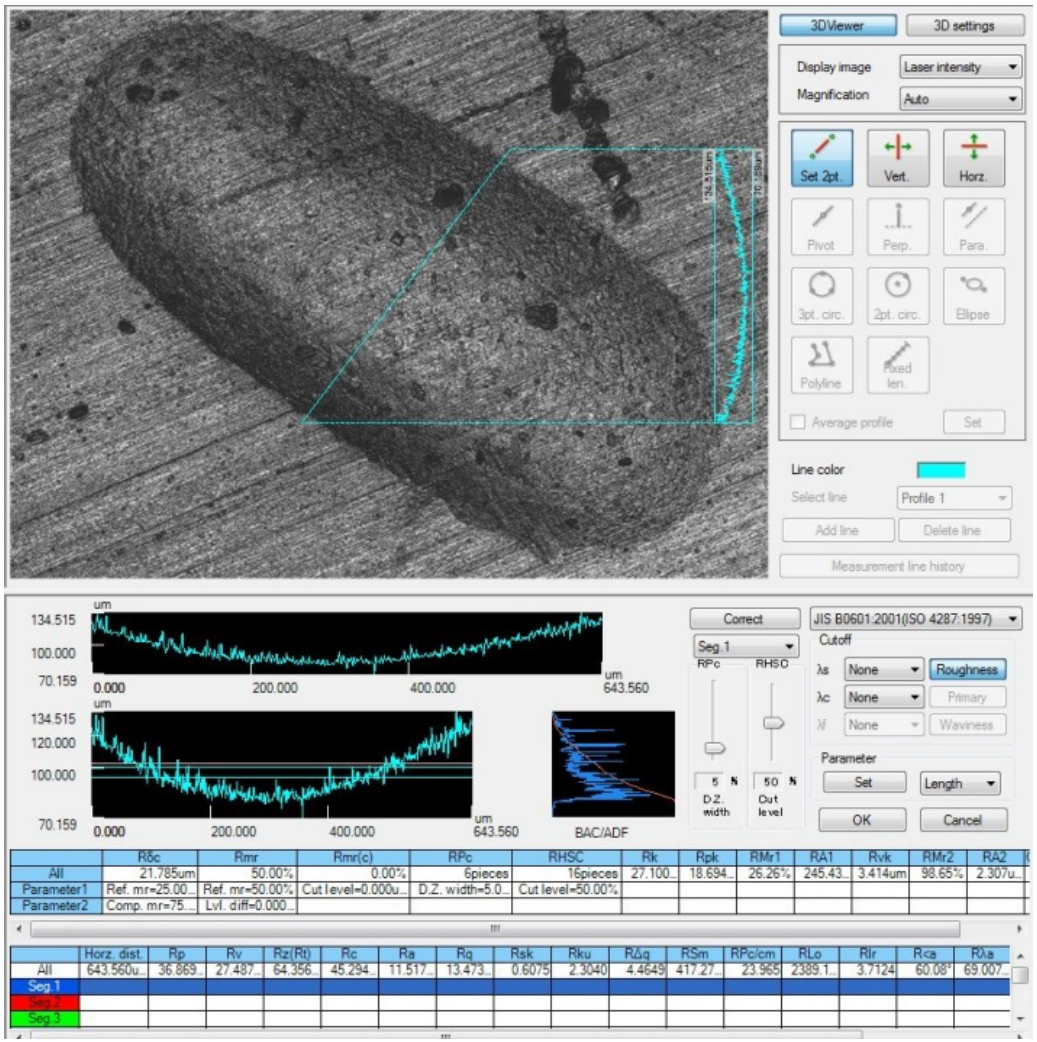
150µm of plastic deformation



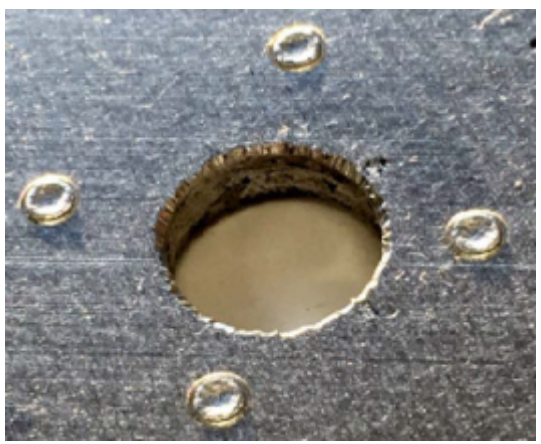
Ongoing - Experimental Work

70µm of plastic deformation

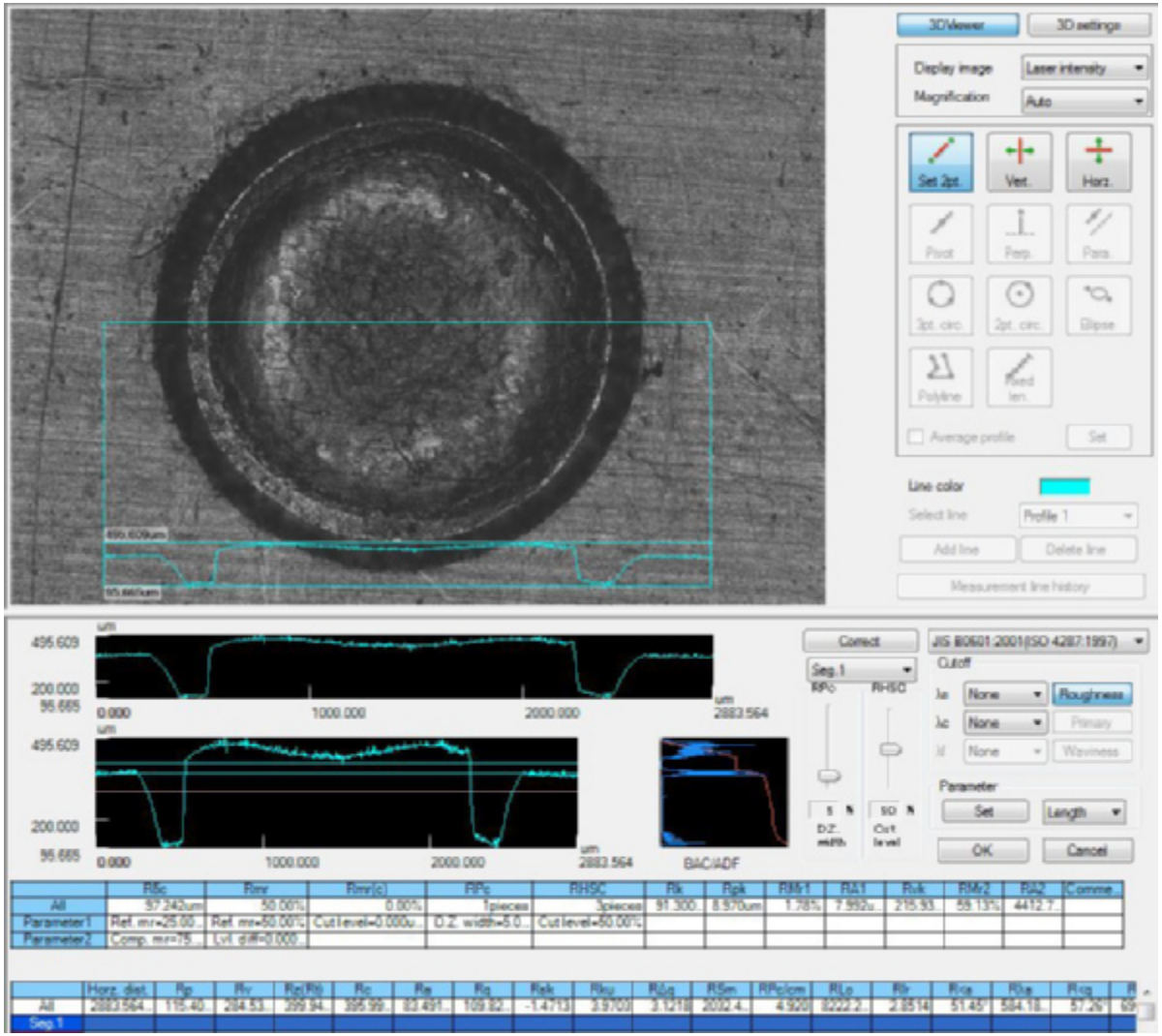
"Brinelling" Action



Ongoing - Experimental Work



200µm of plastic deformation



Additional Research Needed

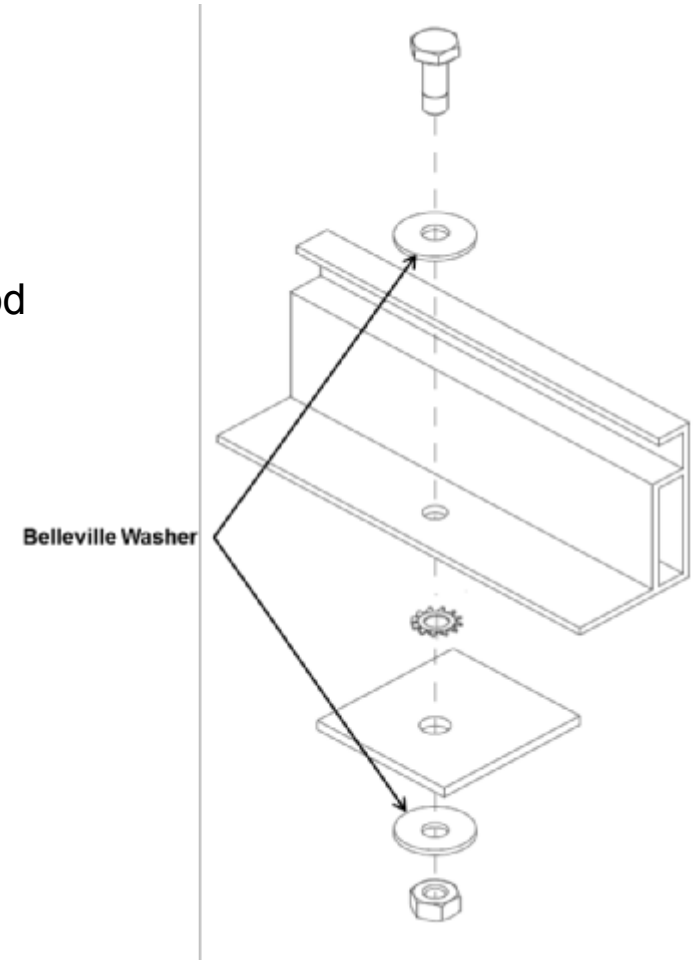
Unfortunately, very little research has been published related to the relaxation of racking bolted joints due to bonding devices in the joint interfaces of PV racking systems.

- Comparison of preload relaxation in commercially available bonding devices.
- Effect of bolt and joint stiffness on preload relaxation.
- Number of joint interfaces
- Material properties of joint and bonding device(s)
- Initial fastener preload level
- Effects of dynamically applied joint loading (both axial and transverse)

Generalized Best Design and Assembly Practices

- Retightening of the PV racking fasteners one or more times is generally required to reduce preload loss due to embedment relaxation if not specifically addressed in the design process.

- **Best Design Practices to Reduce Preload Relaxation**
  - Piercing type bonding devices cause less preload relaxation
  - “Low-cost” star washers cause significantly higher preload relaxation.
    - Saving money on the bonding device may not be a good choice!
  - Reduce the number of embedding surfaces in the joint.
  - Reduce the bolt stiffness, specifically
    - Increase the bolt L/D ratio to reduce the bolt stiffness.
    - Add belleville washer(s) to hardware stack
      - Out of the scope of this discussion.



Thank you!

- Dr Bill Eccles, Bolt Science, LTD
- Dr Todd Letcher, South Dakota State University

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PVQAT Task Group 3 Humidity, Temperature, and Voltage

Peter Hacke

PVRW 2019

Charter

Study of the degradation modes and acceleration factors related to:

- Charge/ion transport
- Ingress of moisture
- Electrical bias
- Climatic specificity
- Module technology factors

Development or publication of several standards for evaluation of potential-induced degradation (PID) and moisture ingress

IEC TS 62804-1 Photovoltaic (PV) modules – **Test methods for the detection of potential-induced degradation – Part 1: Crystalline silicon** Edition 1.0 2015-08, published

62804-1-1 Photovoltaic (PV) modules – **Test methods for the detection of potential-induced degradation – Part 1-1: Crystalline silicon delamination**: in Draft Technical Specification phase

IEC 62804-2 Photovoltaic (PV) modules – **Test methods for the detection of potential-induced degradation – Part 2: Thin film** [and for modules with cells requiring moisture-barrier packaging], to second Committee Draft

IEC 62788-5-1 Measurement procedures for materials used in photovoltaic modules – Part 5-1: Edge seals – **Suggested test methods for use with edge seal materials**, to Final Draft phase

IEC 62788-6-2 Measurement procedures for materials used in photovoltaic modules – Part 6-2: General tests – **Moisture permeation testing with polymeric materials**, to Final Draft phase

IEC 62788-5-2 Measurement procedures for materials used in photovoltaic modules – Part 5-2: Edge seals – **Edge-seal durability evaluation guideline**, to second Committee Draft.

Focus 2019
(member discussion results)

Topic
Evaluating component testing vs. full size testing, in coordination with TG 5
Outdoor accelerated testing and amplification of levels (T, RH, Vsys, UV)
Develop sequential and combined-accelerated stress testing, evolve existing tool sets, model cost/benefits
Develop combined-accelerated stress testing, mode agnostic, study new modes with factors of UV light, TC, damp and dry environments, module size, and test combinations, Develop an IEC 61215/61730 alternative
Build robustness around test protocols with interlaboratory studies
Evaluate new module technologies' (bifacial, thin cells, PERC) potential problems
Evaluate acceleration factors: chamber/field
Extended & high temperature testing: evaluate false positives & negatives

IEC Technical reports in progress

IEC TR: Combined and Sequential Accelerated Stress Testing for Derisking Photovoltaic Modules

Review of key milestones in the history of combi and sequential testing

IEC TR: Acceptable volume of investment for Combined Stress Testing

Cost analysis for testing

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PVQAT TG 11 System Verification and Power Electronics Testing: Task Group 11 - subgroup on power electronics

Peter Hacke

Charter

The International Photovoltaic Quality Assurance Task Force's system verification work aims to develop a comprehensive system for certification of PV systems, verifying appropriate design, installation, and operation methods.

PVQAT Task Group 11 subgroup on power electronics: participants have disucssed areas of interest from which the scope of PVQAT TG 11 – subgroup on power electronics is defined

Key outstanding item

IEC 62093 Ed.2

PHOTOVOLTAIC SYSTEM POWER CONVERSION EQUIPMENT

–

DESIGN QUALIFICATION TESTING

Topics

Bold=more emphasis

- **Development and validation of analytical models and tools. For example, thermal, electrical, humidity, and combined models. The idea is to answer what the useful ttest methods are: how to handle derating**
- **Elucidating failure mechanisms at the materials science level**
- Cataloging results from field to understand the stresses under which devices fail
- **Design appropriate tests for specific failure mechanisms seen in the field.**
- **Compare and contrast test protocols in existence. (e.g., IEC, MIL, TUV-Rheinland 2PfG standards, Sunspec 4C, emerging ANSI standards, materials durability, insulation, communication protocols, etc) and merge their best properties.**
- Collect data and information from related products that can clarify the durability of PV electronics products.
- Develop pointers for designing for reliability, including elucidating what is known about the most important failure modes.

Topics

Bold=more emphasis

- **Determine how to test components (boards, subsystems), and conditions for certification of that board within various larger systems. – like for qual testing**
- Determine the potential wear out mechanisms; i.e., what is limiting the warranty term, and elucidate areas for improvement to extend life.
- Development of quality assurance programs, including collection of data to elucidate failure points in the production, delivery, installation, and O&M; and identify areas for continuous improvement in the value chains for devices. →IEC TS 63157 ED1 "Guidelines for effective quality assurance of power conversion equipment for photovoltaic systems"

Next steps -

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Thank you

www.nrel.gov

Publication Number

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PVRW 2019

Standardization of non-uniform wind-load test method on PV module in PVQAT TG7

Shu-Tsung (Anderson) Hsu

CMS, ITRI

2019 02 27

Agenda

1. *Non-uniform wind-loads test*
2. *PVQAT TG7 (wind load) status*
3. *Summary*

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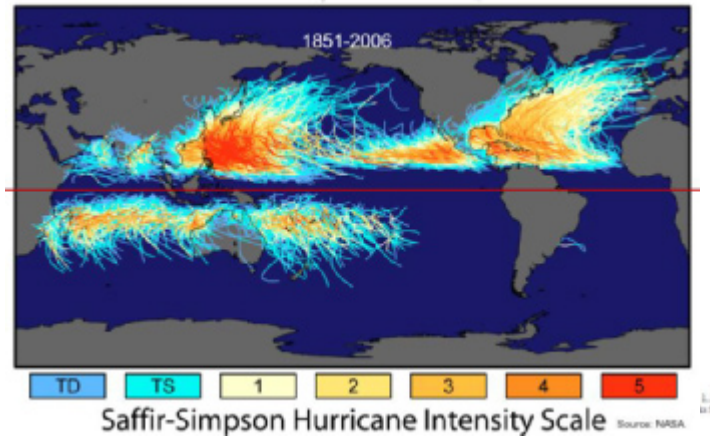
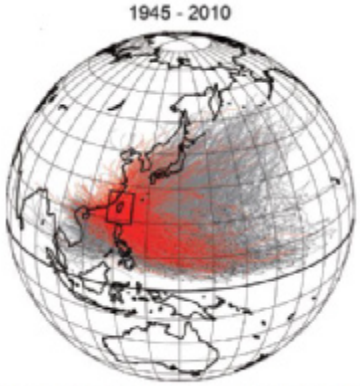
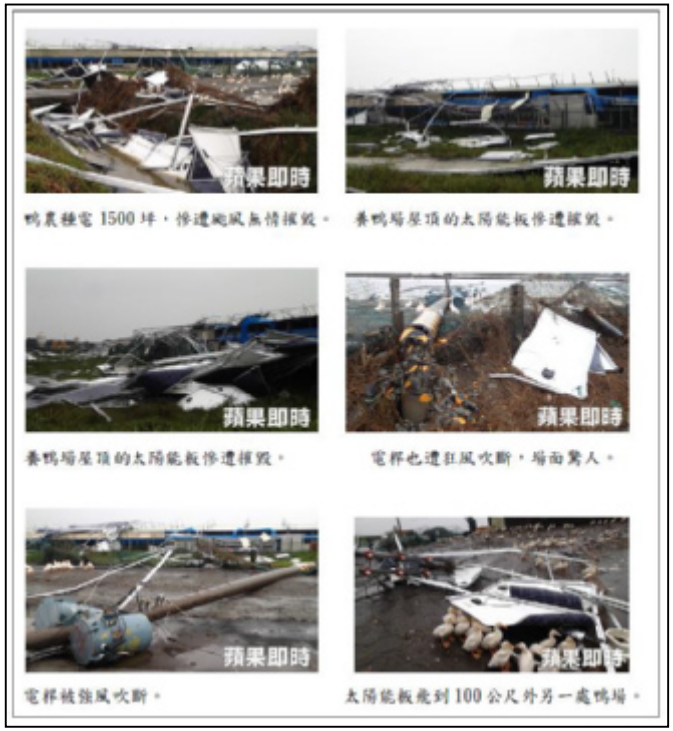
Typhoons damaged PV system





1. JTWC typhoon tracks in the western North Pacific for 1945 - 2010. The gray lines indicate the typhoon tracks and the red lines indicate the is for typhoons which moved through the study area (19 - 28°N, 113-125°E, shown in the box).



鴨農種電 1500 坪，慘遭颱風無情摧毀。
養鴨場屋頂的太陽能板慘遭摧毀。
養鴨場屋頂的太陽能板慘遭摧毀。
電桿也遭狂風吹斷，場面驚人。
電桿被強風吹斷。
太陽能板飛到 100 公尺外另一處鴨場。

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Beaufort scale (BS) – wind levels

Beaufort scale (BS)	Description	Wind speed V (m/s)
0	Calm	< 0.3
1	Light air	0.3-1.5
2	Light breeze	1.6-3.3
3	Gentle breeze	3.4-5.4
4	Moderate breeze	5.5-7.9
5	Fresh breeze	8.0-10.7
6	Strong breeze	10.8-13.8
7	Near gale	13.9-17.1
8	*Gale	17.2~20.7
9	*Strong gale	20.8~24.4
10	*Storm	24.5~28.4
11	*Violent storm	28.5~32.6
12	*Hurricane (*Typhoon)	32.7~36.9
13		37.0~41.4
14		41.5~46.1
15		46.2~50.9
16		51.0~56.0
17		56.1~61.2
>17		>61.2

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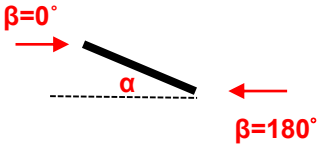
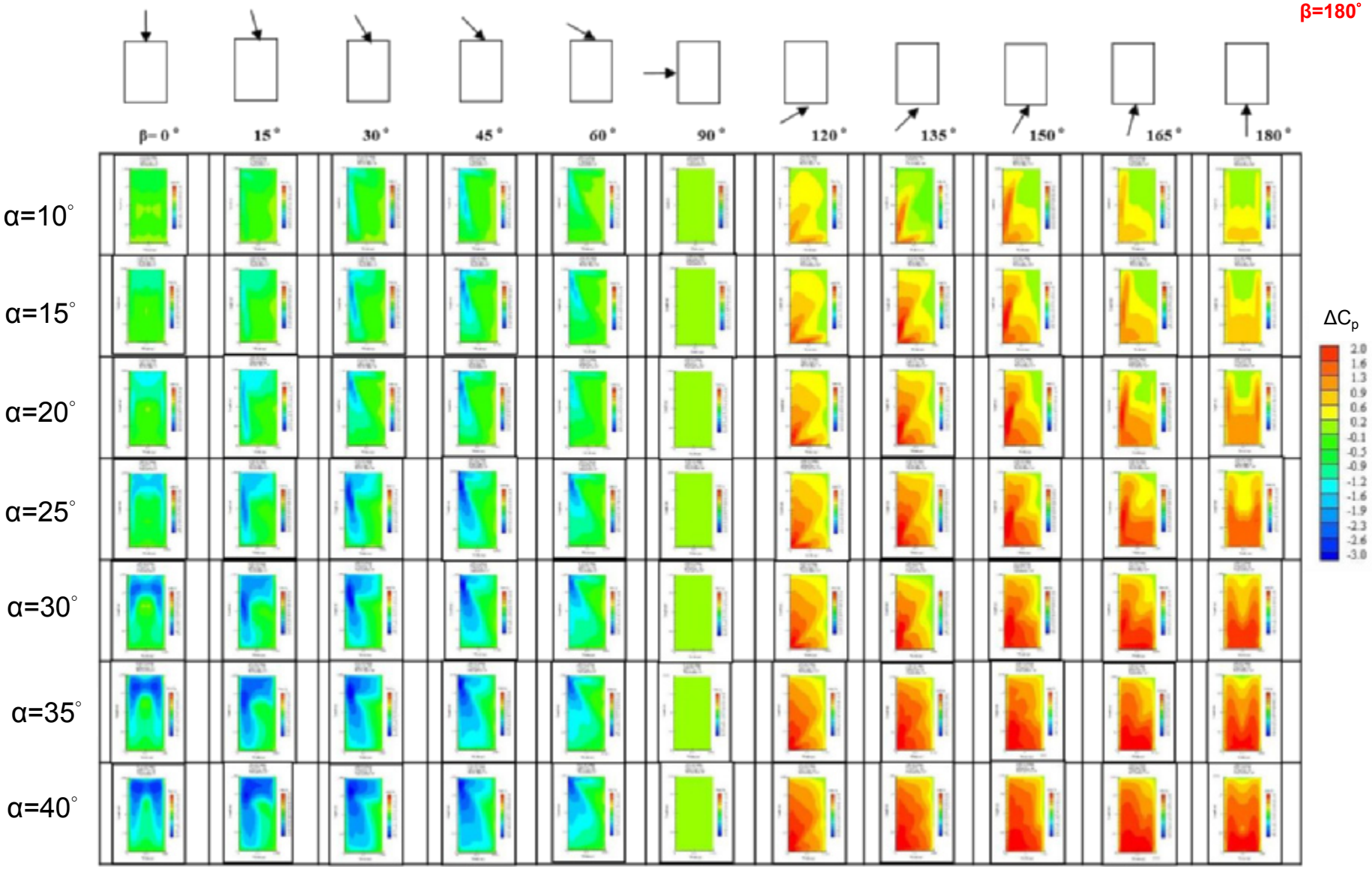
Non-uniform ΔC_p@(V=20m/s, α, β)





Suction load ← → **Pressure load**

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Test protocol

Non-uniform wind-load simulated by ΔC_p or MSPP

Get ΔCp from wind tunnel test or CFD

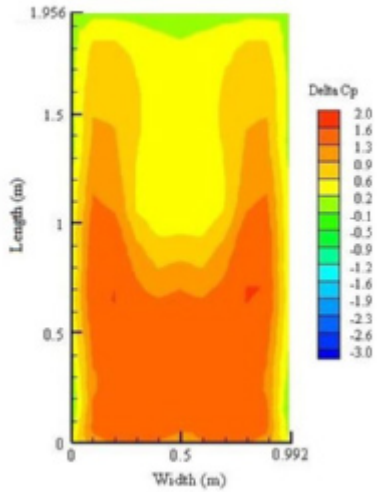
x SF

Mean surface pressure pattern

MSPP (V_a, P_a) → **MSPP (V_b, P_b)**

Run non-uniform wind load test by ML system

ΔC_p, V_a



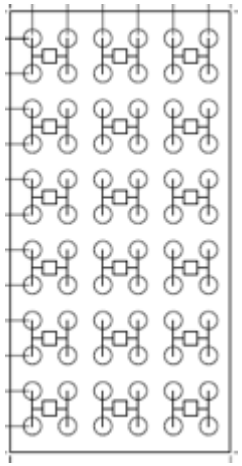
Δp_a, V_a

P3	P2	P1
P6	P5	P4
P9	P8	P7
P12	P11	P10
P15	P14	P13
P18	P17	P16

Δp_b, V_b

P3	P2	P1
P6	P5	P4
P9	P8	P7
P12	P11	P10
P15	P14	P13
P18	P17	P16

ML system



Pneumatic cylinder

Flow similarity
Independent Reynolds number

$$C_p = (p_a - p_\infty) / (0.5\rho V_a^2) = (p_b - p_\infty) / (0.5\rho V_b^2)$$

$$\Delta C_p = C_{p\,upper} - C_{p\,lower}$$

$$\Delta p_b = p_{b\,upper} - p_{b\,lower} = \Delta C_p (0.5\rho V_b^2)$$

Un-even wind-loads distribution on PV module rely on wind velocity (V), module tilt (α) and wind direction angle (β)

Non-uniform dynamic mechanical loads (NUDML) system with eighteen pneumatic cylinder

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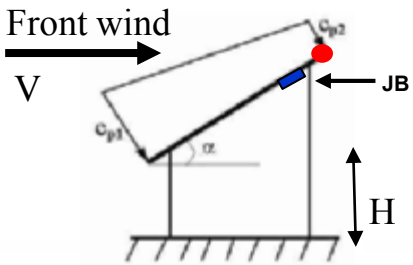
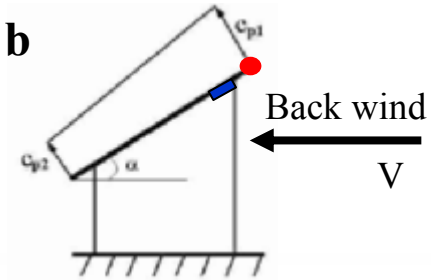
Case study of MSPP@(p_1 – p_{18})

(V_b= 61.2 m/s, α , β)

a



b



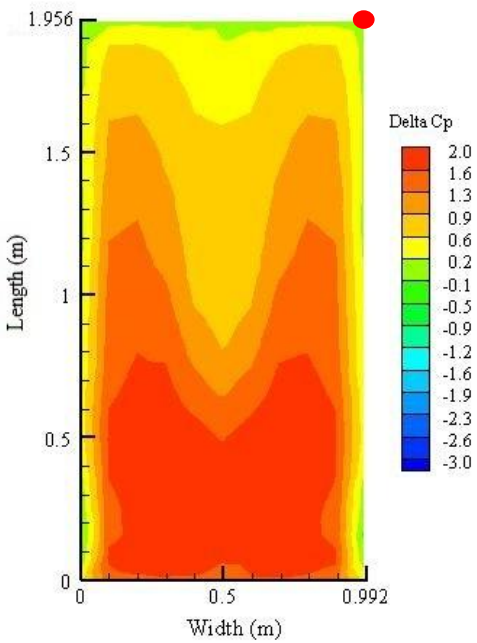
e Unit: Pa

3192	2514	3192
5449	4495	5449
6783	5208	6783
8312	7626	8312
9289	11450	9289
8316	11146	8316

MSPP@(p_1 – p_{18})
(V_b = 61.2 m/s, α = 30˚, β= 180˚)

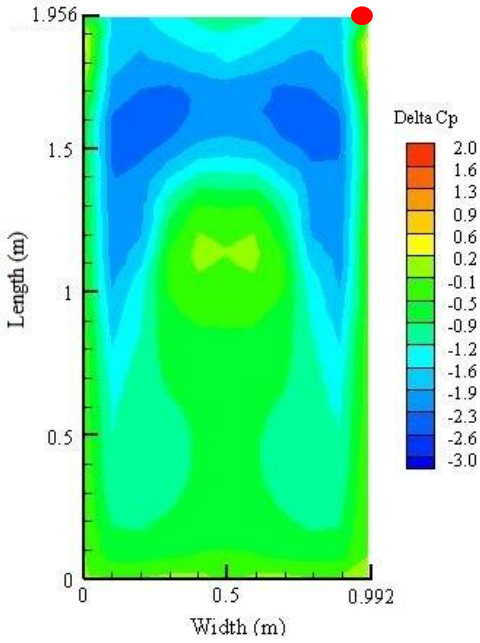
Safety factor = 3

c



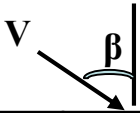
ΔC_p
(V_a = 20 m/s, α = 30˚, β= 180˚)

d



ΔC_p
(V_a = 20 m/s, α = 30˚, β= 0˚)

f



Unit: Pa

-9710	-11165	-9710
-11091	-8413	-11091
-7511	-1234	-7511
-5953	-4075	-5953
-5622	-5227	-5622
-3220	-3134	-3220

MSPP@(p_1 – p_{18})
(V_b = 61.2 m/s, α = 30˚, β= 0˚)

Safety factor = 3

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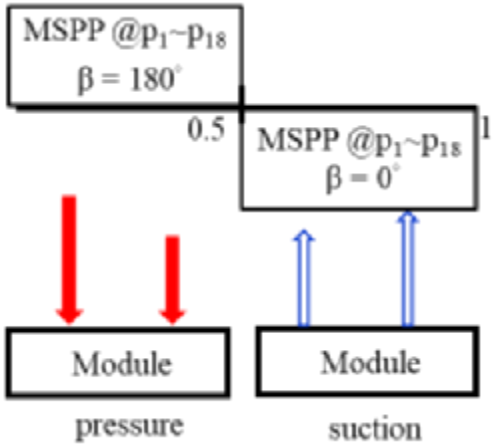
Cyclic test

- Cyclic test
  - Cycle rate
  - Test time
  - Customer's installation menu or rigid mounting type for test sample

- MSPP (or non-uniform loads) instead of uniform loads
  - Choose the environmental factors (V, α, β)
  - Refer wind tunnel/ CFD simulation data: ΔC_p
  - Get (MSPP @p_1~p_{18})



Cyclic test

ITRI data

- MSPP (α =10°- 40°; β = 0°, 180°; V = 61.2 m/s)
  - Pressure cycle: MSPP@ (β = 180°) – front wind
  - Suction cycle: MSPP@ (β = 0°) – back wind

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MSPP@ (p_1~ p_{18})

V_b = 61.2 m/s (BS = 17)

Unit: Pa

α = 10° , β = 0°			α = 10° , β = 180°			α = 30° , β = 0°			α = 30° , β = 180°		
-3464	-4187	-3464	682	283	682	-9710	-11165	-9710	3192	2514	3192
-2751	-3750	-2751	1158	632	1158	-11091	-8413	-11091	5449	4495	5449
-1345	-1484	-1345	1218	1087	1218	-7511	-1234	-7511	6783	5208	6783
-1050	-1101	-1050	1735	2113	1735	-5953	-4075	-5953	8312	7626	8312
-1180	-1334	-1180	2985	3536	2985	-5622	-5227	-5622	9289	11450	9289
-699	-685	-699	2967	3815	2967	-3220	-3134	-3220	8316	11146	8316
α = 15° , β = 0°			α = 15° , β = 180°			α = 35° , β = 0°			α = 35° , β = 180°		
-4671	-6203	-4671	1331	181	1331	-11575	-12943	-11575	3486	1890	3486
-4262	-5213	-4262	2402	732	2402	-11965	-7917	-11965	6178	5594	6178
-2551	-2045	-2551	2787	1684	2787	-8647	-3237	-8647	7508	6866	7508
-2400	-1298	-2400	3320	3739	3320	-7170	-5801	-7170	8690	8381	8690
-1968	-2143	-1968	4325	5215	4325	-6498	-5911	-6498	9725	11729	9725
-1320	-1859	-1320	4249	5363	4249	-3457	-3527	-3457	9398	12517	9398
α = 20° , β = 0°			α = 20° , β = 180°			α = 40° , β = 0°			α = 40° , β = 180°		
-5961	-8391	-5961	1621	774	1621	-12329	-14195	-12329	3950	3131	3950
-5997	-7452	-5997	3701	803	3701	-12229	-9734	-12229	6724	7146	6724
-4787	-2621	-4787	5015	2817	5015	-10078	-6055	-10078	7993	9026	7993
-3760	-1712	-3760	5784	6205	5784	-8317	-6545	-8317	8829	9225	8829
-3280	-3008	-3280	5667	7171	5667	-6905	-6064	-6905	10454	11380	10454
-1837	-1644	-1837	5497	7080	5497	-3736	-3540	-3736	10257	13352	10257
α = 25° , β = 0°			α = 25° , β = 180°								
-8054	-10007	-8054	2607	1479	2607						
-7285	-7838	-7285	4309	2352	4309						
-5269	-4791	-5269	5611	2297	5611						
-4972	-3465	-4972	7802	6655	7802						
-4332	-3514	-4332	7533	9649	7533						
-2436	-2021	-2436	6842	9001	6842						

Reference: S. T. Hsu, *et al*, Environmental Factors for Non-uniform Dynamic Mechanical Load Test due to Wind Actions on Photovoltaic Module, *Energy Procedia* (2018)

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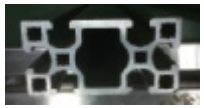
Cyclic test, EL, IV

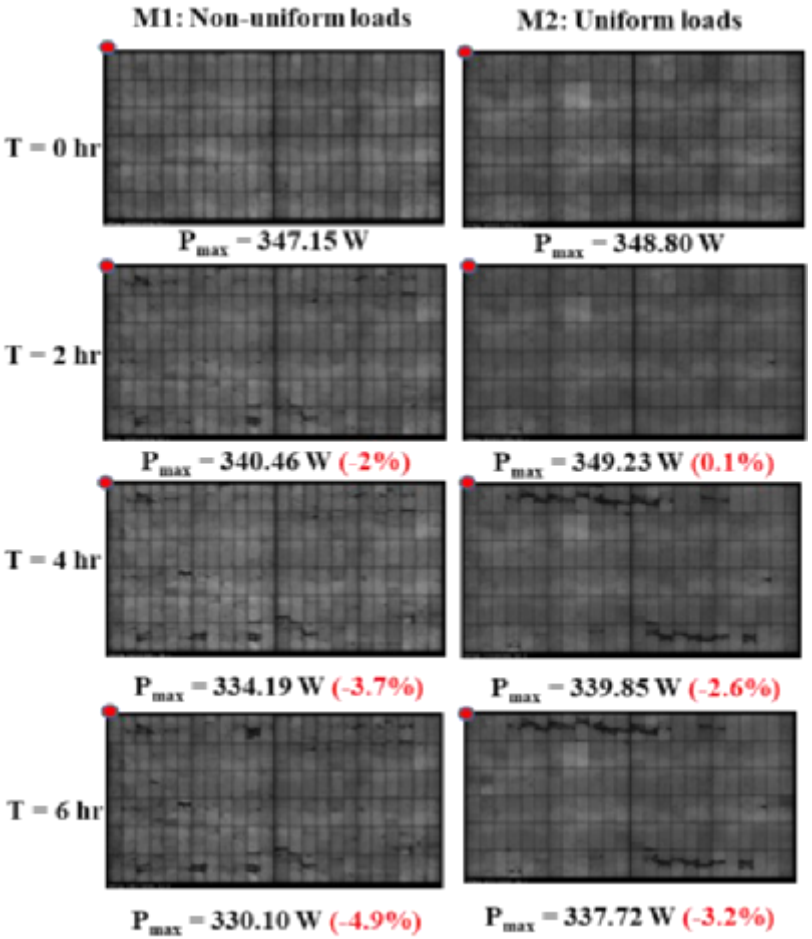
Cyclic test

1. Test module: 2 (M1 , M2)
2. Pre/ Post-test: EL, I-V
3. DML test
   - 7 cyes / min
   - Test time: 6 Hr
   - Pressure force
     - M1:MSPP1 (V = 61.2 m/s, α = 30°, β=180°)
     - M2: 6665 Pa = AVE (MSPP1)
   - Suction force
     - M1:MSPP2 (V = 61.2 m/s, α = 30°, β=0°)
     - M2: -6637 Pa = AVE(MSPP2)



NUDML (ITRI)

EL & IV



Post-pre	ΔI_{sc}	ΔV_{oc}	ΔP_{max}	ΔFF	ΔR_s	ΔR_{sh}
M2	-0.4	-0.1	-3.2	-2.8	7.0	-41.1
M1	-1.7	-0.2	-4.9	-3.1	8.9	-63.7

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Summary

- **Challenge of strong wind**
  - Wind direction angle (0~ 360°)
  - Wind loads distribution (un-even, moment effect)
- **IEC Standards** (IEC 61215-2, IEC TS 62782) still lack of detailed documents for non-uniform loading
- Severity test and localized environmental factors
  - Wind velocity (V) & module tilt (α) & wind directional angle (β)
  - **MSPP(V, α, β)@(p_1~p_{18})**
- **Non-Uniform Dynamic Mechanical Loads (NUDML) System**
  - Module
  - Fixed parts : aluminum extrusion structure, bracket, clamp, fixture (including screws)
- On-going **correlation**, **field data**, **standardization** and **compromise**
  - Wind tunnel experiment / CFD simulation / on-site demonstration

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PVQAT TG7 (wind load) status

kick-off in March 2018 (PVRW)

ITRI, King Design, ZAE Bayern, SunPower, SUNSET/ TC82, UL, Constellation, Matrix Engineering, NREL, First Solar, Purdue University-Northwest, Lawrence Berkeley National Lab, CanadianSolar, Trinasolar, Yingli Solar, SUNGROW, AIST, Mitsui Chemicals, JET, Toshiba, TTI/ TC82 WG7, KTL, SIMIT, Arctech Solar ……

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PVQAT TG7 Team List

34 attendances /24 companies

	Company	Name
Taiwan	**ITRI**	Anderson Hsu (許書宗) (Dr.)
	King Design	David Lee
		Richard Lin (Dr.)
Germany	**ZAE Bayern**	Claudia Buerhop
USA	**SunPower**	Katherine (Kat) Han
		John Lippiatt
	SUNSET	George J. Kelly, IEC TC82 Secretary
	UL	Liang Ji
	Constellation	Robert Flottemesch
	Matrix Engineering	Jon Ness
	NREL	Donald (Don) Jenket
		Ingrid Repins (Dr.)
		Sarah Kurtz (Dr.)
	First Solar	Sumanth V Lokanath
	Purdue University-Northwest	Hansung Kim (Dr.)
	Lawrence Berkeley National Lab	Gerald Robinson (Dr.)
China	**CanadianSolar**	Yuanjie Yu (尉元杰)
	Trinasolar	Yunhua Shu (束云华)
	Yingli Solar	Eric Liu (刘克铭)
	SUNGROW	Weiwu Wu (吳維武) (Dr.)
	SIMIT	Zhengxin Liu (刘正新),TC82 Vice-Chair
		Bing Gao (高兵)
		Qiang Shi (时强)
		Yahui Shao (邵亚辉)
		Tong Wu (吴彤)
	Arctech Solar	Bruce Wang (王士涛), TC82 WG7 co-convener

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PVQAT TG7 Team List

34 attendances /24 companies

	Company	Name
Japan	**AIST**	Tadanori Tanahashi (Dr.)
		Keiichiro Sakurai
	Mitsui Chemicals	Tsuyoshi Shioda (Dr.)
	JET	Hirofumi Shinohara
	Toshiba	Kei Matsuoka
		Tomohiko Jimbo
	TTI	Kenji Araki, **TC82 WG7**
South Korea	**KTL**	Pilkyu Kim (Dr.)

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Web-meeting and attendees (2018)

Once every two months

Company \ date	4/26 (10P)	6/28 (9P)	8/23 (10P)	10/25(8P)	12/20 (12P)
ITRI	1	1	1	1	1
King Design				2	1
ZAE Bayern				1	1
SunPower	1				
SUNSET/TC 82	1	1	1		1
UL		1			
Constellation	1	1	1		1
Matrix Engineering					1
NREL	1	1	1	1	1
First Solar			1		
Purdue University			1		
CanadianSolar	1	1	1	1	1
Trinasolar	1				
Yingli Solar	1			1	
AIST	2	1	2	1	1
Mitsui Chemicals		1			
KTL		1	1		
JET					1
Toshiba					2

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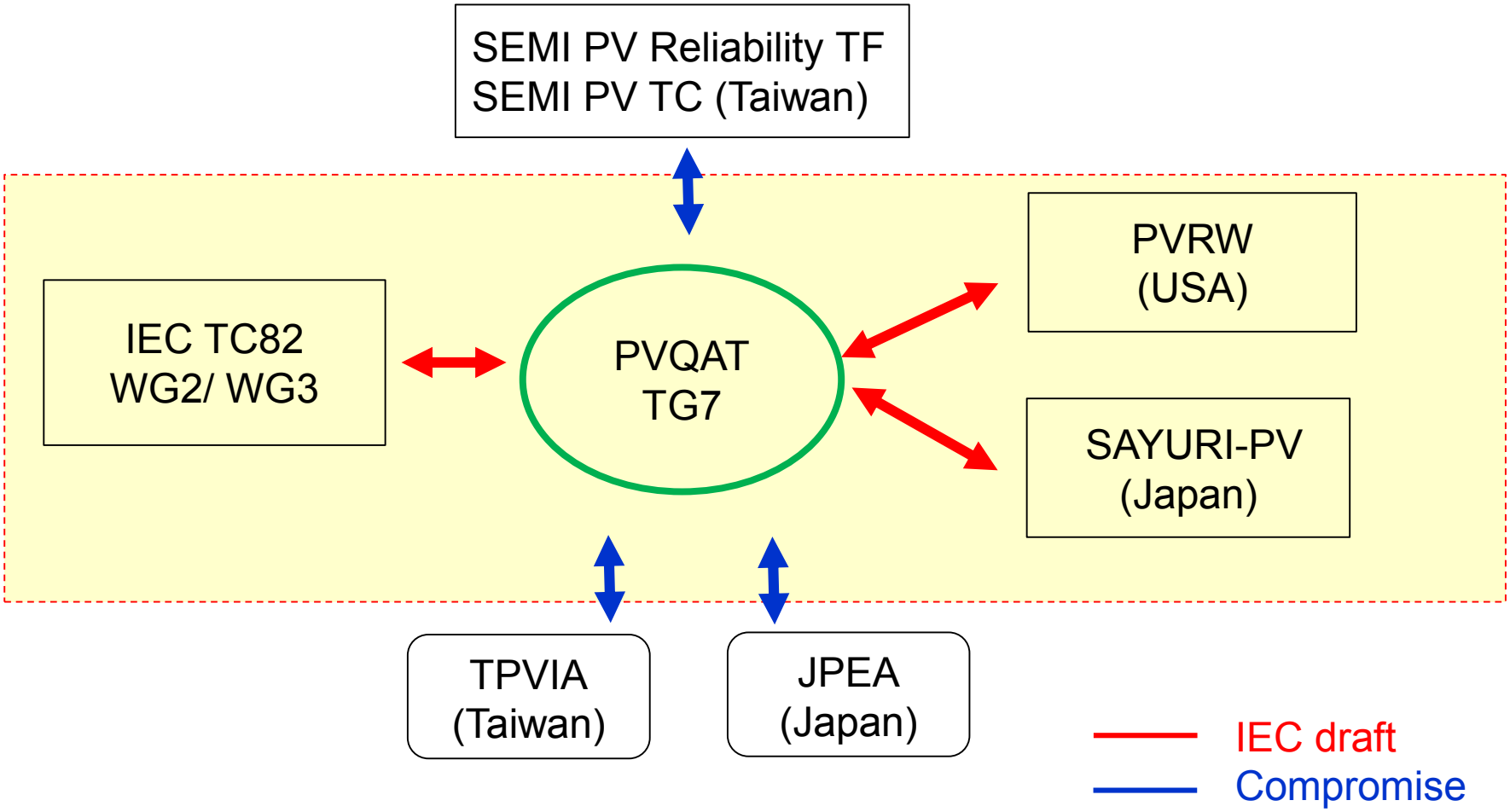
Diversity collaboration globally



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TG7 web-meetings and activities (2018)

	Meeting or conference	Date	Presentation Topics
1	PVRW-Denver	2/28	Severity Test for Non-uniform Wind Loads on Photovoltaic Module (ITRI)
2	IEC TC82 WG2-Wilmington	4/15	PVQAT TG7 introduction (ITRI)
3	**TG7(1)**	4/26	1. kick-off TG7 in PVRW-2018 (ITRI) 2. TG7 scope and goal (ITRI)
4	**TG7(2)**	6/28	1. building code review (CanadianSolar) 2. Japan's anti-wind standards review (AIST)
5	**TG7(3)**	8/23	1. Test module and test data or protocol review (ITRI) 2. Safety factors selection (CanadianSolar) 3. Analysis of snail track modules and mechanical stability of PV system (KTL)
6	IEC TC82 WG3/WG2 Busan	10/15 10/17	PVQAT TG7 - The work of standardization of non-uniform wind-load test method on PV module (ITRI)
7	**TG7(4)**	10/25	1. Site-specific test procedure for uniform wind loads for moderate European climate (ZAE) 2. The refinement of wind load test (King Design) 3. Summary the feedback from WG2 meeting held at Busan Korea (ITRI)
8	SAYURI-PV Tsukuba	10/31	1. Non-uniform Wind-Load Test for PV Module (ITRI) 2. Standardization of non-uniform wind-load test method on PV module by PVQAT Task Group 7 in 2018 (ITRI)
9	**TG7(5)**	12/20	1. Reliability pre-study for non-uniform wind load test results on PV module (AIST) 2. A dynamic PV array wind load analysis and wind tunnel measurement perspect (Toshiba) 3. Outline of NWIP (ITRI)

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Evaluation for non-uniform wind load test on PV module (*on-going*)

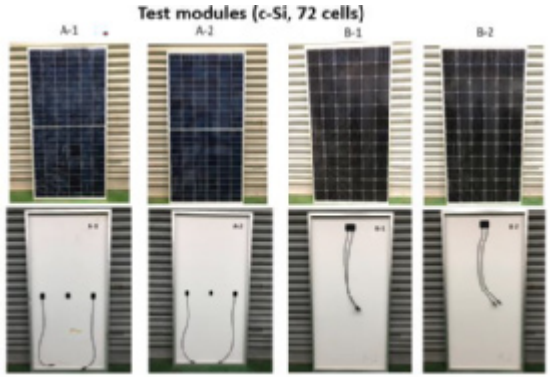
ITRI

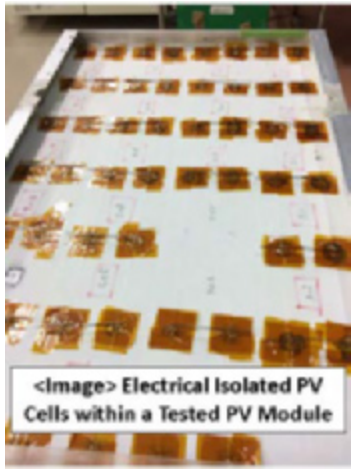
1. 2 types of test PV modules
2. Pre-test: EL, I-V
3. DML test (worst case)
   - 7-10 cyes / min
   - Test time: 2-6 Hr
   - Pressure force
     - M_1: MSPP (V = 61.2 m/s, α , β=180°)
     - M_2: uniform loads
   - Suction force
     - M_1: MSPP (V = 61.2 m/s, α , β=0°)
     - M_2: uniform loads
4. Post-test: EL, I-V

AIST

In electrical isolated PV cells within a tested PV module

1. To analyze the I-V / EL characteristics of individual PV cells
2. Extent of degradation / distribution of degradation-levels (Contour Chart)
3. To analyze the AC impedance characteristics of individual PV cells
4. To find the behavior of solder bond failure in the individual PV cells





Targets in TG7

1	2	3	4	5	6
Test module	**Test capacity**	**Test protocol**	**Test flow**	**Criteria**	**Test report**
Module x2 - reference - experiment	1.NUDML system 2. IV (solar simulator) 3. EL	1.Environmental factors or severity test 2. un-even wind-loads -MEWL (refer NBE-AE/88) -MSPP (refer wind-tunnel or CFD data) 3.Safety factor	1.Pre-test -IV -EL 2.NUWL test -DML -cycle rate -test cycles -Cyclic loads - pressure - suction 3.Post-test -IV -EL	1.Power loss - 5% loss 2.Visual defects -module -branket -clamp -screw	1.installation type 2. Pre-test - IV/EL 3. NUWL test 4. Post-test -IV/EL

Mean Extended Wind Load (MEWL);
Mean Surface Pressure Pattern (MSPP);
Non-Uniform Dynamic Mechanical Loads (NUDML)
New Work Item Proposal (NWIP):
- Photovoltaic (PV) Module – Cyclic (Dynamic) Non-uniform Wind Load Testing

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NWIP status

- NWIP(1): **Photovoltaic (PV) Module – Cyclic (Dynamic) Non-uniform Wind Load Testing**
  - This international standard provides a test method for evaluating the effects of non-uniform wind loads on PV modules and their mounting structures. The purpose of this test method is to evaluate the performance and safety issues for modules, and fixed parts caused by wind and installation conditions

- Will be discussed more in
  - PVQAT TG7/F2F Joint meeting (PVRW, 2/28)
  - IEC TC82 WG2 meeting (Braunschweig Germany, 4/8-4/12)

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Next TG7 meeting

- **TG7/F2F Joint Meeting (Jefferson Boardroom)**
  - Thu, **Feb 28**, 2019 **6:30 AM - 7:30 AM** MST (The meeting will start at 5:30 AM in San Francisco, 6:30 AM in Denver, 14:30 in Central Europe, 21:30 in China, and 22:30 in Korea and Japan)
  - https://global.gotomeeting.com/join/444026021

- **Discussion target**
  - *Electrical characterization of individual PV cells within a damaged PV module from non-uniform wind load test with high pressure (Tanahashi-san/AIST)*
  - *NWIP status -Photovoltaic (PV) Module – Cyclic (Dynamic) Non-uniform Wind Load Testing (Anderson/ITRI)*
  - *Common Issues in PV Racking System Fasteners (Jon Ness/ Matrix Engineering)*

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Non-uniform Wind-Load on Floating Solar Panel under Wind-Wave Environment

*Shu-Tsung Hsu (ITRI), Wei-You Lin (ITRI), Kao-Chun Su (NCKU)

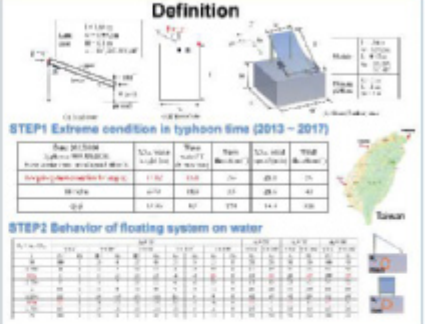
Abstract

Solar power generation has been regarded as an important indicator of global renewable energy policy. Currently, some Asia countries are actively promoting floating solar systems on water, but solar systems are often damaged by strong wind like typhoon. Generally the land based solar system are subjected to non-uniform wind pressure due to the environmental factors such as wind speed (V), wind direction angle (β) and module tilt (α). Similarly, the floating solar system on water need to withstand high winds and waves together, the additional factors are wave direction angle (γ) and wave period (T). This work study the wind-wave effect for floating solar panels on water. Firstly, review the hydrological data of three offshore observatories (Longdong, Hsinchu and Qeqi) in Taiwan, and analysis the extreme condition (wave height, wave period) in the typhoon time. Secondly, analyze the floating PV system upon behavior on water, and define the extreme condition of tilt angle during the wave period (T). Finally, do CFD simulation to get wind-pressure coefficient (C_p) distribution on the floating solar panel under the above extreme conditions. Results have delivered a fully database of non-uniform wind pressure distribution on solar panel under wind-wave environment, and meet the requirements of wind load testing. In addition, some worst conditions occur when the wind and wave are in the same direction, lead to the solar panel is subjected to a more higher and concentrated loading near panel's leading or trailing edge. Whether it is a front wind (β = 180°) or a back wind (β = 0°), the wind resistance increases as the tilt (α) angle increases.

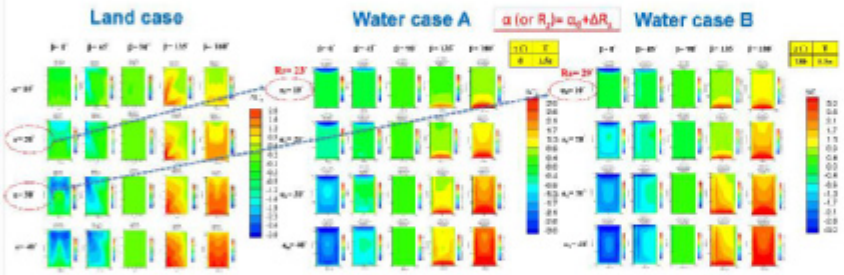
Typhoon Damaged PV System

Beaufort number (BN)	Description	Wind speed V (m/s)
0	Calm	<0.3
1	Light air	0.3-1.5
2	Light breeze	1.6-3.3
3	Gentle breeze	3.4-5.4
4	Moderate breeze	5.5-7.9
5	Fresh breeze	8.0-10.7
6	Strong breeze	10.8-13.8
7	Near gale	13.9-17.1
8	*Gale	17.2-20.7
9	*Strong gale	20.8-24.4
10	*Storm	24.5-28.4
11	*Violent storm	28.5-32.6
12	*Hurricane (*Typhoon)	32.7-36.9
13		37.0-41.4
14		41.5-46.1
15		46.2-50.9
16		51.0-56.0
17		56.1-61.2
>17		>61.2

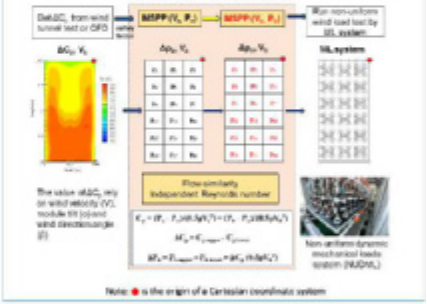
Definition



STEP3 ΔC_p (= $C_{p\ upper}$ - $C_{p\ lower}$) Distribution

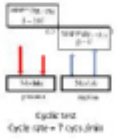


Mean surface pressure pattern (MSPP@p_1~p_{18})



Test samples, Cyclic test, Test data

test sample	module	bracket
Land case	[illegible]	[illegible]
Water case	[illegible]	[illegible]



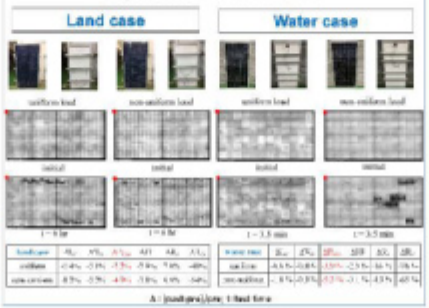
Uniform load (AVE) vs non-uniform load (MSPP)

Land case	AVE		MSPP		AVE		MSPP	
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Water case	AVE		MSPP		AVE		MSPP	
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

"+" means pressure; "-" means suction

Experiment data: EL, IV



landcase	R_x	ΔR_x	$\Delta C_{p,max}$	AVE	ΔR_x	$\Delta C_{p,max}$
uniform	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
non-uniform	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

water case	R_x	ΔR_x	$\Delta C_{p,max}$	AVE	ΔR_x	$\Delta C_{p,max}$
uniform	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
non-uniform	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Δ : (positive)/(one 1-filed time)

Conclusion

1. Land case (V, α, β)
   - Wind flow and wind speed (V) cause PV module to bear uneven pressure. The influence of wind direction angle (β) also change the net pressure coefficient (ΔC_p) distribution of the module surface. Whether it is a front wind (β = 180°) or a back wind (β = 0°), the wind resistance increases as the module tilt (α) increases.
2. Water case (V, α_0, β, γ, T)
   - The installation of the PV system in the land based requires consideration the influence due to wind flow, similarly the floating system on the water need to withstand high winds and waves.
   - The wave angle (γ) and the period (T = 0~3s) can change the pitch angle (R_y). The maximum R_y occurs at (γ = 0°, T = 1.5s) and (γ = 180°, T = 0.5s). The pitch angle also increases as the initial module tilt (α_0) increases.
   - In the case of a change in pitch angle (R_y), the separation flow generated by the wind flowing through the leading edge (or trailing edge) of the module is not immediately generated downstream, so the maximum local wind pressure is generated at the leading edge (or trailing edge).
   - Under the similar condition of module tilt (α_0 or R_x = α_0+ΔR_x), the local maximum wind load (pressure or tension) in the water case is larger than the land case. However, there is no obvious trend in the overall average load comparison.
3. Summary
   - Analysis of environmental factors (V, α, β, γ, T) or special conditions (γ = 0°, 180°; β = 0°, 180°), and derivation the severity test data such as MSPP, can provide NUDML system to simulate non-uniform wind load on PV module, and meet the scenarios for land or water cases.
   - Research work and results will continue to be discussed and compromised by PVQAT TG7 and IEC TC82 WG7, and help to draft the non-uniform wind load testing standards.

1. Shu-Tsung Hsu, Wei-You Lin, Shih-Jyi Wu, Environmental Factors for Non-uniform Dynamic Mechanical Load Test due to Wind Actions on Photovoltaic Module, Energy Procedia (2016) pp. 49-57 DOI information: 10.1016/j.egypro.2016.09.093.
2. Kao-Chun Su, Kung-Ming Chung, Shu-Tsung Hsu, Numerical simulation of wind loads on solar panels, Modern Physics Letters B, Vol. 33, Nos. 12 & 13 (2019) 1940008 (5 pages), DOI: 10.1142/S0217984919400082.
3. Shu-Tsung Hsu, Tieng-Chun Wu, Simulated Wind Action on Photovoltaic Module by Non-uniform Dynamic Mechanical Load and Wind Extended Wind Load, Energy Procedia (2017) pp. 99-101, DOI information: 10.1016/j.egypro.2017.09.481
4. Shu-Tsung Hsu, Hung-Sen Wu, Chia Lee, Mean Surface-Pressure Pattern on PV Module for Non-Uniform Dynamical Mechanical Load Test, IPVSEC 27, 2017.

*Contact: andersonhsu@itri.org.tw

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The authors appreciate the CFD support by Dr. K. M. Chung at ASTRC/NCKU in Taiwan
2019 Photovoltaic Reliability Workshop (PVRW), Lakewood, CO, 2/27/2019

Please give me your business card and joint PVQAT TG7 (wind load)

Thank you for your attention!

andersonhsu@itri.org.tw

Photovoltaic Metrology Laboratory, ITRI

PVQAT

International PV Quality Assurance Task Force

Updates on PVQAT TG5 (UV Weathering) & TG12 (Soiling):

"PVQAT TG5: UV Weathering of PV Modules & Materials"

David Miller

PV Reliability Workshop

Denver West Sheraton

February 27, 2019, 7 minutes

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.

Goal and Activities Task Group 5 (UV, T, RH)

- IEC qualification tests (61215-2 and 61730-2) presently prescribe up to 160 days field equivalent AM 1.5G TUV dose. This is << 25 years!
- **Goal**: develop UV- and temperature-facilitated test protocol(s) that may be used to compare PV materials, components, and modules relative to a field deployment.

Core Activities:

1: Consider **weathering literature**, **climate meteorology**, and **module temperature**.
e.g., known benchmark locations…Miami, FL; Phoenix, AZ.

2: **Leverage existing standards**, including other industries.
√Summary exists from Kurt Scott *et. al.*

3: Improve understanding of existing PV UV tests.

4: Improve understanding of module durability.
4-1 Collect information about **field failure modes**.
e.g., the literature, industry feedback, site inspections
4-2 Confirm appropriate UV weathering models.

5: Consider suitable **artificial UV sources** (e.g. Study 1).
√Summary of *module* capable equipment from David Burns *et. al.*

6: **Generate test procedure for accelerated UV weathering.**
Performing experiments to provide technical basis & confident decisions.

7: Perform **laboratory verification** of proposed test standards/failure mode.
- mini-module study (Japan), SoPhia round-robin (Europe), interlaboratory "Study 2" (TG5 X)

PVQAT TG5 Study 2: 62788-1-7 Optical Durability R-R

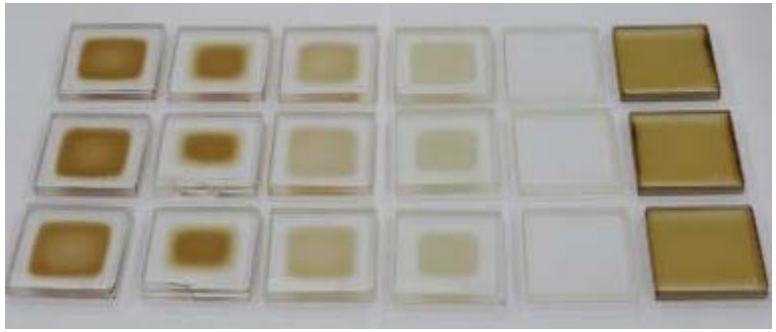
Test materials (3 replicates)

1. A9918 **EVA-A** (known bad **benchmark** material)
2. Contemporary **EVA-2** (commercial product , **UV cut-off 360 nm**)
3. Contemporary **EVA-3** (commercial product, **low PID**, **UV cut-off 360 nm**)
4. Contemporary **EVA-4** (commercial product, **low PID, UV cut-off 230 nm**)
5. **TPO-1** (R&D formulation, **thermoplastic**, **lower crystallinity**)
6. **TPO-2** (R&D formulation, **thermoplastic**, **higher crystallinity**)
7. **TPO-3** (commercial product, **thermoplastic, contemporary**)
8. **POE-1** (R&D formulation, **thermoset**, **with UVA**)
9. **POE-2** (R&D formulation, **thermoset**, **no UVA**)
10. **PVB** (commercial product, **BIPV** material)
11. **BS-A** (commercial transparent backsheet) air configuration
12. **BS-S** (commercial transparent backsheet) sun configuration
13. **9PS** reference (SAE J2412/SAE J2527 reference material)

(14.) Reference material (1 replicate coupon, do not weather)

Goals

1a. Verify test temperature for IEC 62788-1-7
1b. Verify pass/fail criteria for IEC 62788-1-7
1c. Quantify r & R of IEC 62788-1-7 (SS weathering)
2. Quantify activation energy of contemporary materials
3. Quantify acceleration factor in benchmark locations



As in Study 1, coupon specimens will be used to support the development of the weathering test for transparent PV packaging materials .

Participants (artificial weathering)

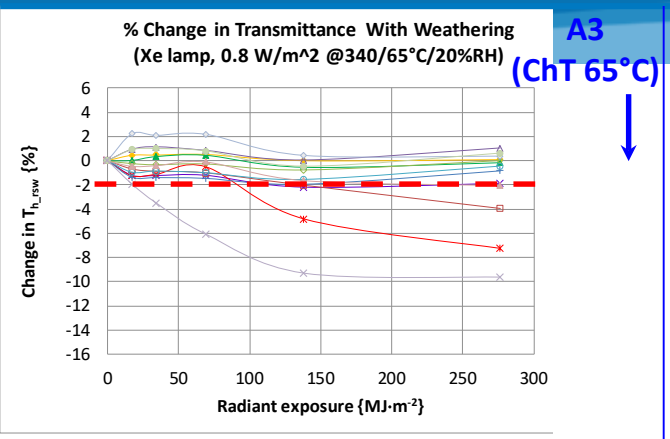
1. CREST (Loughborough University)
2. DNP
3. Dow-Chemical
4. DuPont
5. Eye Applied Optics
6. Fraunhofer CSE
7. NREL (√A3 & √A4 & A5 → E_a/Arrhenius)
8. Q-Lab
9. RenewSys (QUV, B2)
10. Suga
11. Sun Power

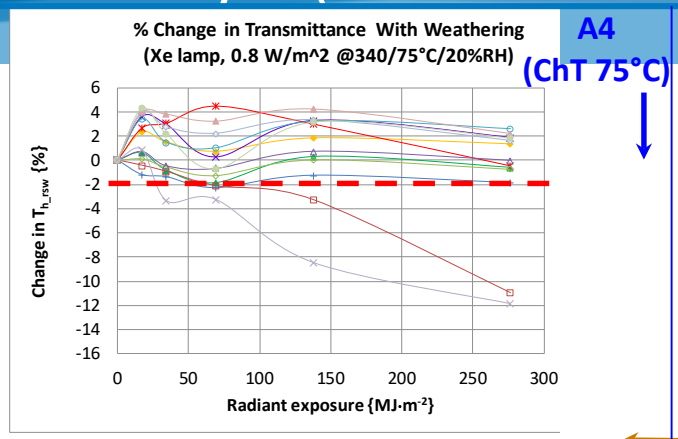
Participants (natural weathering)

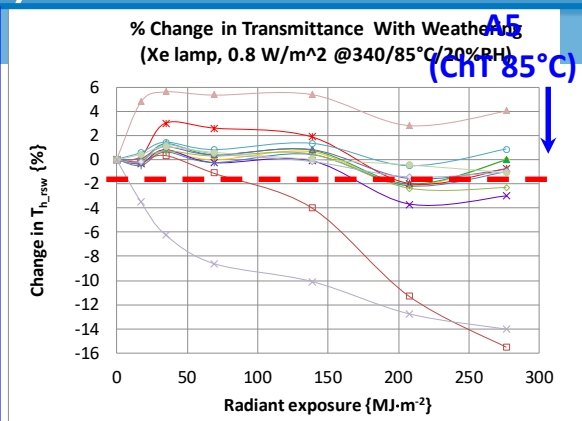
a. ATLAS (Miami)
b. ATLAS (Phoenix, 1x)
c. ATLAS (Phoenix, EMMA)
d. KACST (Riyadh)
e. NIST (Gaithersburg)
f. NREL (Golden, 1x)
g. Q-Lab (Cleveland)
h. SERIS (Singapore)

Contact:
David.Miller@nrel.gov

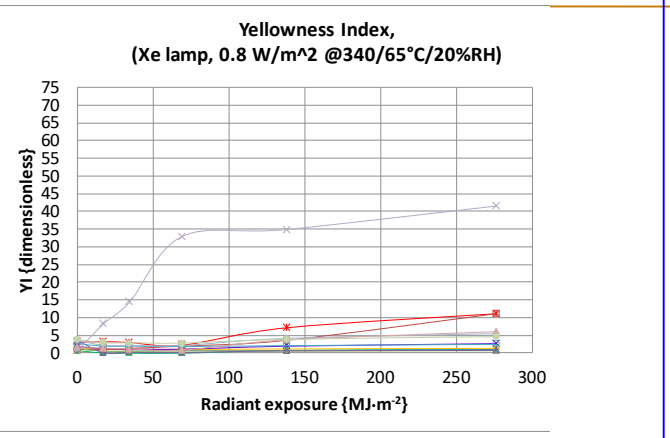
Results of the PVQAT TG5 Study 2 (All Materials)

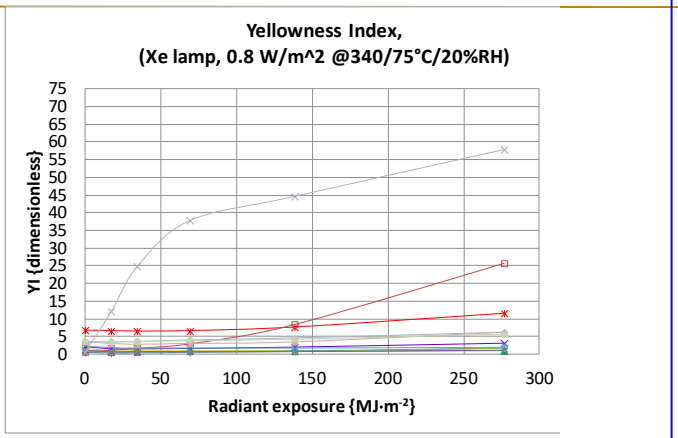


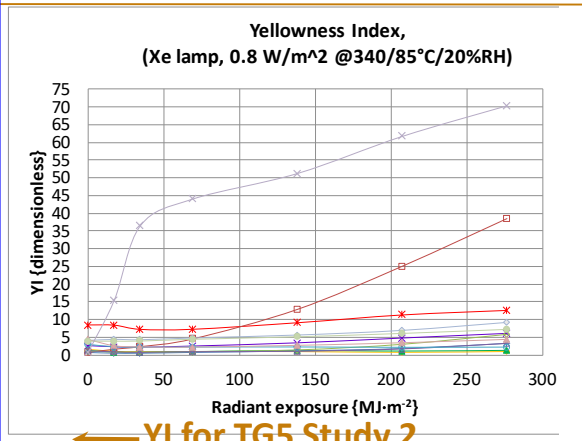




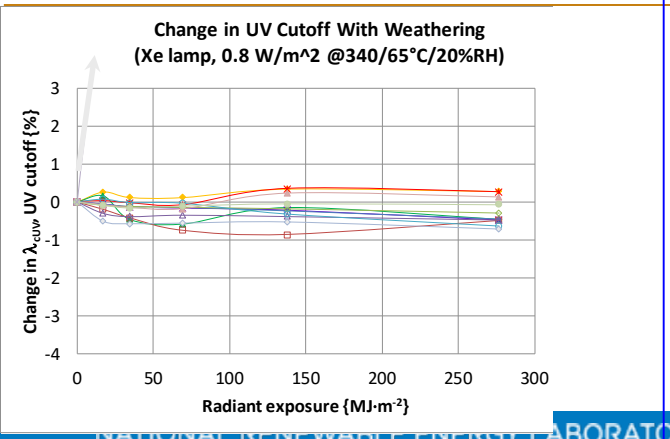
Δ[representative solar weighted transmittance] for TG5

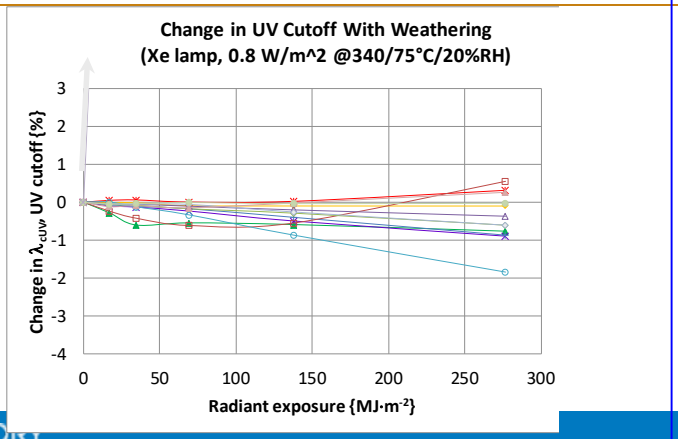


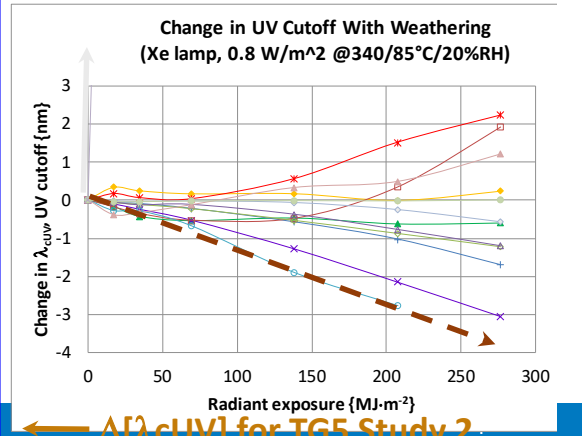




YI for TG5 Study 2







Δ[λcUV] for TG5 Study 2

Results of the PVQAT TG5 Study 2 (All Materials)

- The A3 (ChT 65°C), A4 (75°C), A5 (85°C) methods at NREL have finished (4000h = 6m).

*Many materials had minimal ΔT_{rsw} (≤2% pass/fail IEC 62788-1-7 for method A3). ☺

- Materials that stand out:
  - -9PS: known bad SAE reference material (see ΔT_{rsw}, YI, $\Delta\lambda_{cUV}$).
    Degradation appears to saturate/asymptote.
  - -G: known bad STR A9918 EVA-A (see ΔT_{rsw}, YI, $\Delta\lambda_{cUV}$)
    Lost UV absorber at ≥80°C in TG5 S1.
  - -D: TPO-3, contemporary
    ΔT_{rsw} >2%, overt $\Delta\lambda_{cUV}$ in A5.
  - -H: EVA-2, contemporary
    ΔT_{rsw} >2% in A5.
  - -E: custom TPO-2, higher crystallinity
    High YI (from scattering) with trends through experiment.
    Overt $\Delta\lambda_{cUV}$ in A5.
  - -J: custom POE-1, with UV absorber
    Overt $\Delta\lambda_{cUV}$ in A5.
- + and – trends observed for $\Delta\lambda_{cUV}$ at A5.

Future Efforts For TG5 X

Advanced UV weathering methods must balance:

Critical characteristic(s)

- Both method & specimen geometry.
- In some cases still in development, e.g., tensile testing of backsheets.
- Presently developed through IEC 62788-series (not TG5).

UV-related module degradation modes

- Optical durability of encapsulants. (IEC 62788-1-7 nearing publication ☺)
- Embrittlement/cracking of backsheet.
- Material erosion/abrasion, e.g., interaction/susceptibility with weathering.
- Delamination/loss of adhesion between layers.
- Loss of mechanical integrity of edge seal.
- Others: ground faults (cable jacket or connector), j-box, LID, LeTID

Accelerated test methods

- Methods for hot modules (mounting and/or climate), i.e. aid IEC TS 63126.
- Use of water spray during UV weathering.
- 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.

Getting Involved… Including Regional TG5 Efforts

There are three regional TG5's.
Each group focusing on different supporting activities (experiments).
You may participate/follow more than 1 of the groups. ☺

- TG5 "X" (encapsulants; now also looking ahead).
  We welcome participants from other regions!
  Contact: David MILLER <David.Miller@nrel.gov>

- TG5 Japan (sequence of tests; MiMo study; encapsulant delamination).
  Combined work with TG2 & TG3.
  Contact: Tsuyoshi SHIODA <Tsuyoshi.Shioda@mitsui-chem.co.jp>

- TG5 China (encapsulants & backsheets).
  Contact: Carol CHEN <chenxinx@cei1958.com>

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

also: http://pvqataskforceqarating.pbworks.com (minutes, references, attachments, meeting recordings)

Acknowledgements

☞There has been fantastic participation in TG5.

Thank you to the many participants for your ongoing support!!!

- If interested in TG5 activities or the experiments, please contact the corresponding regional TG5 leader. (See slide 7).

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory.

✋Your questions and feedback are much appreciated! Please help me to cover the important details & perspectives.

NREL STM campus, Dennis Schroeder

PVQAT

International PV Quality Assurance Task Force

Updates on PVQAT TG5 (UV Weathering) & TG12 (Soiling):

"PVQAT TG12: The Contamination (Soiling) of Solar PV"

David Miller

PV Reliability Workshop

Denver West Sheraton

February 27, 2019, 7 minutes.

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.

The Subgroups of TG12 (Soiling)

PVQAT
International PV Quality Assurance Task Force

Task Group 12 Webinars (**all general topics**)

- Quarterly webinars on soiling topics.
- Contact: Greg SMESTAD <smestad@solideas.com>

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

- Contributed to IEC 61724-1 (quantifying effect of soiling on PV systems).
- Anticipating interlaboratory precision study in CY 2019.
- Contact: YuePeng DENG <Yuepeng.Deng@FIRSTSOLAR.COM>.

Task Group 12-2 (solutions for **cleaning**)

- Module cleaning best practices (manual & robotic methods).
- Contact: Lin SIMPSON <Lin.Simpson@nrel.gov>

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

- Focus on PV abrasion methods, IEC 62788-7-3.
- Reference: Miller et. al., NREL/TP-5J00-66334, 2016, 1-25. http://www.nrel.gov/docs/fy16osti/66334.pdf
- Contact: David MILLER <David.Miller@nrel.gov>

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

- Example: analysis of soiling loss & rate from PV installation power production data.
- Reference: Deceglie et. al., Proc. IEEE J PV, 2018. also: http://www.nrel.gov/docs/fy16osti/65763.pdf
- Contact: Leo MICHELI <lmicheli@ujaen.es>

See: http://www.pvqat.org (PVQAT effort) **also: http://pvqataskforceqarating.pbworks.com (minutes, references, attachments, meeting recordings)**

Field Coupon Study (Background and Ongoing Progress)

Samples:

- 7.5 cm x 7.5 cm coupons.
- Includes AR, AS (-phobic & -philic), reference glass.
- Black backpane (similar temperature to PV).

Test sites:

- Contamination and abrasion prone locations.
- **Mesa**, Arizona; **Sacramento**, California; **Mumbai**, India; **Kuwait City**, Kuwait; **Dubai**, United Arab Emirates.

Original specimen set deployed in Sacramento.

Cleaning methods:

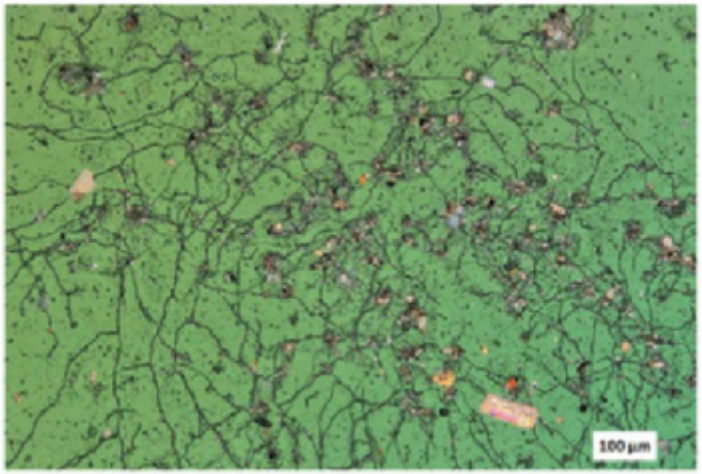
- No clean (NC); dry brush (DB); low-pressure water spray (WS); wet sponge and squeegee (WSS).
- Clean 1x/month.
- Examine 1 set of duplicates each year for 5 years.

References:

- Einhorn et. al, J PV, 9 (1), 2018, 233-239.
- Toth et. al., SOLMAT, 185, 2018, 375-384.
- Moutinho et. al., Proc. IEEE PVSC, 2018, 3439-3444.

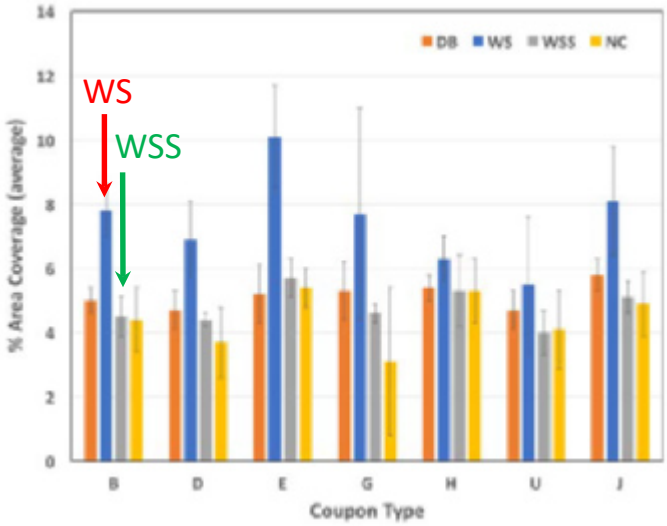
Recent Findings From the Ongoing Field Coupon Study

- Biological species (e.g. fungi) have been observed on veteran modules (Sacramento & Argenbühl, Germany) and field coupons (Sacramento & Mumbai).
- Contact cleaning (wet sponge and squeegee) most effectively removed fungus.
- The stage of fungus colonization could be quantified using optical analysis, to aid prescription of cleaning.



Optical microcopy of fungus observed on Mumbai coupon.

- Coatings and cleaning methods were distinguished between the sites. (e.g., WS vs. WSS in Mumbai)
- Common correlation between PAC and transmittance for all sites for uncoated glass.
- Present focus on most mechanically durable coatings. Aid development of PV abrasion standard.



Comparison of Particle Area Coverage (PAC) for coupons & cleaning methods in Mumbai

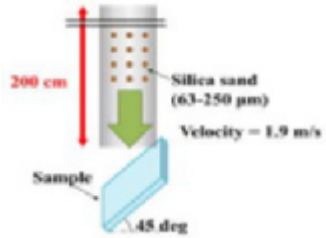
IEC 62788-7-3 (PV Abrasion) Standard Is Under Development

- Upon review, no existing standard from other industries was found readily suited for PV.
  - -Example: frosted –glass- specimens. See: Miller et. al., NREL/TP-5J00-66334, 2016, 1-25.

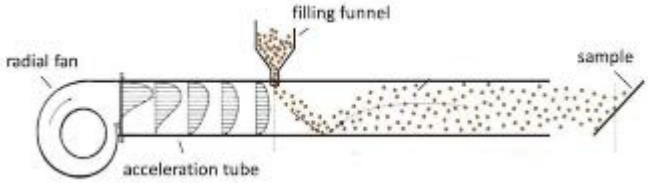
⇒Accelerated abrasion standard for PV surfaces is presently being developed in IEC WG2.

Methods

- Falling sand test.
  - -Natural abrasion (wear from typical meteorological conditions).
  - -Front surface coatings & backsheets.
- Forced sand impingement test.
  - -Covers severe storms (infrequent, but high velocity wind).
  - -Front surface coatings & backsheets & vehicle integrated PV.
- Artificial machine abrasion.
  - -**Cleaning** of PV (front surface coatings & VIPV).
  - -Includes slurry or dry dust abrasive.
  - -Linear translation or rotating brush.



Schematic of falling sand test. From Nishioka et. al., Proc. Asian PVSEC 2013.



Schematic of forced sand impingement test. From Klimm et. al., Proc. Euro. Weathering Symp. 2015.

Example (PB-8100) linear machine abrasion tester. www.byk.com

International Soiling Workshop

- Convened in 2016, 2017, 2018.
- "Proceedings" on PVQAT PB Works website: https://pvqataskforceqarating.pbworks.com/w/page/87300091/Soiling%20and%20Dust
- Topics including: cleaning technologies (robots) & best practices, field observation & mechanisms, contamination & its characterization, power loss quantification, loss prediction, standards, soiling mitigation.
- Participants include: R&D community, module manufacturers, system installers, academia, national labs, soiling sensor manufacturers, and solar asset managers

Attendees & participants in 2018.

- ***2019 International Soiling Workshop***

When: historically in October, e.g., **Oct 28-30**

Where (recent survey):

Candidate hosts included…

-***IRESEN in Morocco***, *Ahmed Alami El Merrouni. See: http://www.greenenergypark.ma/*

-***Kuwait Institute for Scientific Research*** *(KISR),* *Kuwait, Feras G. Alzubi*

-*2019 International Solar Energy Society Congress,* ***Santiago, Chile,*** *November 4-7, 2019*

-***India Institute of Technology,*** *Bombay India, Anil Kottantharayil*

Contact (volunteers & inquiries): Lin SIMPSON, Lin.Simpson@nrel.gov

Results of 2019 survey.

Acknowledgements

☞ After years of interest, there has been fantastic participation in TG12.

Thank you to the many participants for your ongoing support!!!

- If interested in TG12 activities or the experiments, please contact the corresponding topic leader. (See slide 10).

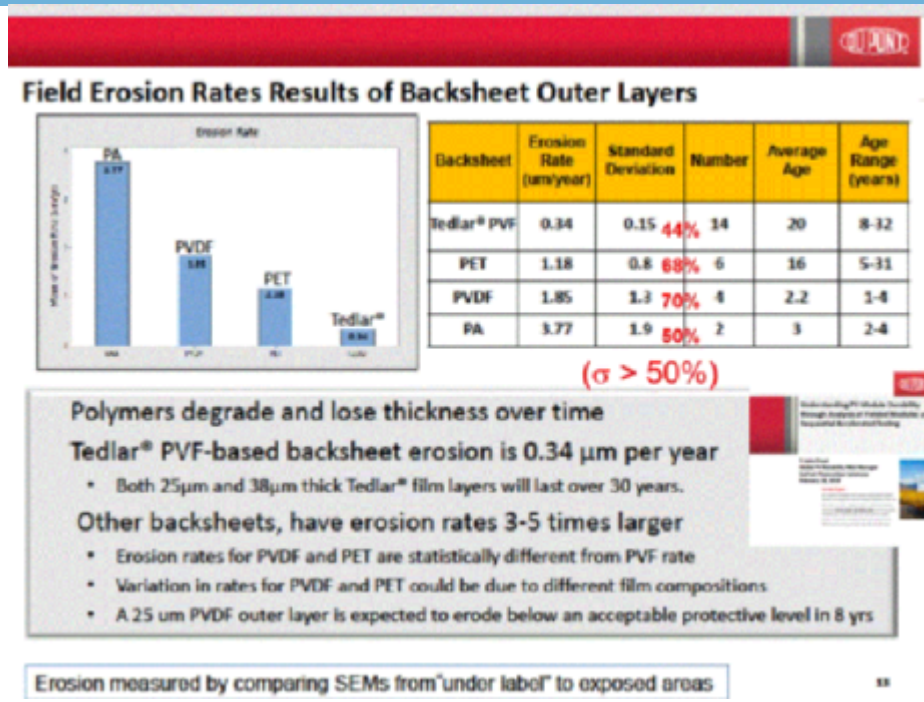
This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory.

✋ Your questions and feedback are much appreciated! Please help me to cover the important details & perspectives.

NREL PV soiling map.
https://www.nrel.gov/pv/soiling.html

"The Abrasion of Backsheets & VIPV May Also Be Addressed"

- The erosion of backsheets was recently identified in veteran PV modules.
- Caveat: polymers may erode from photodegradation (loss of volatiles) in addition to physical abrasion.
- More evidence & understanding is sought within IEC 62788-2 (backsheet standard group).



Roy Choudhury et. al., IEEE PVSC, 2018.

- IEC WG2: consider backsheets within the scope of IEC 62788-7-3.

☞To participate in the backsheet abrasion survey, contact:

Jürgen JUNG <juergen.jung@agfa.com>

- Accelerated test sequence for PV modules may ultimately include abrasion, in a test sequence (e.g., UV → abrasion —?→ TC200)

- IEC WG7: consider vehicle integrated PV within IEC 62788-7-3.

PVQAT

International PV Quality Assurance Task Force

PVQAT updates: toward further global collaboration

Tadanori Tanahashi (AIST)

2019 PV Reliability Workshop (2019/2/27), Lakewood, CO

PVQAT

International PV Quality Assurance Task Force

PVQAT updates

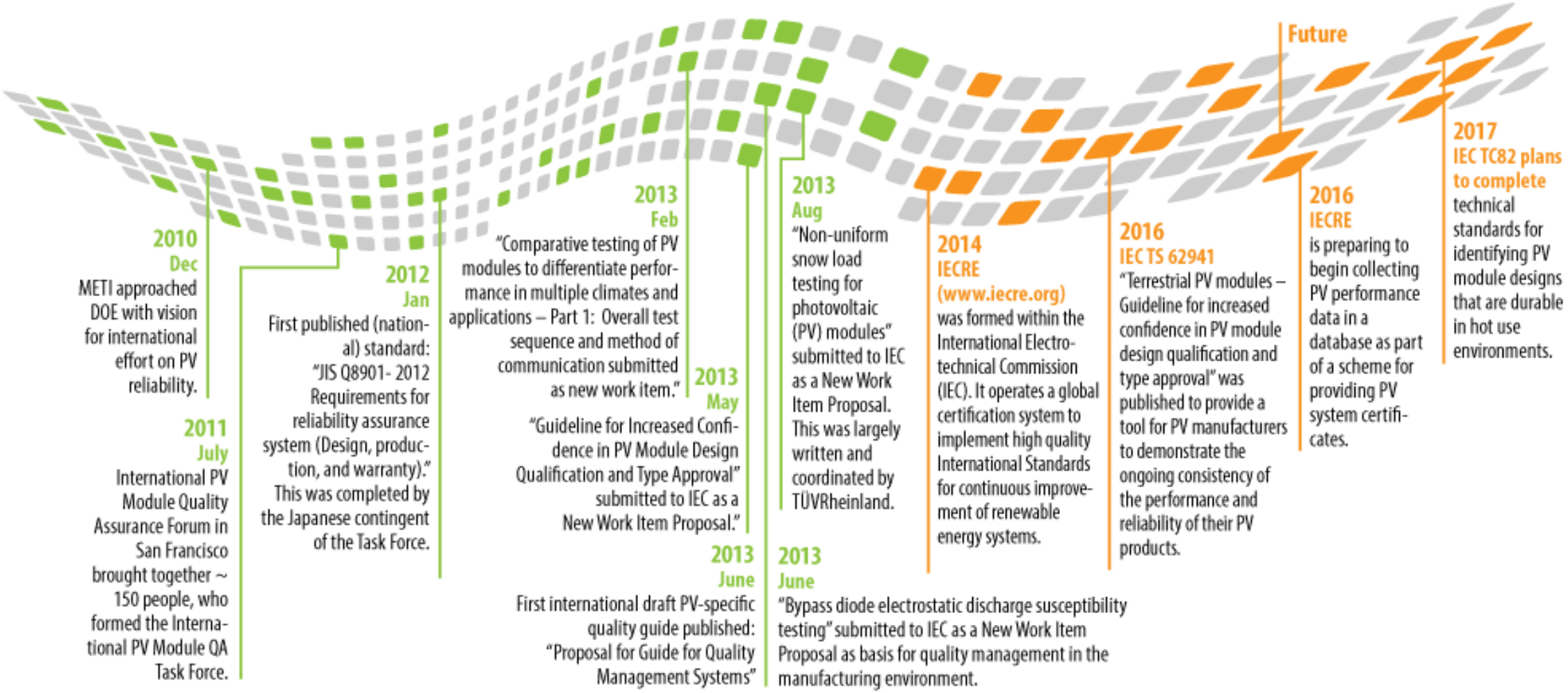
- PVQAT Activities

- Topic 1: PV Reliability Workshops

- Topic 2: Collaboration

PVQAT: History

http://www.pvqat.org/



PVQAT is a Liaison (Category A) of IEC TC82

PVQAT: We are…

Establish Standards

IEC

IECRE

Establish ODs

Support

PVQAT

OPEN FORUM
(Volunteers)

- Collaborative Research
- Discussions on Current Issues
- Data Collection and Comparison of Results

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

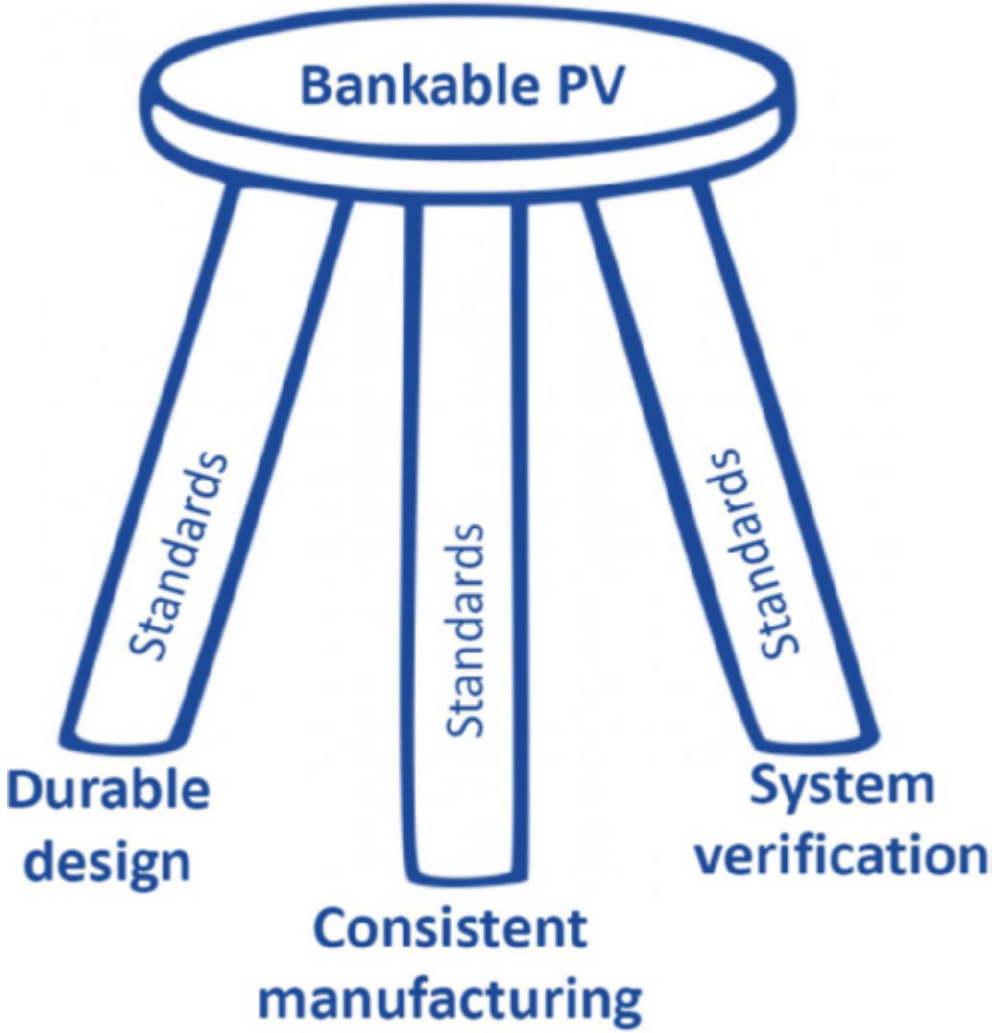
Tasks 13 + others

PVQAT: Approach to “Bankable PV”

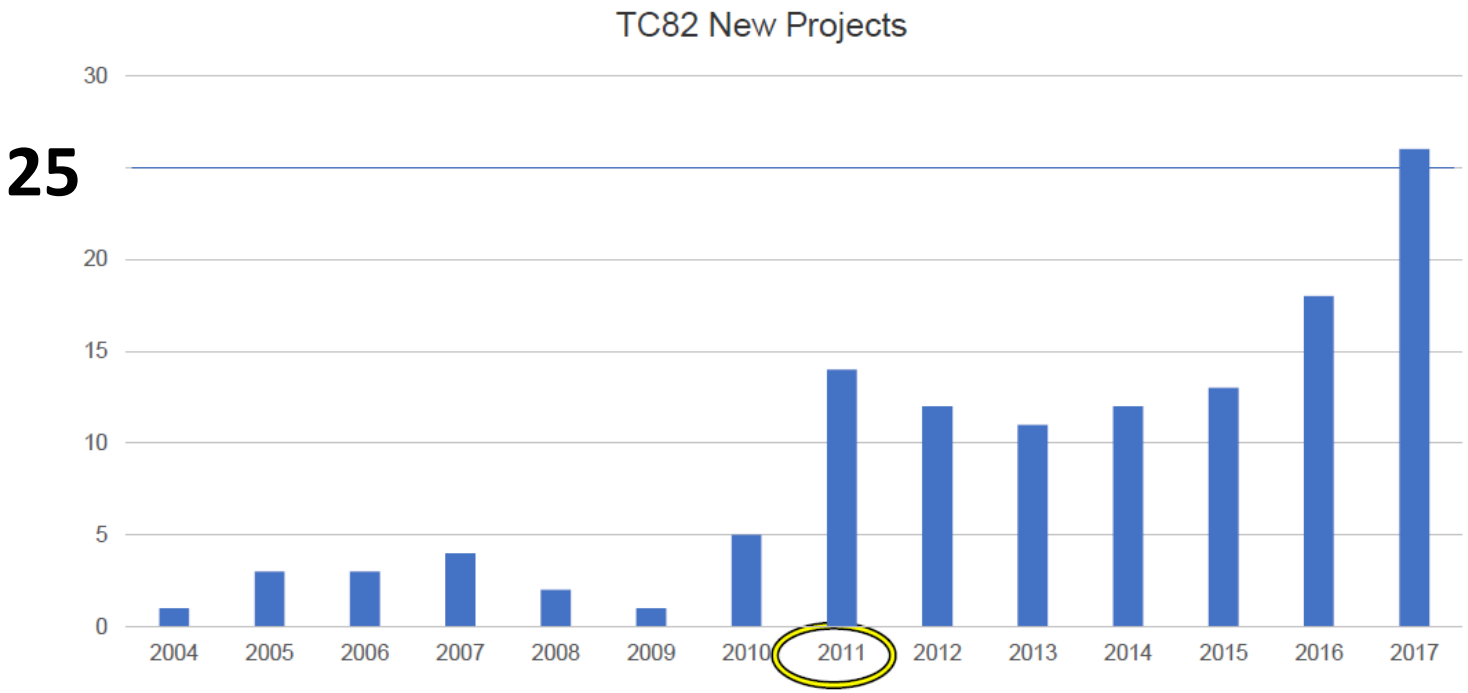
- A rating system to ensure durable design of PV modules for the climate and application of interest.

- 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.



‘PVQAT Effect’ on TC 82



Remarkable results, demonstrating the importance and visibility of IEC standards in PV

Source: George Kelly (2018) Technical Committee 82 Secretary’s Report in IEC TC82 Meeting in Busan

PVQAT: Task Group Overview

Task Group 1:	Manufacturing Consistency	
Task Group 2:	Thermal and Mechanical Fatigue	
Task Group 3:	Humidity, Temperature, and Voltage	
Task Group 4:	Diodes, Shading, and Reverse Bias	
Task Group 5:	UV, Temperature, and Humidity	
Task Group 6:	Communication	inactive
Task Group 7:	Snow and Wind Loading	Re-Activated
Task Group 8:	Thin-Film Photovoltaic Modules	
Task Group 9:	Concentrator Photovoltaic Modules (CPV)	inactive
Task Group 10:	Junction Box & Connectors	
Task Group 11:	System Verification and Power Electronics Testing	
Task Group 12:	Soiling and Dust	
Task Group 13:	Cells	

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

Task Group 1: Manufacturing Consistency

IEC 62941 (QMS Guideline) will be published in 2019.

Task Group 2: Thermal and Mechanical Fatigue

IEC 62892 (ATC) has been submitted as FDIS to IEC CO.

Task Group 3: Humidity, Temperature, and Voltage

IEC 62804s & Combi-Test TR are processing, as reported by P. Hacke.

Task Group 4: Diodes, Shading, and Reverse Bias

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

Task Group 5: UV, Temperature, and Humidity

IEC 62788s are processing, as reported by D. Miller.

Task Group 6: Communication (inactive)

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

Task Group 7: Snow and Wind Loading

Anderson Hsu reported the updates in their activities.

Task Group 8: Thin-Film Photovoltaic Modules

IEC TS 63140 (Shading) is processing.

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

Task Group 10: Junction Box & Connectors

DFMEA / IEC 62852 (Connector/Safety) review / UL 6703 harmonization

Task Group 11: System Verification and Power Electronics Testing

PE subgroup: Scope Definition = Elucidating failure mechanisms / …

Task Group 12: Soiling and Dust

IEC 62788-7-3 is processing, as reported by D. Miller, + Active Webinars

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

Task Group 13: Cells

IEC 63202-1	<WG8>	LID in c-Si PV Cells	RFDIS
IEC TS 63202-2	<WG8>	EL for c-Si PV Cells	ADTS

- **If I have missed any update, please let me know.**
- **PVQAT Website will be updated in March /April.**
  Please visit the websit to confirm the details in TG activities .

PVQAT

International PV Quality Assurance Task Force

PVQAT updates

- PVQAT Activities

- **Topic 1: PV Reliability Workshops**

- Topic 2: Collaboration

Research Center for Photovoltaics

3rd International Workshop on the Sustainable Actions for "Year by Year Aging" under Reliability Investigations in Photovoltaic Modules

SAYURI-PV 2018

Date: October 30 – 31, 2018 **Venue: AIST Tsukuba Campus**

Participants: ca. 60
(25%= from Asia w/o JP)

SAYURI-PV 2018: Agenda

October 30, 2018 (Tue)

Keynotes	DuraMAT (NREL), JP Activities (AIST)
Combined Stress Tests	C-AST (NREL)
	LeTID (Canadian Solar/EternalSun)
Materials / Mechanisms I & Field Experience I	Field Experience (Korea Univ./Mitsui Chem.)
	PID Mechanism (AIST)

October 31, 2018 (Wed)

Materials / Mechanisms II	Degradation (Canadian Solar),
	Measurement (ASI)
Field Experience II	Performance/Degradation (AIST)
General Discussion	

Details: https://unit.aist.go.jp/rcpv/cie/

Details in SAYURI-PV 2019 would be announced in April, 2019.

SOPHIA
European Research Infrastructure

9th SOPHIA Workshop PV-Module Reliability 2019

Expected Date: May 28th – 29th, 2019

Expected Venue: Graz, Austria

More information and details coming up soon!

https://www.pv-reliability.com/workshop-2019

Agenda has been uploaded.

Fraunhofer ISE

Visit the workshop's website: www.pv-reliability.com

For more information please register your interest with:

kerstin.koerner-ruf@ise.fraunhofer.de

PV Reliability Workshop

2020 Workshop

Date: ???

Venu: ???

Details: https://www.nrel.gov/pv/pvmrw.html

PVQAT

International PV Quality Assurance Task Force

PVQAT updates

- PVQAT Activities

- Topic 1: PV Reliability Workshops

- **Topic 2: Collaboration**

Collaboration with IEA PVPS Task 13 (*in my opinion*)

International Energy Agency
Photovoltaic Power Systems Programme

http://www.iea-pvps.org/
http://www.iea-pvps.org/index.php?id=57

TASK 13
Performance, Operation and Reliability of Photovoltaic Systems

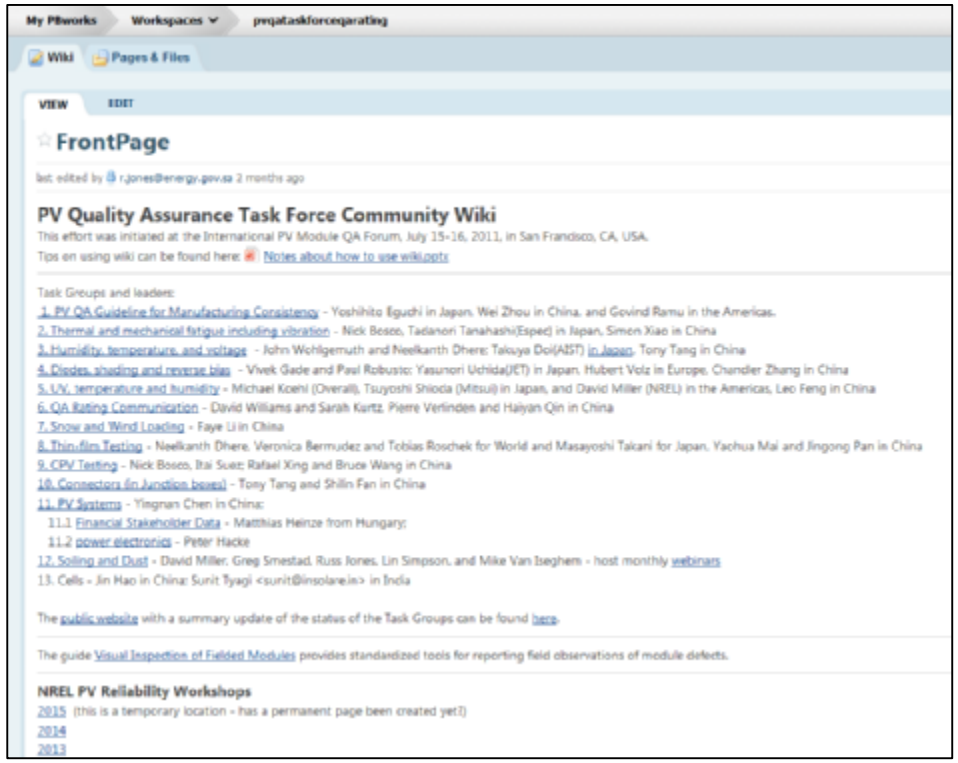
in their "Work Plan 2018 – 2021"

IEA Task 13 will also collaborate with the International PV Quality Assurance Task Force (PVQAT). The aim of this collaboration is to exchange and disseminate results jointly. By this measure it can be expected that the output of Task 13 will reach a larger audience and that the work results are considered in the standardization process.

http://www.iea-pvps.org/fileadmin/dam/intranet/task13/IEA-PVPS_Task_13_Workplan.pdf

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/

Performance, Operation and Reliability of Photovoltaic Systems

IEA PVPS Task 13

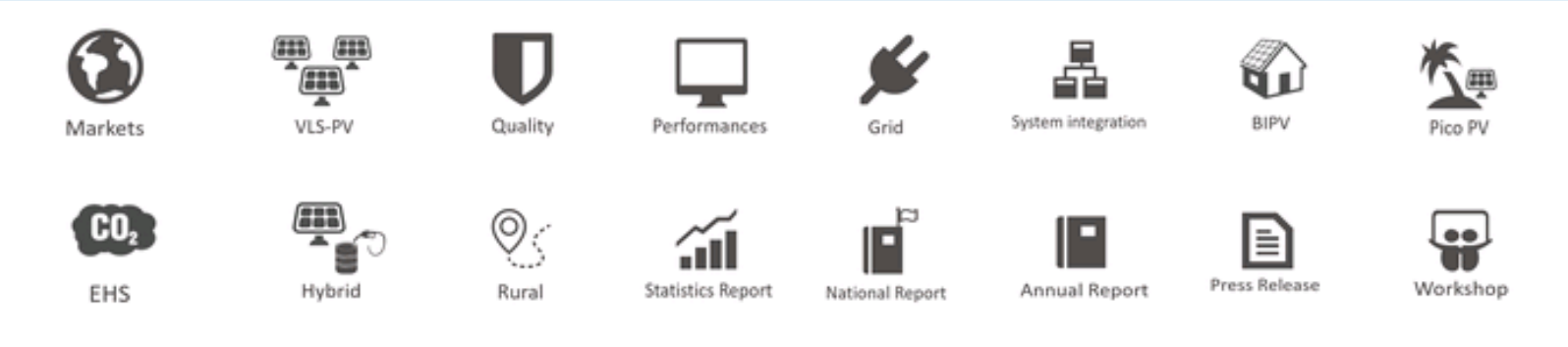
Ulrike Jahn, TÜV Rheinland
Operating Agent Task 13

PVPS

IEA PVPS is

- A global reference on PV for policy and industry decision makers
- A global network of expertise for information exchange and analysis
- An impartial and reliable source of information

All information is available at http://www.iea-pvps.org



PVPS

PVPS Task 13
PV Performance, Operation and Reliability

14th Task13 Meeting in Bolzano, Italy, 06-08 April 2016

23+ IEA countries, 47+ institutions

$\Rightarrow$ 45 participants, 60+ members

PVPS

Motivation

- PV is utilizing new materials, manufacturing methods, module and systems designs in order to lower costs and hopefully increase or maintain reliability.
- New focus areas and challenges: “New Module Materials and Constructions” and “New System Concepts”.
- PV performance analysis and monitoring will lead to more qualified assessments of PV plants and thus lower risk in PV investments.
- **Task 13 extension 2018-2021**: Global network required to improve the quality and reliability of PV systems and subsystems by collecting, analyzing and disseminating information on their technical and financial performance.

PVPS Task 13 Structure 2018–2021

Subtask 1: New Module Concepts and System Designs

Subtask 2: Performance of Photovoltaic Systems

Subtask 3: Monitoring - Operation & Maintenance

Subtask 4: Information Dissemination

3rd period: Sep 2018 – Sep 2021

Task 13 – Subtask 1

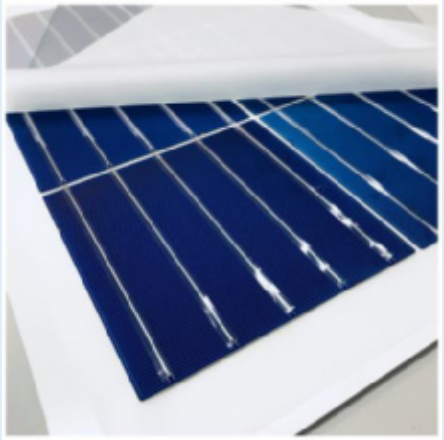
Subtask / Activity	Activity Leader
Subtask 1: New Module Concepts and System Designs	
1.1 New Module-Concepts, -Designs and -Materials	J. Stein / G. Oreski
1.2 Bifacial Photovoltaic Modules and Concepts	J. Stein / Ch. Reise
1.3 Performance of New Photovoltaic System Designs	M. Köntges
1.4 Service Life Prediction	KA. Weiß

ST 1.1: Advanced Materials for PV

- **Encapsulants & Backsheets**
  - Replacement of EVA and fluorine polymers using Polyolefines: Thermoplastic encapsulants; Co-extruded BS; Combined Backsheet – back encapsulant film
  - Functional properties: Selective permeability; Selective optical properties; Flame retardant encapsulants

© Isovoltaic

- **Thin glass**
- **Coatings**
  - Anti soiling, AR, Aesthetic
- **Interconnection**
  - Lead free solderings; Electrically conductive adhesives (ECA); Tape interconnection; multi-wire; plated contacts
- **New cell technologies and their impact on module reliability**



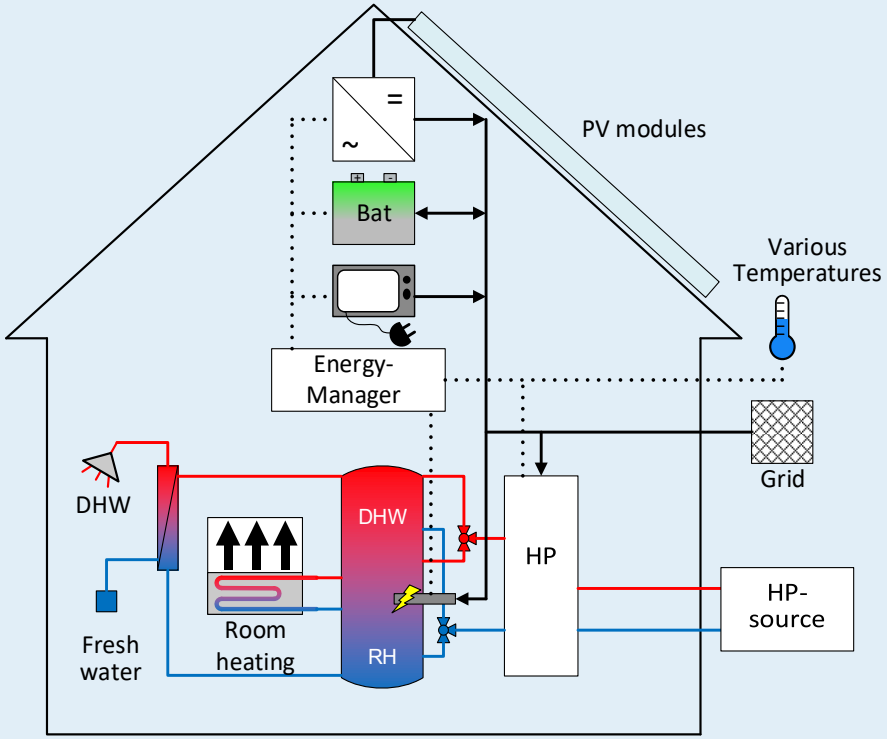
Tape interconnection, J. Buddgård et al., EU-PVSEC 2017

ST1.3 - Performance of New PV System Designs

AL: **Marc Köntges**, ISFH, DEU
Koentges@isfh.de

Objectives:

- Provide status of methods for performance characterization of new PV system components
- Provide methods for performance characterization of new PV systems
- Give an overview of the performance of complex PV systems with multiple function with showcases



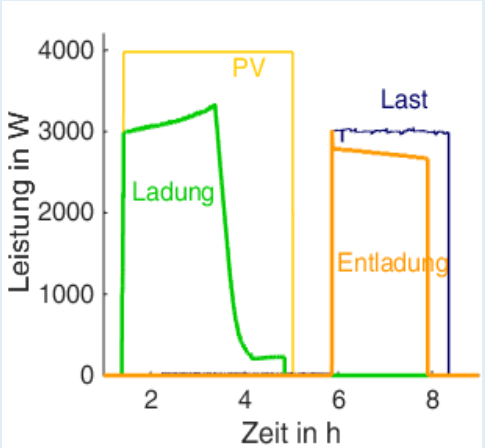
Source: ISFH

ST1.3 - Performance of New Photovoltaic System Designs

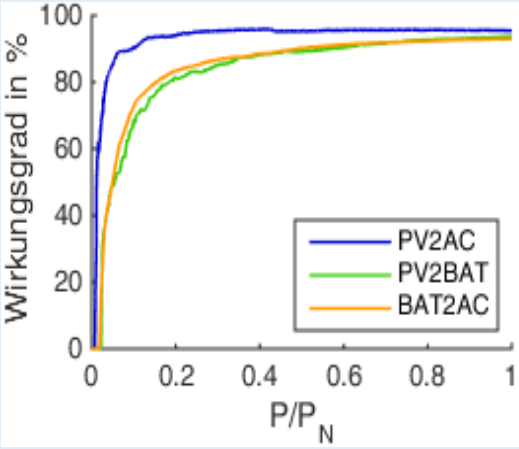
5.1 Performance ratios to characterize system components

Example: Measurement of PV battery storage

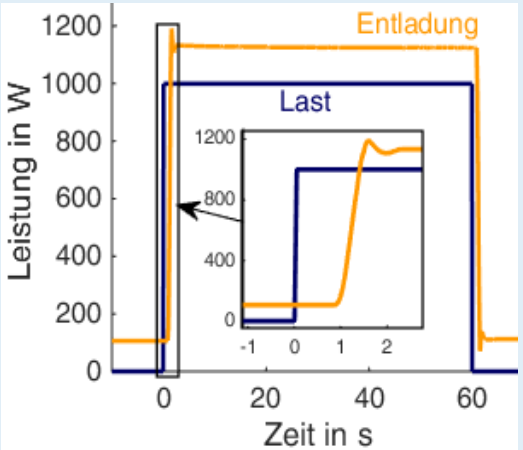
PV battery storage load cycles



Power path efficiency curves



Step response, control deviations



+ Power consumption of BMS and EMS (idle, stand-by, in operation)

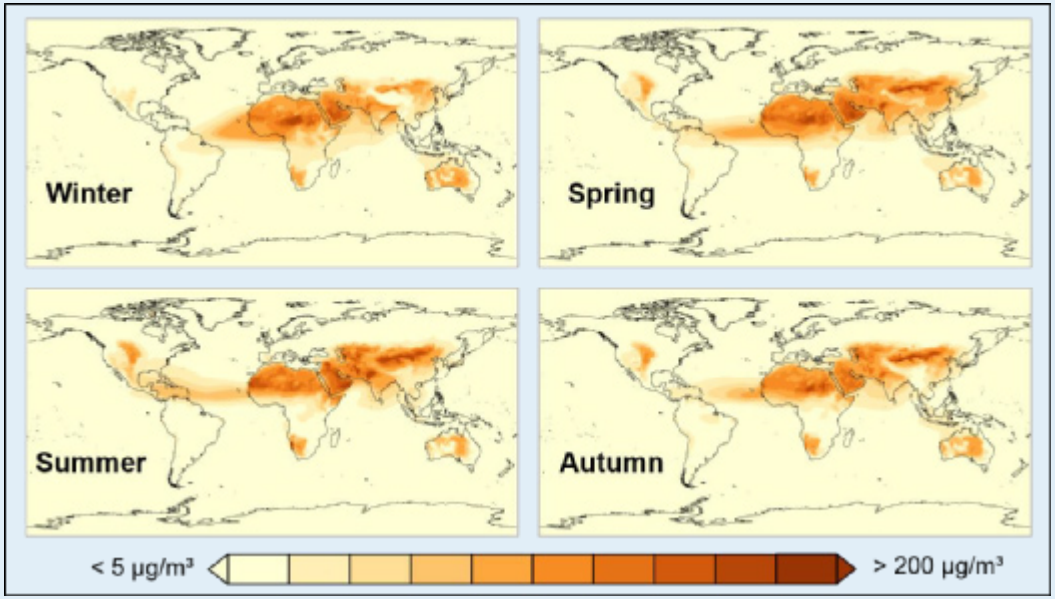
M. Knoop *et al.*, “MATLAB-basiertes Simulationsmodell zur Berechnung der elektrischen Leistungsflüsse im PV-Speichersystem”, in 32. Symposium Photovoltaische Solarenergie, Bad Staffelstein (2017).

Task 13 – Subtask 2

Subtask / Activity	Activity Leader
Subtask 2: Performance of Photovoltaic Systems	
2.1 Uncertainty in Yield Assessments and PV LCOE	D. Moser
2.2 Predictive Monitoring	M. Green / D. Moser
2.3 Climatic Rating of Different Technologies for Different Countries	M. Schweiger
2.4 Impact of Soiling on PV System Performance and Reliability	Ch. Schill
2.5 Assessment of Performance Loss Rate	R. French / D. Moser

ST 2.4: Impact of Soiling on PV System Performance and Reliability

- Australia
- Belgium
- Canada
- Chile
- Finland
- Germany
- Israel
- Morocco
- South Africa
- Spain
- Sweden
- Switzerland
- Taiwan
- USA



Soiling potential seen from satellites

Representative atmospheric concentration of mineral dust, based on long-term data (MACC-II)

Jan Herrmann, Uni Freiburg, GloBeSolar project, unpublished

AL: Christian Schill

Fraunhofer ISE (DEU)
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ST 2.4: Impact of Soiling on PV System Performance and Reliability

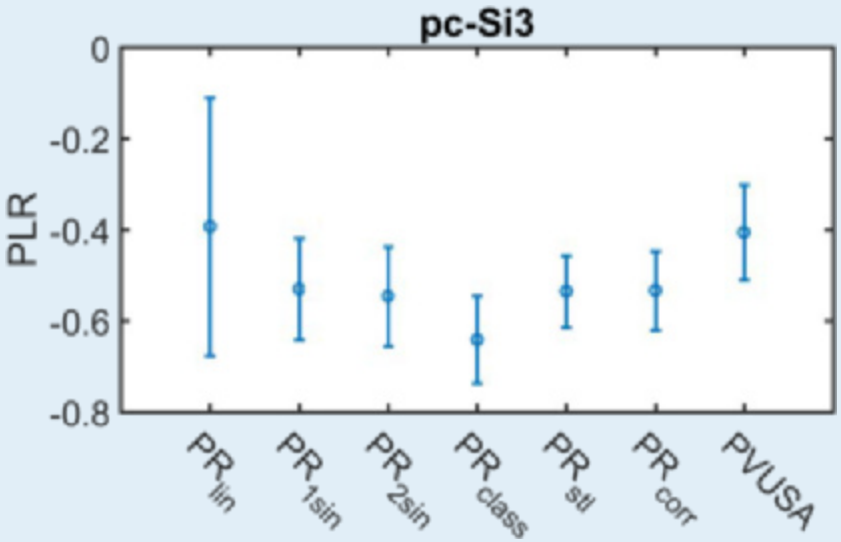
Subtask Focus Areas

- Sensing of soiling and snow
- Model the impact (satellite derived soiling risk maps, performance models, best-time-to-clean)
- Data provision (real world soiling losses)
- Mitigation of soiling losses (cleaning technologies, new plant concepts, link to new materials)
- Summary of cleaning technologies - effectiveness vs. cost vs. water consumption

ST 2.5: Assessment of Performance Loss Rate

Determination of the uncertainty in the calculation of degradation / PLR based on high quality data (irradiance, yield, etc.) and based on low quality data (only energy data available)

- What is the uncertainty of degradation/PLR when high quality data is available?
- What happens if only energy data is available (large amount of data)?
- Use of database from Task 2 / Task 13
- In Part 2 we will compare uncertainties and perform a survey



U.S. DOE RTC Baseline Systems

8 Systems in 4 KG Climate Zones

Mono-Si, Al-BSF

- 270 P_{MP}, 38.4 V_{OC}, 9.18 I_{SC}

3 - 4 years of data

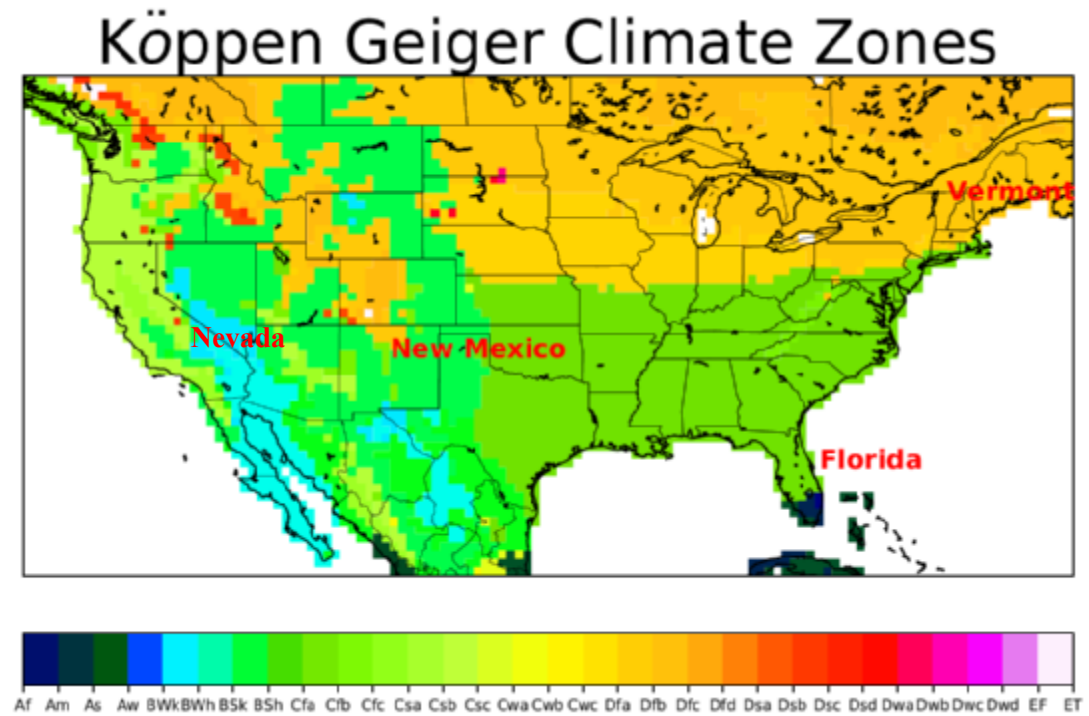
- 1 minute interval

12 modules per inverter

- 8 inverters total,

2 systems in each location

- Florida: Cfa KG Climate Zone
- Vermont: Dfb
- New Mexico: BSk
- Nevada: BWh



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Task 13 – Subtask 3

Subtask / Activity	Activity Leader
Subtask 3: Monitoring - Operation & Maintenance	
3.1 Quantification of Technical Risks during O&M	M. Herz / D. Moser
3.2 Characterization of PV Power Plants using Mobile Devices	W. Herrmann / K. Berger
3.3 Guidelines for O&M Procedures in Different Climates/Countries	U. Jahn / Ch. Schill

ST 3.1: Quantification of Technical Risks during O&M

Activity lead

- Magnus Herz, TÜV Rheinland (TUV), DEU
- Ulrike Jahn, TÜV Rheinland (TUV), DEU

Email: **magnus.herz@de.tuv.com**

Phone: +49 221 806 4946

- David Moser, EURAC Research, (EURAC), ITA
- Sascha Lindig, EURAC Research, (EURAC), ITA

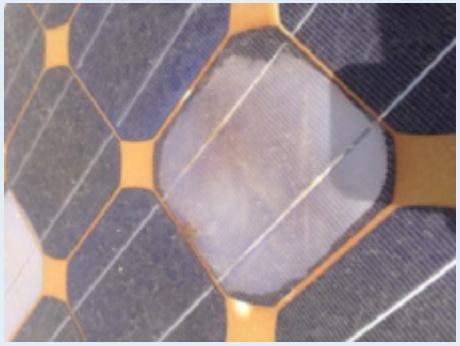
Email: david.moser@eurac.edu

Phone: +39 0471 055 627

ST 3.1: Quantification of Technical Risks during O&M

Part 2.1: Definition of the most important risks and risk parameters:

- PV modules failures
- Inverters failures
- Soiling
- Failure rates
- Yield loss
- Repair costs



Part 2.2: Collection of real case studies

- Derive the characteristic risk values

Part 3.2: Real case studies:

- Monetized yield losses
- Costs of O&M measures / Lab tests

ST 3.1: Quantification of Technical Risks during O&M

Risks and costs templates

Basic data - PV system	
Project ID [e.g. XY-01]	
Location [Country]	
Climate zone	
System Type [Roof/ground]	
Nominal system power [MWp] (1)	
PV module type	
Inverter type	
Mounting system [fix/tracking]	
Orientation [0° south]	
Inclination of the PV modules	
Number of modules	
Number of inverters	
Number of strings	
Number of combiner boxes	
Expected annual yield [kWh/kWp]	
Electricity contract, PPA, FIT [€/kWh]	
Start of operation [Month, Year] (1)	

Case data - Detected risk	
Risk - short description	
Date of detection [Month, Year] (2)	
Detected power loss due to the risk [%] (2)	
Detected yield loss du to the risk[kWh]	
Response time until measures taken [(2) → (3)	
Time of implementation/repair time [d (3) → (4)	
Power loss before mitigation applied [% (3)	
Add. downtime loss during det/rep [kWh]	
Power loss after mitigation applied [% (4)	
Type of degradation (linear,drop) (1) → (2)	
Risk - long description, comments	

Cost data - Economic impact	
Cost of inspection/detection O&M contract [€/a]	
Cost of inspection/detection third party [€]	
Cost of laboratory tests [€]	
Cost of preparation/coordination [€]	
Cost of substituted components [€]	
Cost of additional required componments [€]	
Cost of transportation of new components [€]	
Cost of dismantling, sorting, re-installation [€]	
Cost of disposal [€]	
Cost - long description, sum of all cost, involved parties, chronology of events	

Survey version 1.2

1. Start of operation nominal system power
2. Date of detection detected power loss
3. Date of mitigation additional lost energy
4. Date of completed regeneration system power after mitigation

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ST 3.2: Characterization of PV Power Plants using Mobile Devices

Activity lead

- Werner Herrmann, TÜV Rheinland Energy (TUV), DEU

  Email: **werner.herrmann@de.tuv.com**

  Phone: +49.221.806 2272

- Karl Berger, Austrian Institute of Technology (AIT), AUT

  Email: karl.berger@ait.ac.at

  Phone: +43.664.825 1033

ST 3.2: Characterization of PV Power Plants using Mobile Devices

Objectives

- Identifying defective PV modules as origin of power loss
- Provide good practice on methods for portable devices to qualify PV power plants
- Evaluate uncertainties of mobile devices for characterizing PV power plants and comparison to laboratory methods

Target Audience

- PV industry, test equipment developers, PV power plant inspectors, O&M providers

Report (months 36)

"Good Practice Recommendations to Qualify PV Power Plants using Mobile Devices"

ST 3.2: Characterization of PV Power Plants using Mobile Devices

Overview of inspection methods:

A3.2.1	Daylight I-V measurement of PV string and modules	AIT
A3.2.2	Dark I-V measurement of PV string and modules	AIT
A3.2.3	Module characterization with mobile test center	SUPSI
A3.2.4	Module characterization with portable LED solar simulator	TUV
A3.2.5	Daylight electroluminescence imaging	ISE
A3.2.6	UV fluorescence imaging	ISFH
A3.2.7	Spectroscopic methods for polymeric materials	OFI
A3.2.8	Electrical impedance spectroscopy	SICON
A3.2.9	Drone-mounted EL & IR inspections of PV arrays	MU / IMEC
A3.2.10	PV plant testing vehicle	CAS

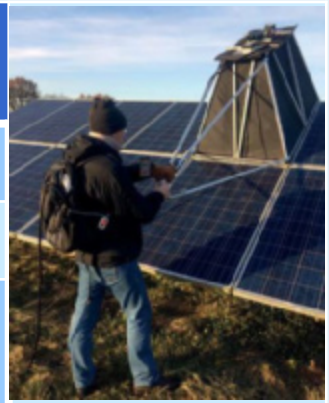
Activity 3.2: Characterization of PV Power Plants using Mobile Devices

Catalogue of evaluation aspects:

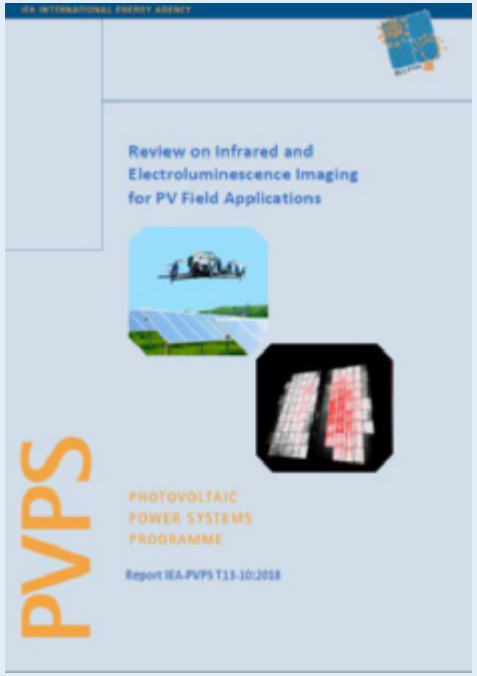
- Detectable failure types for modules and arrays
- Classification of failure type (qualitative or quantitative)
- Test conditions (i.e. daylight or dark, disconnection of module from array)
- Power supply (i.e. mains, battery, PV powered)
- Transportability: Dimensions & weight (i.e. car, truck, air freight)
- Cost effectiveness (i.e. purchase costs, maintenance costs, no. of inspected modules per day, required staff deployment)
- Status of standardization and licensing
- Strengths and weaknesses

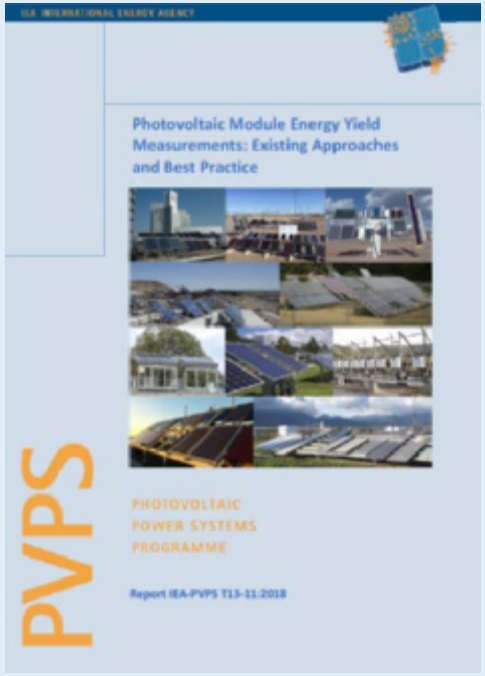
ST 3.2.6: Characterization of PV Power Plants using Mobile Devices

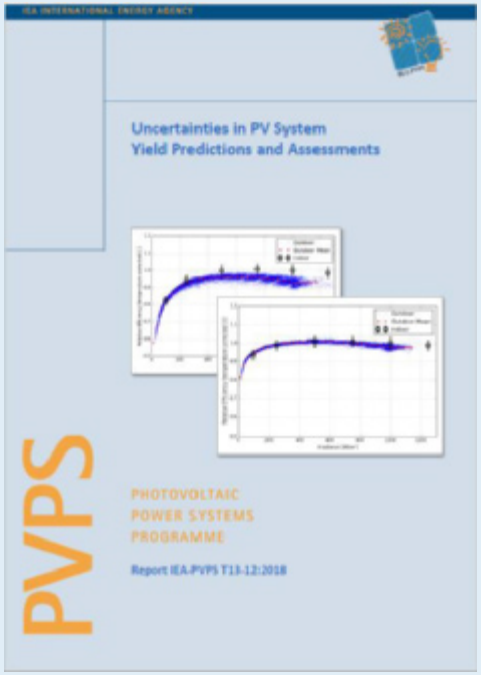
Mobile Device	UV Fluorescence Imaging
Leadership	Marc Köntges, ISFH (DEU)
Contributors	AIT, OFI, CWRU, PV Guider, …
Applicability in the field	▪ Detect and classify cracks in cells ▪ Crack propagation ▪ Hot cell detection ▪ Differentiation of backsheet and encapsulation materials
Work items	▪ Functional principle ▪ Literature review, market overview of commercial devices ▪ State of development (commercial, prototype, research) ▪ Gather existing knowledge and data from contributors
References	– A. Morlier, M. Siebert, I. Kunze, G. Mathiak, M. Köntges, Detecting Photovoltaic Module Failures in the Field During Daytime With Ultraviolet Fluorescence Module Inspection, IEEE J. Photovoltaics. 7 (2017) 1710–1716 – https://www.photovoltaikbuero.de/pv-know-how-blog/uv-fluoreszenz-an-photovoltaikmodulen/ – https://www.mbj-services.com/produkte/equipment/smart-uv-light/



Results & Outcomes of the Previous Work







Technical Reports – Public Documents in 2018

For Download at: www.iea-pvps.org

PVPS

Task 13 TEAM

23+ countries
47 organizations
60+ experts

PVPS

Interested to Join?

Contact:
Ulrike.Jahn@de.tuv.com

PVEL

MAKE DATA MATTER.

LET'S TALK ABOUT LETID TESTING

Tristan Erion-Lorico, Head of PV Module Business

PV Evolution Labs

February 2019

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

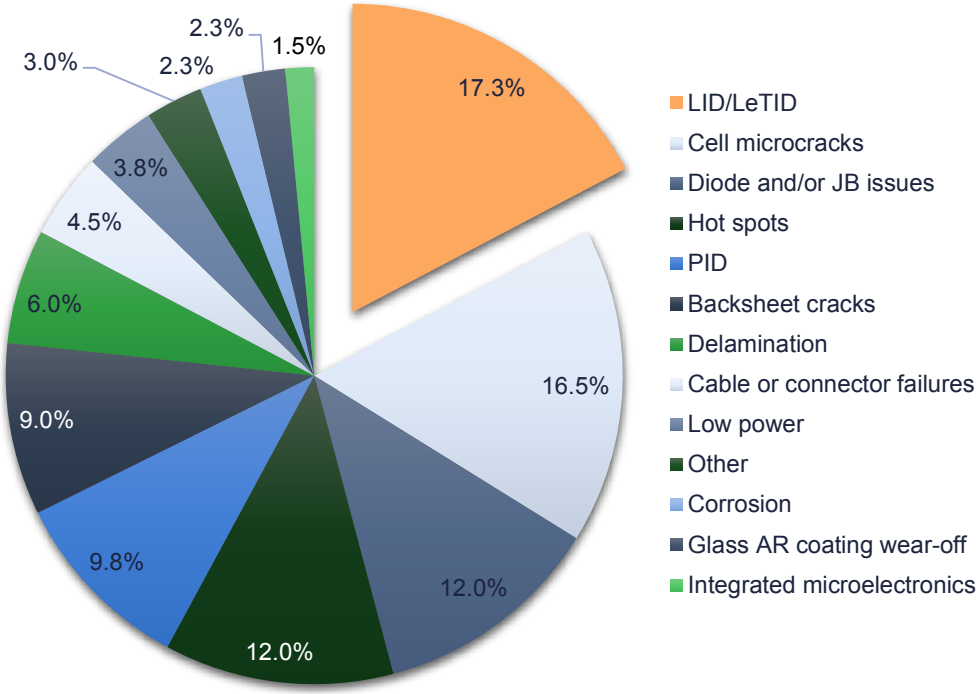
Pioneered bankability testing for PV products nearly a decade ago

Market-driven

Continuously refining test programs to meet partner needs

LeTID: Why Do We Care?

- LeTID (Light and Elevated Temperature Induced Degradation) is a growing concern.
- LeTID has wide ranges of susceptibility, quantification and mitigation.
- This presentation will step through:
  - What LeTID is;
  - How the standards realm is responding;
  - How PVEL as a test lab is informing the industry through collaborative knowledge and our own experiments.



Responses to PVEL Survey of Downstream Partners:
What module defect(s) concern you the most?

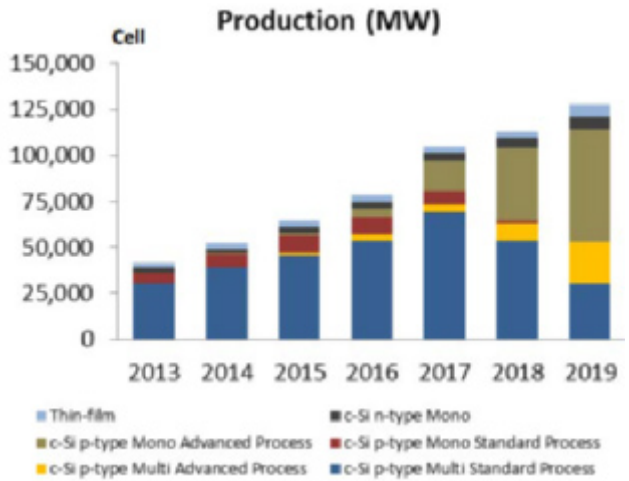
How Does LeTID Relate to LID?

- Historically “LID” usually only refers to boron-oxygen complex induced LID (“BO-LID”) as the main factor of the initial LID in crystalline Si solar cells.
- In a more general sense, some use “LID” to refer to any light induced degradation, including BO-LID and LeTID; there is inconsistency in the terminology being used.

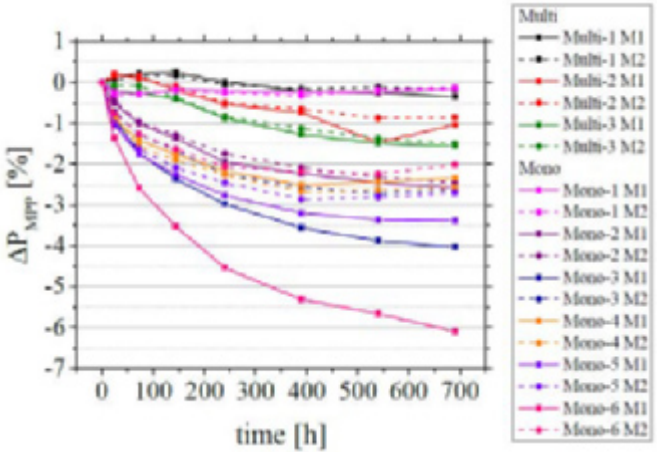
	BO-LID	LeTID
Industry’s understanding	Fairly high (decades of research)	Growing (~4 years of research)
Timeframe	Hours/days/weeks	Weeks/months/years
Cell types affected	p-type x-Si	Mainly x-Si PERC/PERT
Temperature required	Lower cell temperatures (<50°C?)	Higher cell temperatures (>50°C?)
Maximum power loss	Typically <5%	Up to 10% or more

What is Affected by LeTID?

- Studies have shown that advanced cell architectures (PERC/PERT/PERL) are most susceptible to LeTID, including both mono and multi.
- There are known methods to mitigate LeTID at the cell level.



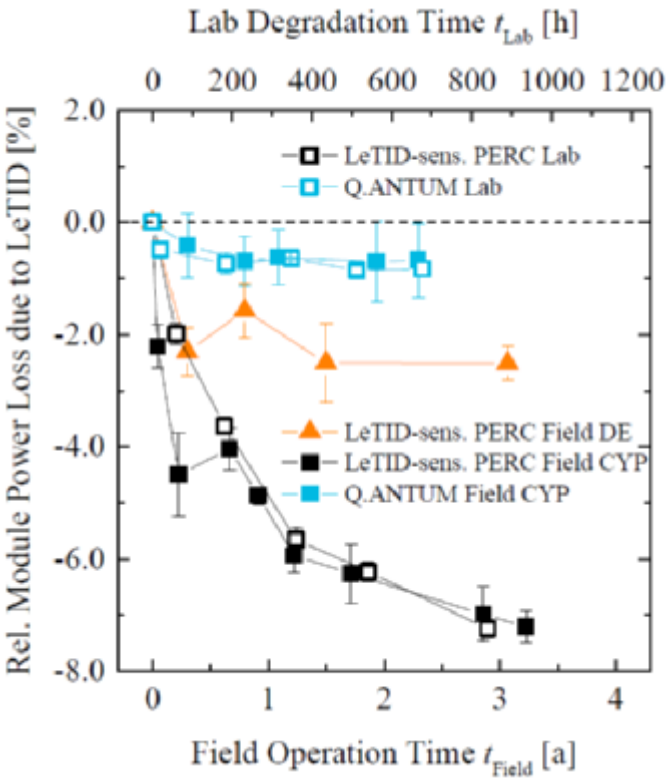
Advanced cells: >50% of market share in 2019
Source: PVTech, 2018



Benchmarking commercially bought modules for LeTID
(75°C, Isc-Imp, 690 hrs.)
Source: M. Pander et al., 2018

Correlating Lab Testing and Field Degradation

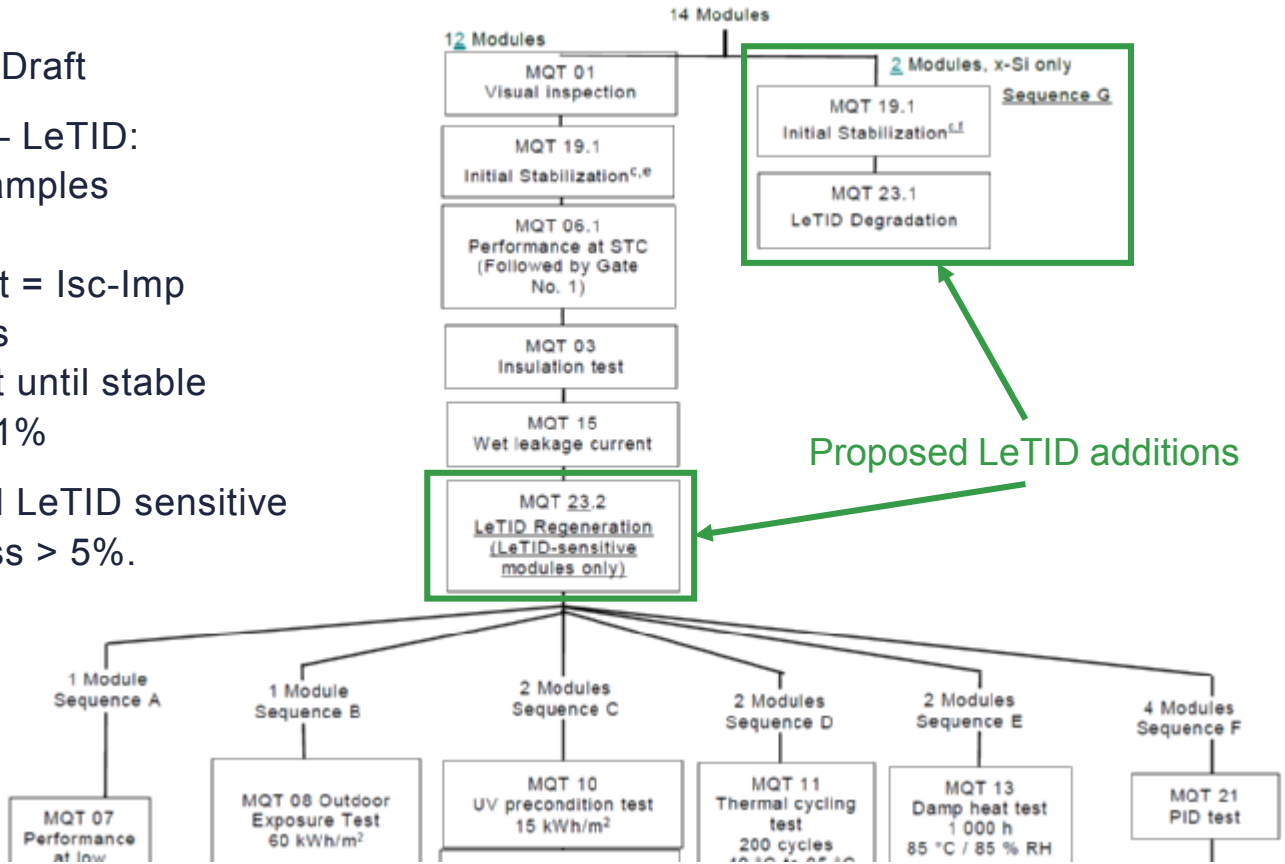
- 290 hours in chamber at 75°C/Isc-Imp is equivalent to 1 year of exposure in Cyprus
- Degradation rates >6%
- Lower degradation in more temperate climates (Germany)



Source: Kersten et al., 2017

How Are Standards Bodies Responding?

- IEC 61215 Draft
- MQT 23.1 – LeTID:
  - Two samples
  - 75°C
  - Current = Isc-Imp
  - 162 hrs
  - Repeat until stable within 1%
- Considered LeTID sensitive if power loss > 5%.



IEC 61215 Draft – Modified Flow Charts Based on LeTID Sensitivity

If deemed not LeTID sensitive:

12 Modules

↓

MQT 1
Visual Inspection

↓

MQT 19.1
Initial Stabilization

↓

MQT 06.1
Performance at STC
(used for Gate 1)

↓

MQT 03
Insulation Test

↓

MQT 15
Wet Leakage Test

↓

Continue to six other tests
(DH, TC, PID, etc)

If deemed LeTID sensitive:

12 Modules

↓

MQT 1
Visual Inspection

↓

MQT 23.1
LeTID Detection

↓

MQT 06.1
Performance at STC
(used for Gate 1)

↓

MQT 03
Insulation Test

↓

MQT 15
Wet Leakage Test

↓

MQT 23.2
LeTID Regeneration

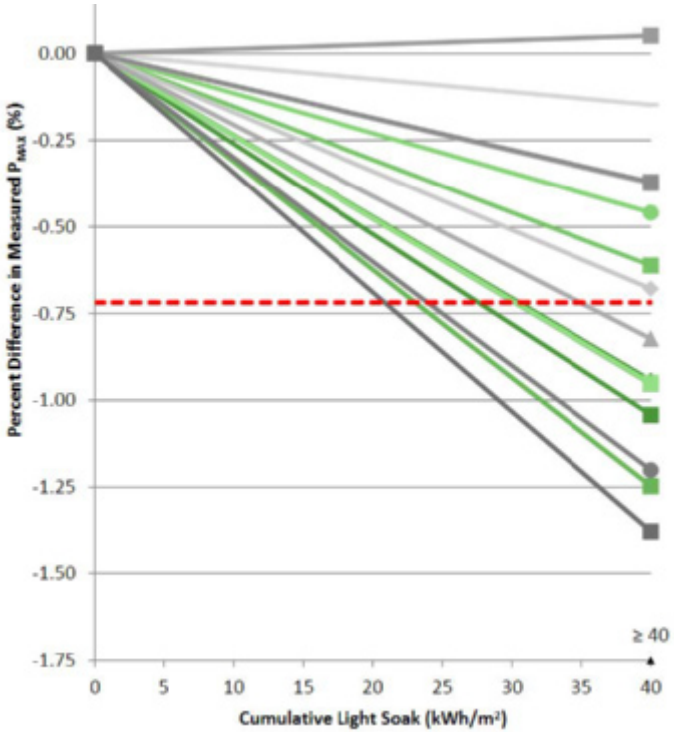
↓

Continue to six other tests
(DH, TC, PID, etc)

- MQT 23.1 for all
- MQT 23.2 – LeTID Regeneration:
  - all samples
  - 85°C,
  - current = Isc
  - 500 hrs
  - repeats for 162 hrs until stable within 1%

Concerns and Open Questions with LeTID Testing

- Complete BO-LID testing at a maximum of 50°C before MQT 23.1 – how is this done realistically and affordably?
- Is 5% degradation too high to be deemed LeTID sensitive?
- How will the module respond to other stresses post MQT 23.2 regeneration? Has this been fully vetted?
- Is using only two samples statistically relevant to determine LeTID sensitivity?



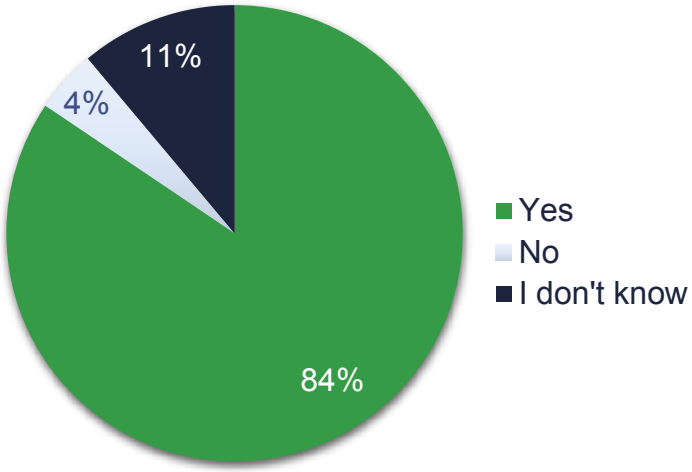
Varying LID Results on Identical Modules
Source: PVEL

PVEL launched the Product Qualification Program (PQP) in 2012 with two goals:

1. Provide PV equipment buyers and power plant investors with independent and consistent reliability and performance data to support implementation of an effective supplier management process.

2. Provide independent recognition to module manufacturers who outpace their competitors in product quality and durability.

› LeTID susceptibility testing is one of the most requested additions to PVEL's PQP from our Downstream Partners (developers, investors, insurance companies).



Responses to PVEL Survey of Downstream Partners:
Should PVEL's Module PQP include an LeTID Susceptibility Test?

PVEL's LeTID Experiments

- PVEL is currently working with NREL, UNSW, Downstream Partners and >10 module manufacturers on a number of LeTID tests.

Test Location	Test Conditions
Climate Chamber	MQT23.1: 75°C, Isc-Imp, 162 hrs – repeat until stabilized
Climate Chamber	90°C, Isc-Imp, 24 hrs – repeat until stabilized
Climate Chamber	90°C, Isc, 24 hrs – repeat until stabilized
Climate Chamber	85°C/85% RH, Isc, 24 hrs – repeat until stabilized
Indoor Sun Simulator	~95°C, 5 min. IV curves, flash every 24 hrs – repeat until stabilized
Indoor Sun Simulator	~75°C, 5 min. IV curves, flash every 24 hrs – repeat until stabilized
Outdoor	Rooftop with insulation behind module to raise temp, keep at Mpp, 5 min. IV curves, flash weekly – repeat until stabilized
Outdoor	Rooftop with insulation behind module to raise temp, keep at Voc, 5 min. IV curves, flash weekly – repeat until stabilized

- The goal is to correlate chamber tests to indoor sun simulator and outdoor results.
- Plan to publish results as part of the next PQP launch.

PVEL

MAKE DATA MATTER.

THANK YOU

Tristan Erion-Lorico, Head of PV Module Business

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pvel.com

Qualification of PV Modules – Status of the IEC 61215 New Edition

Tony Sample

The European Commission's science and knowledge service

Joint Research Centre

ESTI

European Commission

61215 New Edition Project Team

43 Members

Project leader ***Ingrid Repins***

Keita Arihara, Markus Beck, Karl Berger, Rakesh Bohra, Yoshihito Eguchi, Peter Hacke, Nadeem Haque, Werner Herrmann, Jin Hao, Takamitsu Inoue, Takashi Ishihara, Lukas Jakisch, Eckart Janknecht, Jurgen Jung, Noboru Kawase, George Kelly, John Jongin Kim, Gerhard Kleiss, Max Koentopp, Jaesun Lee, Kyumin Lee, Michael Li, Bill Liu, Lifang Liu, Christos Monokroussos, Georg Muelhoefer, Nancy Phillips, Ingrid Repins, Paul Robusto, Keichiro Sakurai, Tony Sample, Darshan Schmitz, Peter Seidel, Narendra Shiradkar, Ron Sinton, Hiromi Tobita, Shuuji Tokuda, Guido Volberg, Kent Whitfield, Harrison Witterdink, John Wohlgemuth, Isao Yoshida

30 Companies and 10 National Committees

European Commission

Overview

Overview of existing IEC 61215: 2016

Some of the planned technical changes in the new edition

- Procedures for bifacial modules
- Addition of dynamic mechanical load test
- Addition of potential induced degradation test
- Simulator requirements
- Use of representative samples
- Proposed test for Light and Elevated Temperature Degradation (LeTID)

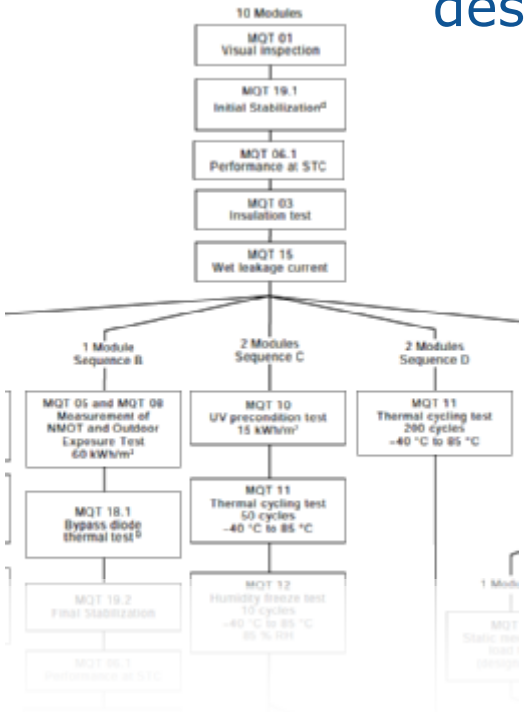
Keeping costs and testing times reasonable

How you can get involved

European Commission

Existing IEC 61215 Series for PV Module Design Qualification

Are modules of this design likely to last?



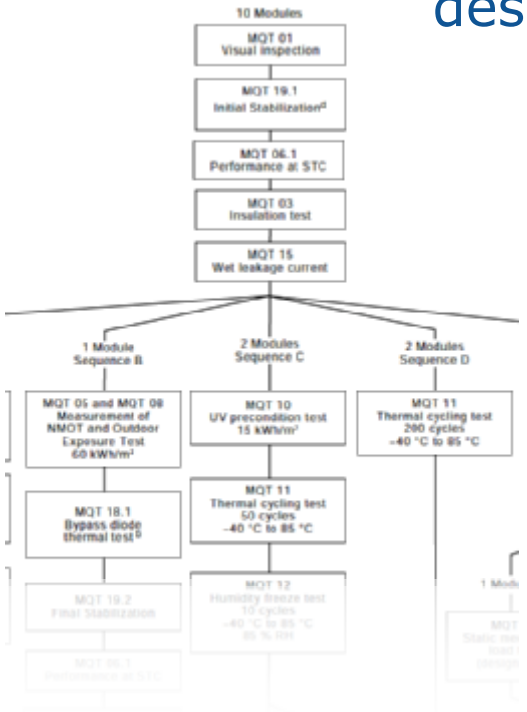
Small sample set: 10 modules

Sequence of accelerated stress tests that have been empirically related to field failures.

European Commission

Existing IEC 61215 Series for PV Module Design Qualification

Are modules of this design likely to last?



Small sample set: 10 modules

Sequence of accelerated stress tests that have been empirically related to field failures.

Evaluate whether performance matches label ("gate 1") and whether there is 95% performance retention after stress ("gate 2").

European Commission

Existing IEC 61215 Series for PV Module Design Qualification

Are modules of this design likely to last?

Small sample set: 10 modules

Sequence of accelerated stress tests that have been empirically related to field failures.

Evaluate whether performance matches label ("gate 1") and whether there is 95% performance retention after stress ("gate 2").

Six documents (61215-###) describe general requirements, test flows, test procedures and apparatus, and small differences needed to implement some tests for different cell technologies.

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Procedures for Bifacial Modules – Performance Verification

Bifacial modules are qualified under IEC 61215:2016 as if back side produces no power.
New edition - Gates 1 and 2 are performed at two irradiances: STC, and with 135 W/m^2 on backside.
Rear irradiance based on published studies involving typical albedos and row spacings.
Measurement may be made using any method prescribed in IEC TS 60904-1-2.

New edition will check this and apply higher current during stress tests

IEC 61215-2:2016 tests only this

Electrical Specifications

		Specifications Including Backside Irradiation Contribution in ISC as a Percent of STC					
Model: HIP-190DA3	STC[1]	5%	10%	15%	20%	25%	30%
Rated Power (Pmax)[1]	190 W	199 W	208 W	216 W	225 W	234 W	243 W
Maximum Power Voltage (Vpm)	55.3 V	55.30 V	55.36 V	55.42 V	55.50 V	55.52 V	55.56 V
Maximum Power Current (Ipm)	3.44 A	3.60 A	3.75 A	3.91 A	4.06 A	4.22 A	4.37 A
Open Circuit Voltage (Voc)	68.1 V	68.3 V	68.4 V	68.5 V	68.6 V	68.6 V	68.8 V
Short Circuit Current (Isc)	3.7 A	3.89 A	4.07 A	4.26 A	4.44 A	4.63 A	4.81 A

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Procedures for Bifacial Modules – Applied Stress Conditions

- Where measured current determines applied stress, a higher current is used.
- The higher current is that measured with near worst-case rear irradiance of 300 W/m^2.
- The general approach of multiple irradiances will likely persist to publication. The choice of irradiances may be further discussed in IEC working group 2.

Stress	Test # (MQT)	Level for Monofacial Module	Level for Bifacial Module
Hot Spot Endurance	09	1000 W/m^2	1300 W/m^2
UV Exposure	10	Front side only	Front then rear side
Thermal Cycling	11	I_{mp} @STC	I_{mp}@(STC+ 300 rear)
Bypass Thermal Diode Test	18.1	Test Current = 1.25 x I_{sc} @STC	Test Current = 1.25 x I_{sc} @(STC + 300 rear)
Bypass Diode Functionality Test	18.2	Test Current = 1.25 x I_{sc} @STC	Test Current = 1.25 x I_{sc} @(STC + 300 rear)

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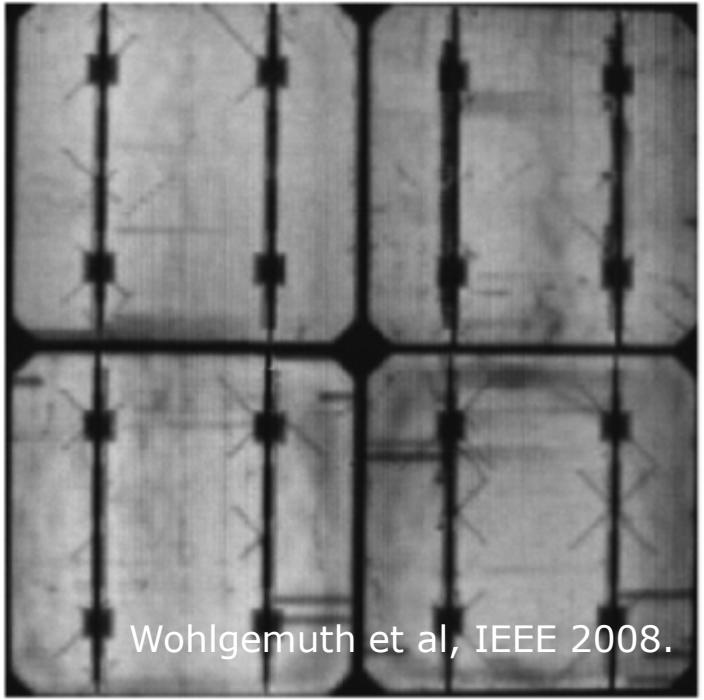
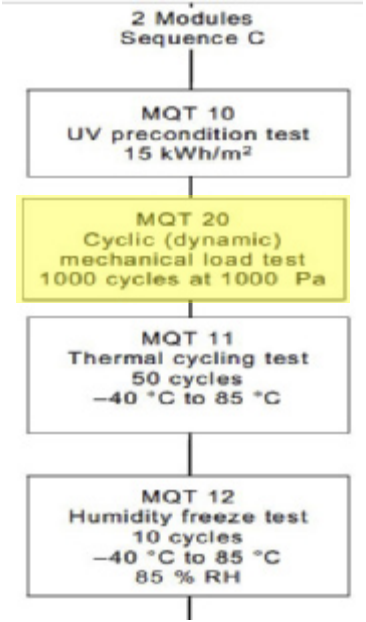
Addition of Dynamic Mechanical Load (DML) Test



- Tests for extreme susceptibility to mechanical stress. (E.g. cells that are already cracked at left.)
- 1000 Pa for 1000 cycles, based largely on BP data.
- Enough force and repetition to detect pre-existing problems.
- It is *not* a module abuse test.
- Test is added in. sequence C, between UV and thermal cycling
- Test is taken from IEC TS 62782.



Why Choose the Harshest PID Test Level?

$$Acceleration\ Factor = \frac{time\ to\ failure\ in\ field}{time\ to\ failure\ in\ test}$$

- Difficult choice: Acceleration factors vary with module design, cell type, mounting configuration, climate, etc.
- The PID test for Si may be around 20 years equivalent exposure in a climate like Florida, USA – less than a standard warranty period.
- Several major module manufacturers had already selected the 85°C/85% RH/96 hr stress level for internal qualification programs.
- Use of modules in PID-prone environments (e.g. rainy) may warrant a harsh test.
- The most susceptible designs from each device technology fail.
- Application of the same conditions to all module designs where possible is consistent with the rest of the standard (now stated explicitly in scope.)

Simulator Requirements – Why Change?

Simulator options for power measurement in 61215:2016

Class AAA simulator

(A Really Good Simulator)

BBA simulator + reference module of same size and cell technology

(A Really Good Reference Module)

Spectral responsivity of module + BBA simulator spectral data

(Really Good Data)

- Module fill factors are increasing (larger impact from spatial nonuniformity)
- Larger variety of class A simulator spectra, particularly with use of LED's
- Today's technology makes low total uncertainty possible, but published standard does not specify a requirement

Reminder: CBA = class C wavelength distribution, class B uniformity, class A stability

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Simulator Requirements – Uniformity

Irradiance non-uniformity [1]	Approximate power rating uncertainty due to all effects, when simulator irradiance is calibrated using a reference module's…	
	…maximum power	…short-circuit current
2% (class A limit)	2.6%	3.2%
5% (class B limit)	3.2%	6.2%

- Use of simulator with class B non-uniformity may result in unacceptably large errors.
- Simulators with class B uniformity are rarely used for qualification. All test labs attending working group 2 meeting already used simulators class A uniformity.

[1] Calculations are from: Monokroussos et al., EUPVSEC, 2013

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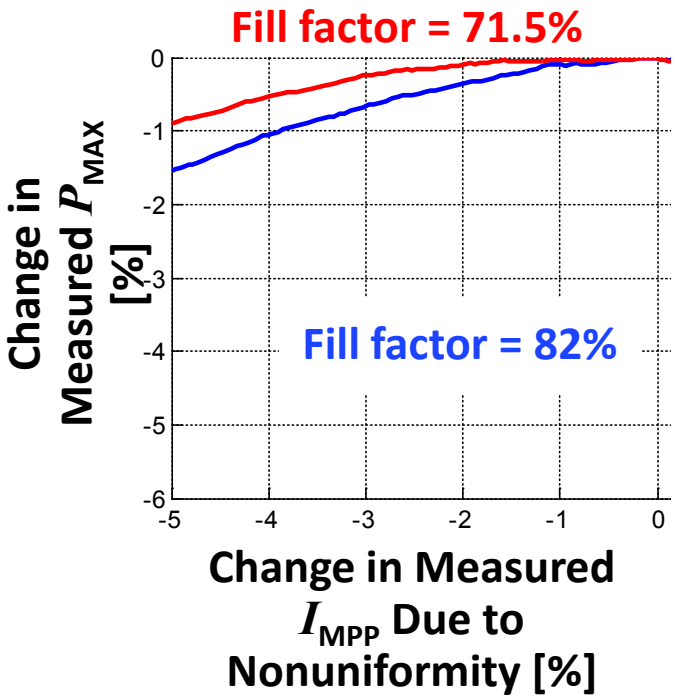
Simulator Requirements – Uniformity



- Use of simulator with class B non-uniformity may result in unacceptably large errors. Effect is larger for new, higher-efficiency modules.
- Simulators with class B uniformity are rarely used for qualification. All test labs attending working group 2 meeting already used simulators class A uniformity.

[1] Calculation method is from: Monokroussos et al., EUPVSEC, 2013

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Simulator Requirements – Uniformity

Simulator options for power measurement in 61215:2016

Class AAA simulator

(A Really Good Simulator)

~~B~~A BBA simulator + reference module of same size and cell technology

(A Really Good Reference Module)

Spectral responsivity of module + ~~B~~A BBA simulator spectral data

(Really Good Data)

- Module fill factors are increasing (larger impact from spatial nonuniformity)
- Larger variety of class A simulator spectra, particularly with use of LED's
- Today's technology makes low total uncertainty possible, but published standard does not specify a requirement

Reminder: CBA = class C wavelength distribution, class B uniformity, class A stability

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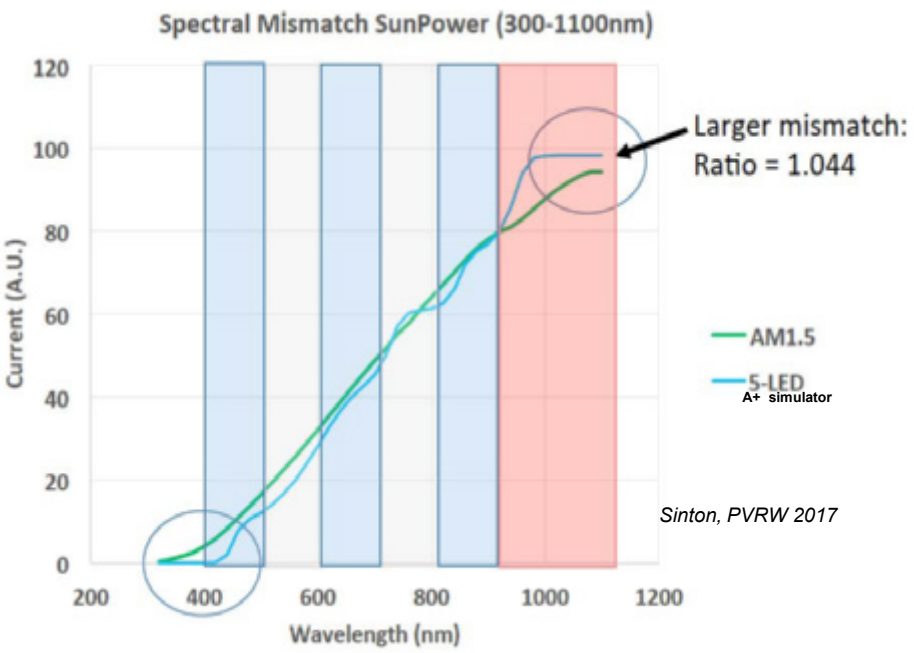
Change in Simulator Requirements –Spectral Match



Sinton, PVRW 2017

- Problem: Published data show that use of AAA simulator without spectral mismatch correction can result in large systematic offset.
- > 4% in extreme cases
- With spectral mismatch correction, CBA simulator provides accuracy current measurement <1%.
- However, requiring a matched module or spectral responsivity measurement may put an unrealistic burden on test labs who only measure more typical cases.

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Simulator Requirements – Why Change?

Specifically state that uncertainty (m_1 in gate 1) must include spectral mismatch component. Can be evaluated from worst-case *published* values for technology type.

Class AAA simulator

(A Really Good Simulator)

A

C ~~BBA~~ **simulator + reference module of same ~~size and cell technology~~** **or cell**

BOM

(A Really Good Reference Module)

Spectral responsivity of module + ~~BBA~~ simulator spectral data

A

C

(Really Good Data)

Upper limits on m_1 in technology-specific parts: 3.0% for x-Si, 4.0% single-junction thin film, 5.0% for multi-junction thin film.

- Module fill factors are increasing (larger impact from spatial nonuniformity)
- Larger variety of class A simulator spectra, particularly with use of LED's
- Today's technology makes low total uncertainty possible, but published standard does not specify a requirement

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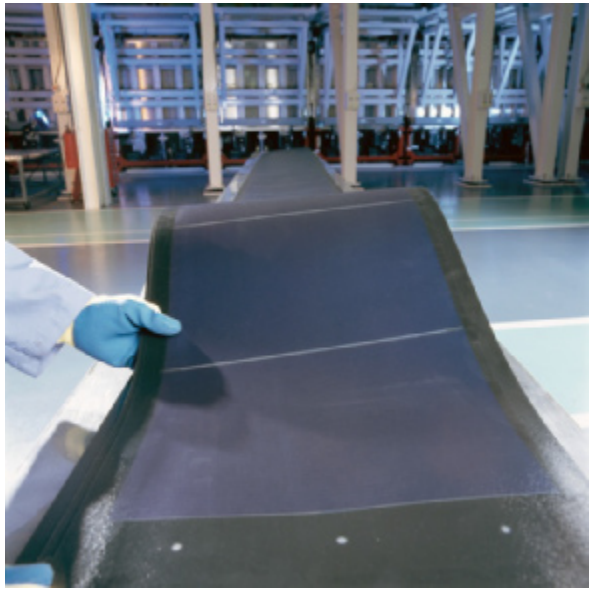
Use of "Representative Samples"

- A small fraction of new products anticipated for qualification are much larger than typical test equipment.
- Requiring a test lab to obtain custom test equipment for one product is expensive and would create an unfair barrier to certification.
- Thus, representative samples may be used for applying stress and evaluating gate 2 on very large modules.
- Eligible modules are those that will not fit on typical large commercially-available AAA simulators. (2.6 m x 2.1 m)



- Reduced dimension(s) shall be no less than one half those that define an eligible module. (Thus one-cell mini-modules, for example, are NOT acceptable for qualification testing.)
- A full-sized sample is still required for nameplate verification (gate 1).

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LeTID

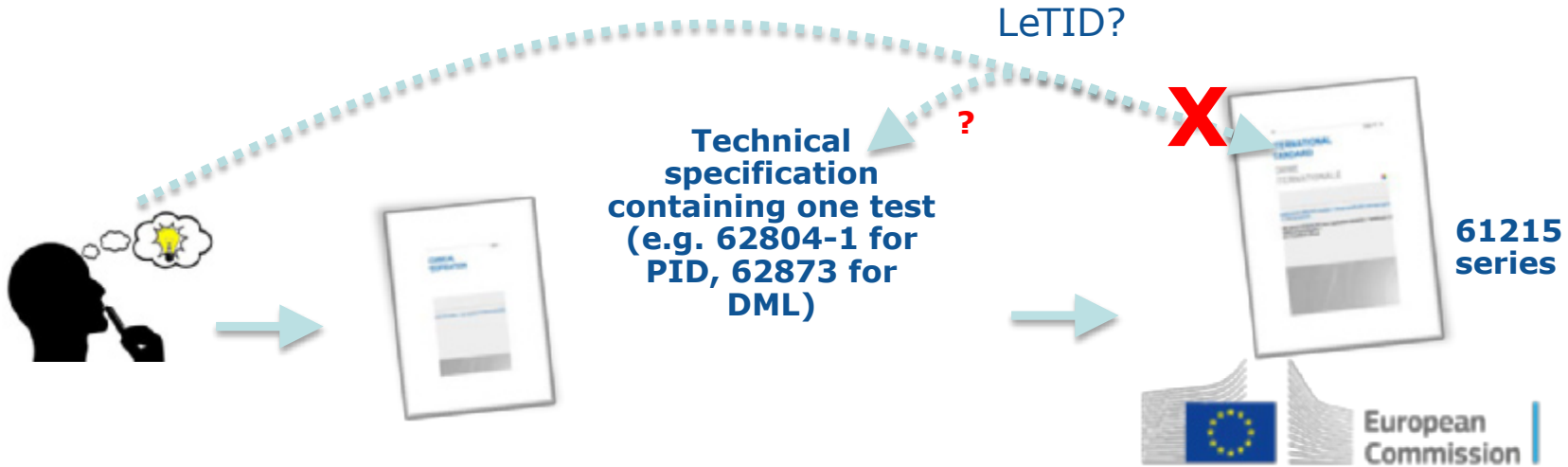
Some of the planned technical changes in the new edition

- Proposed test for Light and Elevated Temperature Degradation (LeTID)

Has been discussed previously, so won’t go into detail

Proposed LeTID Test in IEC 61215 New Edition

- The usual progression for introducing a new test into 61215 is to develop a separate technical specification first.
- However, IEC working group 2 felt that addressing LeTID is urgent, and it should be attempted to introduce a LeTID test directly into the 61215 new edition.
- Developed procedure. Evaluating its maturity via international collaborative study.
- Prior to CDV (this spring) recommend inclusion in 61215 or separate TS.



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Balancing Cost Versus Confidence

- Added DML, PID, weight on jbox during TC, and (maybe) LeTID tests.
- These tests each address observed field failures.

- Removed NMOT test
- Harmonize voltage levels between 61215 and 61730 insulation tests
- Limit bypass diode testing to 3 diodes
- Reduce # modules in sequence A (characterization) from 3 to 1.
- Provide flexibility in simulator requirements
- Introduced representative samples

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How You Can Get Involved

- **Contact Project leader (ingrid.repins@nrel.gov) or your colleagues on the project team with specific suggestions.**
- **(This process works; for example, it's how the decision to remove NMOT began.)**

- **Join (or start) a PV Quality Assurance Task Force (PVQAT) subject area task group.**
- **PVQAT task groups meet by telecon and collaborate to help develop the scientific basis for standards.**
- **The PVQAT organization has a formal liaison with the IEC.**

- **Become an IEC working group 2 member through your national committee, or be an observer.**

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Summary - Status of the IEC 61215 New Edition

- The committee draft for vote (CDV) is being prepared.
- Publication is expected early in 2020.
- The largest technical changes in the new edition relate to
  - Procedures for bifacial modules
  - Addition of dynamic mechanical load test
  - Addition of potential induced degradation test
  - Simulator requirements
  - Use of representative samples
  - Proposed test for Light and Elevated Temperature Degradation (LeTID)
- The LeTID test may be separated from 61215 into a stand-alone technical specification later this year if working group 2 believes it is not mature enough for the 61215 CDV.
- The project team has attempted to balance confidence (from new tests) with steps to minimize qualification cost and time.
- Your input is important!

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Changes in solar simulator classification and significance for PV power measurement

NREL PV Reliability Workshop 2019
26-28 February 2019, Lakewood Denver West Sheraton

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Outline

- Introduction
- Solar simulator classification
- Major changes in IEC 60904-9 Ed. 3 (CDV)
- Comparative spectral analysis of commercial solar simulators
- Informative Annex – Tool for PV device specific spectral evaluation
- Summary

Introduction

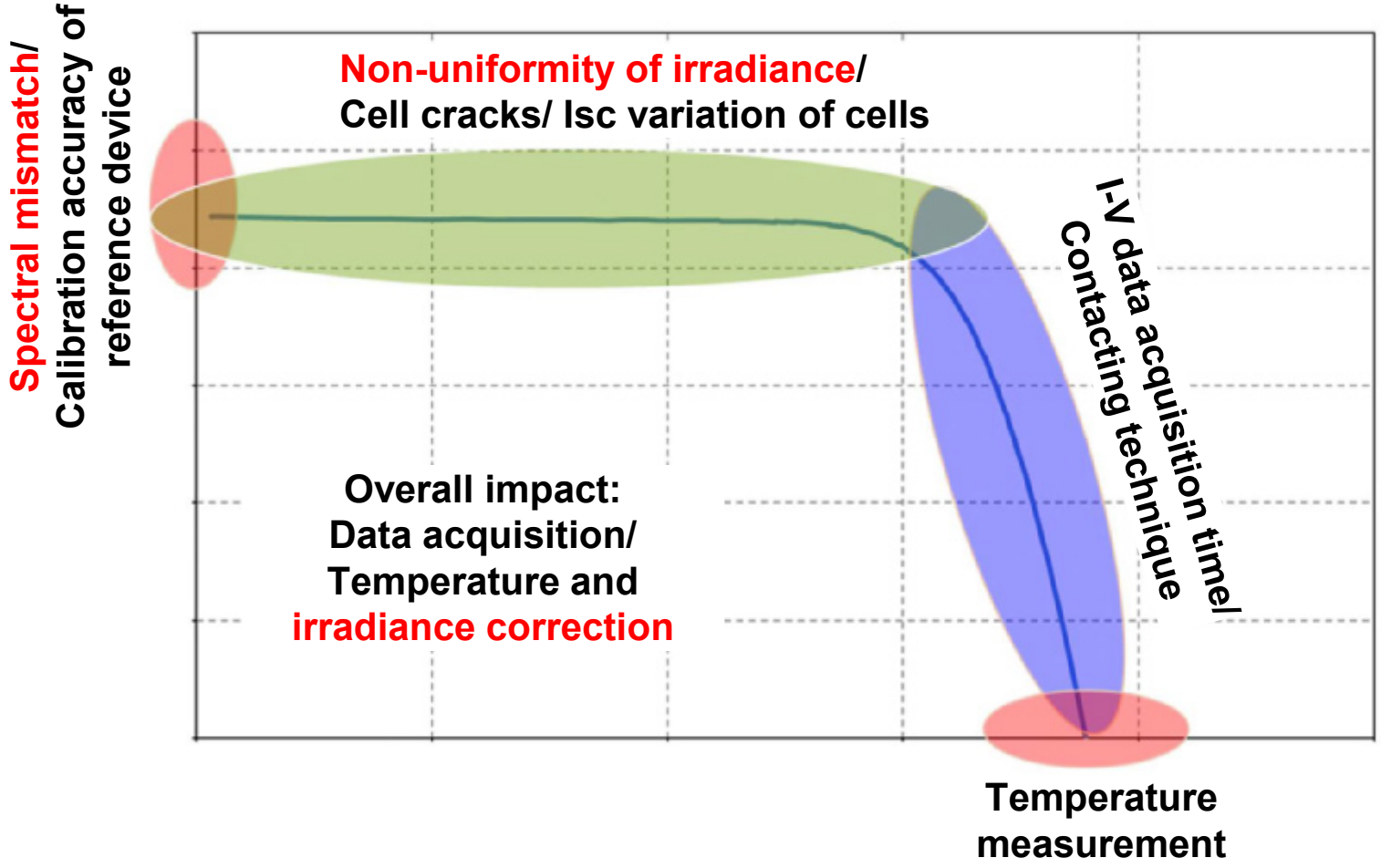
PV module output power characterization is the most common application for solar simulators in PV industry and in PV test institutes

Advantages
▪ Measurement is independent from weather conditions ▪ High reproducibility <±0.5% is achieved due to adjustable test conditions

- **Performance at STC** (cell and module level): IEC 60904-1,IEC 60904-3, IEC 60904-8, IEC 60904-10
  ⇨ Calibration measurement, power class sorting in production lines (cells and modules)
- Determination of **PV module parameters** for temperature and irradiance correction: IEC 60891
- PV module **energy rating**: IEC 61853-1, IEC 61853-2
- PV module **angular response**: IEC 61853-2
- **Electrical stabilization** of PV modules: IEC 61215-1-X
- Quantification of **output power degradation**: IEC 61215-1

Solar simulator are no perfect light sources compared to natural sunlight ⇨ **Uncertainty of PV power measurement**

Introduction – Complexity of PV power measurements



Uncertainty sources:

- Calibration accuracy of sensors
- I-V data acquisition
- **Solar simulator properties**
- Measurement technique
- PV device properties

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Solar simulator classification – IEC 60904-9 Ed. 2 (2007)

The test standard **IEC 60904-9** provides the required methodologies for determining the classification of solar simulators in three categories:

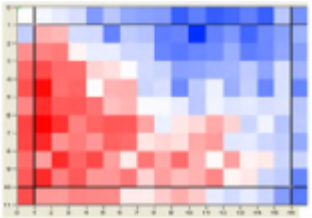
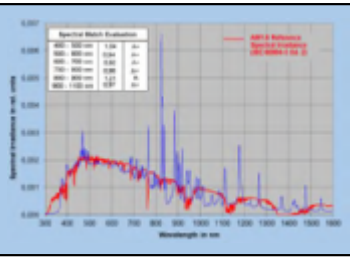
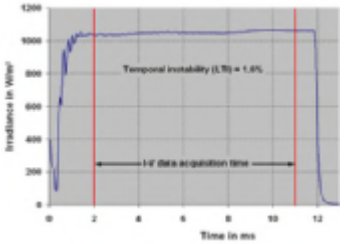
a) **Spectral match** to AM1.5 reference spectral irradiance distribution as defined in IEC 60904-3.
b) **Spatial non-uniformity of irradiance** in the test area;
c) **Temporal instability of irradiance** during I-V data acquisition time (if power measurement);

- Based on the technical criteria, for each category solar simulators are classified as A, B or C.

The calculation procedures of the quality parameters are only based on light properties and not on the PV device technology (irradiance approach). !

Using a solar simulator of a particular class does not eliminate the need to quantify the influence of the simulator on the measurement. !

Solar simulator classification – IEC 60904-9 Ed. 2 (2007)

QUALITY PARAMETER	EXAMPLES	CLASSIFICATION		
		A	B	C
Non-uniformity of Irradiance $\frac{Max - Min}{Max + Min} x100\%$		<2 %	<5 %	<10 %
Spectral match to AM 1.5 reference spectral Irradiance (IEC 60904-3) in six wavelength intervals: 400 – 500 – 600 – 700 – 800 – 900 – 1100 nm		±25 %	± 40 %	–60 % to +100 %
Temporal instability of emitted light during I-V data acquisition: LTI = Long Term Instability (STI) = Short Term Instability (relevant for non-simultaneous I-V data acquisition)		<2 % (0,5%)	<5 % (2%)	<10 % (10%)

Solar simulator classification – Impact of non-uniform irradiation

- PV module I-V curve results from interaction of three parameters:

Irradiance distribution at cells
⇨ Measurement, dependent on module size

Reverse I-V curve of cells
⇨ Determination by module I-V measurement and cell shading

Isc tolerance of cells
⇨ Data sheet: Isc difference of consecutive power classes

Irradiance distribution [W/m²]

994	993	990	985	977	965
1002	1002	999	994	987	976
1007	1006	1004	998	991	982
1010	1009	1006	1000	993	985
1012	1010	1007	1002	995	987
1014	1011	1008	1002	996	988
1014	1012	1009	1004	997	990
1014	1013	1011	1006	999	989
1015	1014	1011	1007	999	987
1014	1014	1011	1005	997	984

Shunt resistance [Ohm]

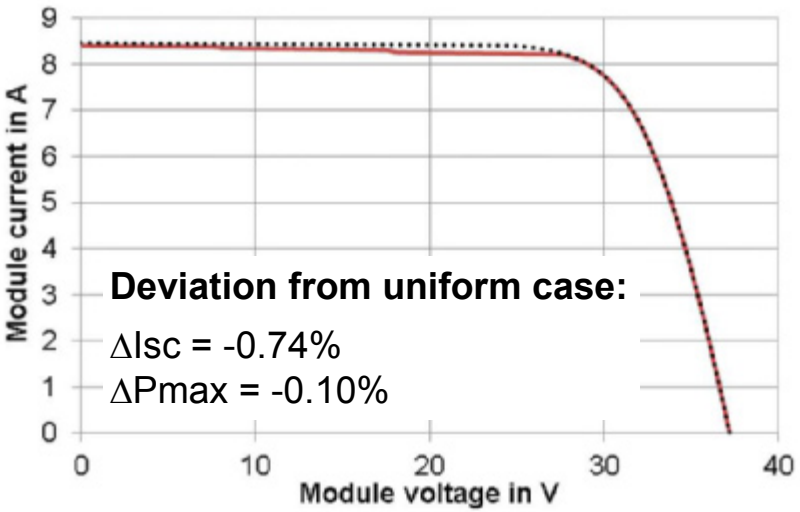
361	554	527	380	299	217
338	169	191	215	140	259
154	453	257	214	575	372
330	367	173	269	478	333
224	235	338	316	252	388
380	335	314	257	425	378
220	241	290	441	122	328
428	261	315	253	218	357
232	177	305	286	363	121
325	476	63	391	233	274

Isc spread related to nominal Isc [%]

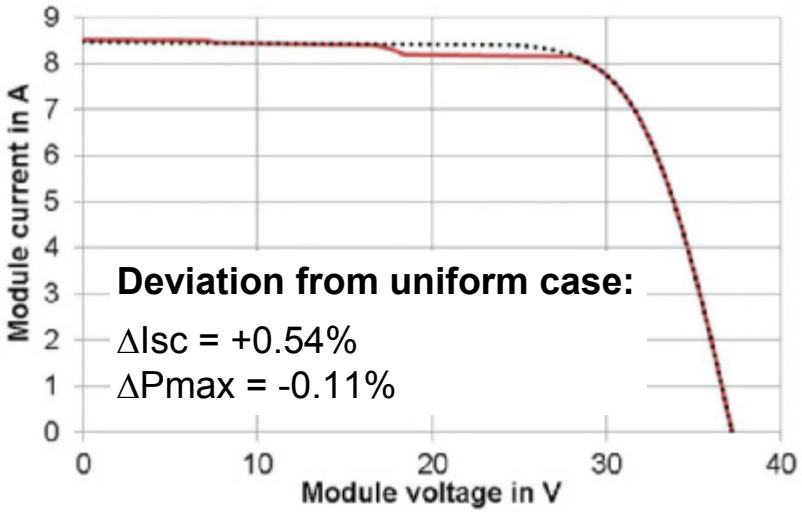
0,22	-0,49	-0,25	-0,60	-0,25	0,34
0,81	-0,84	-0,49	-0,84	-0,60	0,34
-0,60	-0,13	-0,13	0,10	-0,02	-0,49
-0,49	-0,02	-0,13	0,10	0,57	-0,37
-0,13	0,69	0,22	0,34	-0,49	0,46
-0,02	-0,72	-0,02	-0,37	0,46	-0,13
-0,37	-0,02	-0,84	1,04	0,34	0,10
0,22	0,46	-0,02	-0,84	-0,37	0,81
0,10	-0,37	0,57	-0,02	0,10	0,46
-0,49	0,22	0,81	0,22	0,81	1,04

Solar simulator classification – Impact of non-uniform irradiation

Initial measurement



Module 180° rotated



Simulation inputs

- **PV module:** 60 c-Si cells, 3 diodes
- **Average irradiance:** 1000 W/m²
- **Irradiance non-uniformity:** 2.5% ,
- **Isc variation of cells:** 1%
- **Cell shunt resistance:** 60 Ω – 600 Ω

- 2% non-uniformity can cause Isc error up to 1% ⇨ **PV Module calibration requires <1% non-uniformity!**
- Minor impact on Pmax value as long as average irradiance corresponds to the target value.

Detection of module degradation: To achieve highest accuracy, I-V re-measurements shall be performed with the same solar simulator, at same position and with the same module orientation **!**

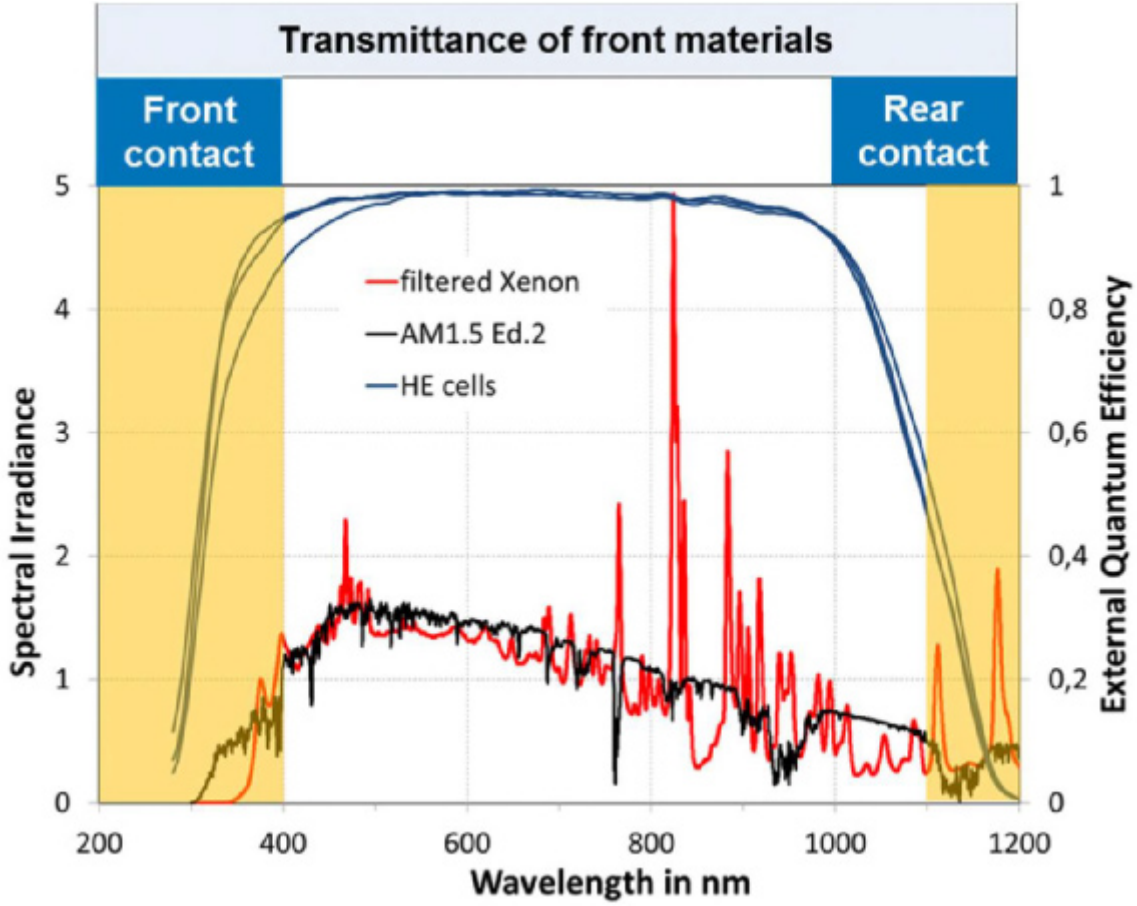
Solar simulator classification – Needs for change of spectral classification

Natural sunlight : For c-Si PV devices up to 4% of photocurrent of is generated outside the wavelength range 400 nm to 1100 nm.

Limited wavelength range 400 -1100 nm will not detect output power changes due to:

- Variation in spectral responsivity <400 nm or >1100 nm (i.e. HJT, PERC).
- Improvements in transmittance of front materials (<400 nm)
- Degradation of cells or front materials, which occurs outside 400 nm – 1100 nm.

Isc temperature coefficient of c-Si devices: Precise measurement will require spectral irradiance contribution in the wavelength range >1000 nm.



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Major changes in IEC 60904-9 Ed. 3 (CDV)

- Changed title **“Classification of solar simulator characteristics”**
- Added spectral match classification in the **extended wavelength range 300 nm to 1200 nm**;
- Introduction of **new A+ class** (twice as good as class A): This class category is primarily intended for calibration laboratories and is not considered necessary for power measurements in PV manufacturing and in qualification testing.
- Definition of additional parameters for spectral irradiance evaluation: **AM1.5 spectral deviation (SPD), AM1.5 spectral coverage (SPC);**
- Added **apparatus sections** for spectral irradiance measurement and spatial uniformity measurement;
- Revised procedure for spectral match classification (minimum 4 measurement locations);
- Revised measurement procedure for spatial uniformity of irradiance;
- Clarified applications, where LTI and STI are relevant for classification
- Added **informative Annex** for PV technology specific sensitivity analysis of spectral mismatch error.

Major changes in IEC 60904-9 Ed. 3 (CDV) – Spectral classification

New approach for spectral match classification:

- Extended wavelength range (300 – 1200 nm) but keep six wavelength intervals
- Range limits are defined by AM1.5 reference spectral irradiance (IEC 60904-3)
- Each interval contributes approx. one sixth to the total irradiance in the range 300 nm to 1200 nm

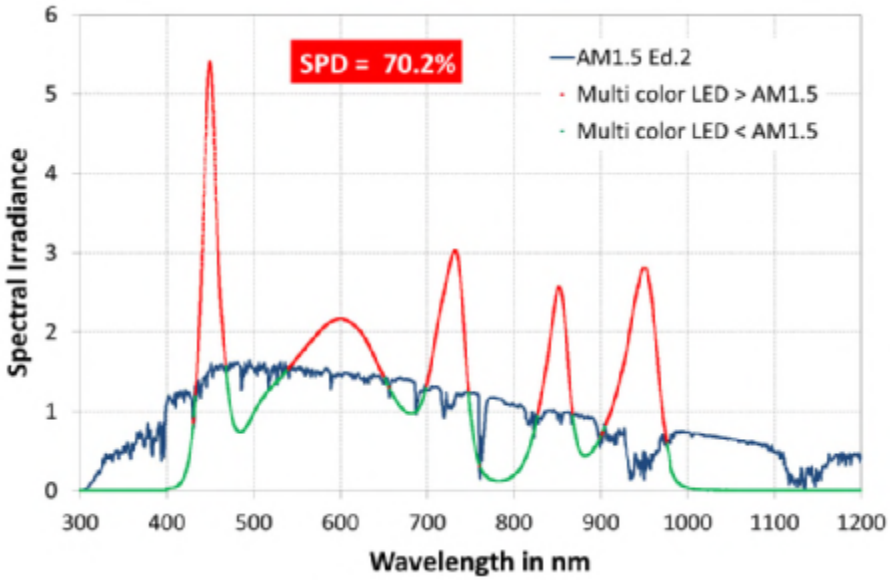
Interval	Wavelength range [nm]	Percentage of interval to total AM1.5 irradiance in the range 300 nm to 1200 nm	Cumulative integrated irradiance
1	**300 – 470**	16.61 %	16.61 %
2	**470 – 561**	16.74 %	33.35 %
3	**561 – 657**	16.67 %	50.02 %
4	**657 – 772**	16.63 %	66.65 %
5	**772 – 919**	16.66 %	83.31 %
6	**919 – 1200**	16.69 %	100.00 %

Backward compatibility: The procedure of the second edition of this standard is still valid, but shall only be applied if backward compatibility of solar simulators already in use is required.

!

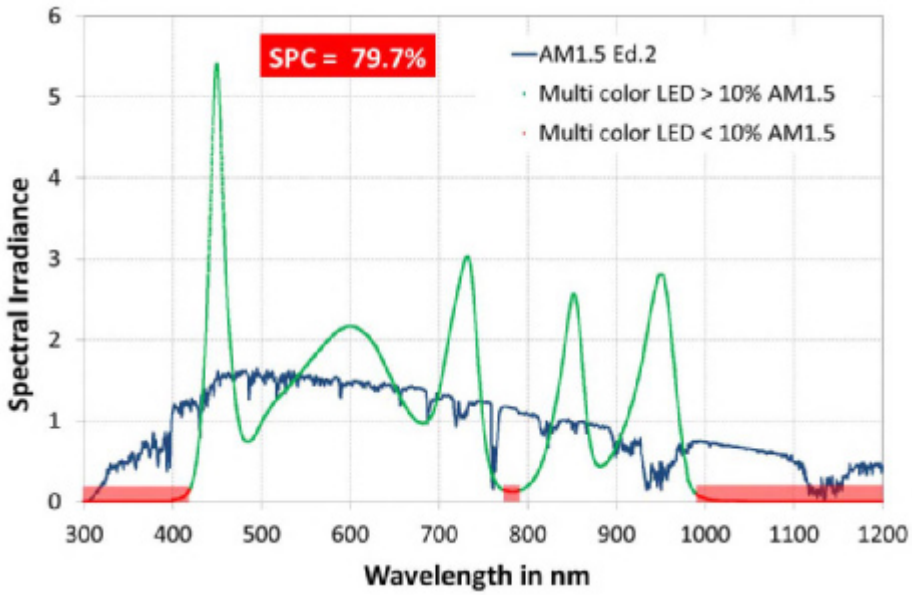
Major changes in IEC 60904-9 Ed. 3 (CDV) – New tools for spectral evaluation

AM1.5 spectral deviation (SPD)



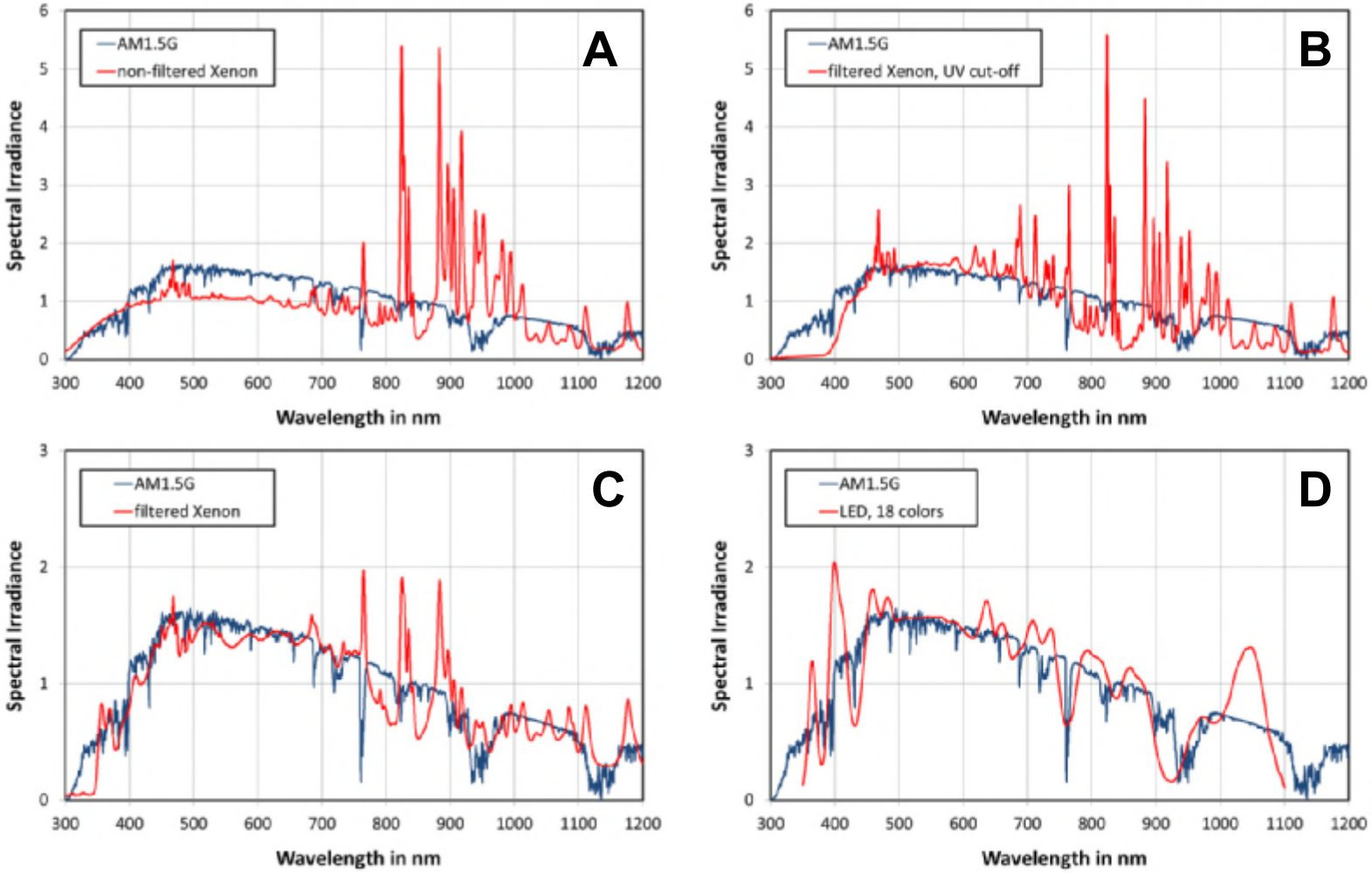
- SPD indicates how well the solar simulator spectral irradiance matches with AM1.5 spectral irradiance.
- SPD is the summed deviation between normalized solar simulator and AM1.5 spectral irradiance curves.
- Optimal match: SPD = 0%

AM1.5 spectral coverage (SPC)



- SPC identifies WL ranges, where solar simulator spectral irradiance is larger than 10% of AM 1.5 spectral irradiance.
- For all data points fulfilling this condition the corresponding AM 1.5 reference spectral irradiance is integrated.
- Optimal match: SPC = 100%

Comparative spectral analysis of commercial solar simulators



A:	Non-filtered Xenon
B:	Filtered Xenon (UV cut-off)
C:	Filtered Xenon
D:	Multi color LED (18 components)

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Comparative spectral analysis of commercial solar simulators

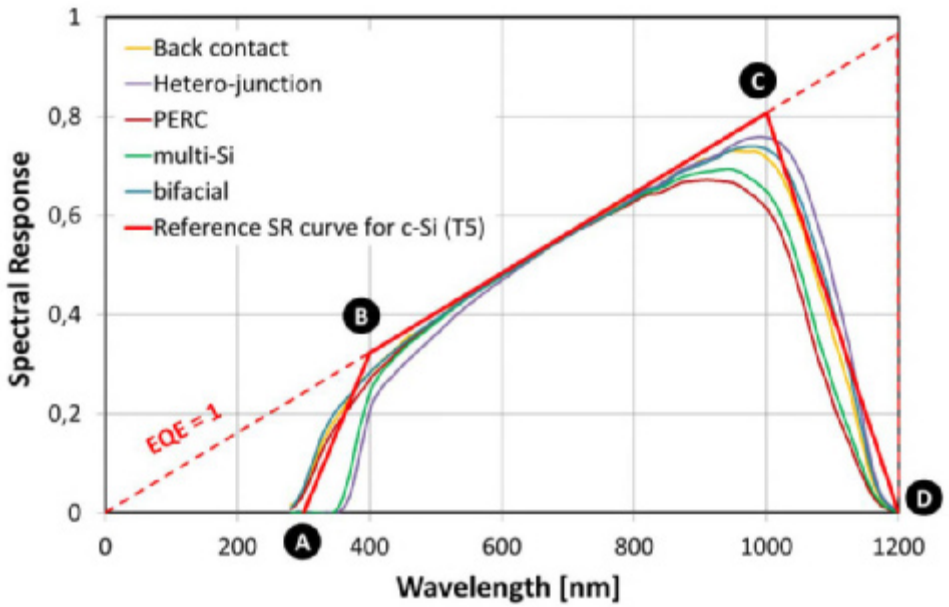
Type	Spectral class IEC 60904-9 Ed. 2	Spectral class acc. to IEC 60904-9 Ed. 3 (CDV)	SPC	SPD
Non-filtered Xenon	A B B A C C	A+ B B A C C	100%	49.9%
Filtered Xenon UV cut-off	A A A A A A	B A+ A+ A A+ A+	96.3%	38.3%
Filtered Xenon	A A A A A A	A+ A+ A+ A+ A+ A+	99.6%	16.6%
5 color LED	A A A A A A	A A B A A+ A	79.5%	70.2%
18 color LED	A A A A A A	A+ A+ A+ A+ A+ A+	94.6%	24.2%

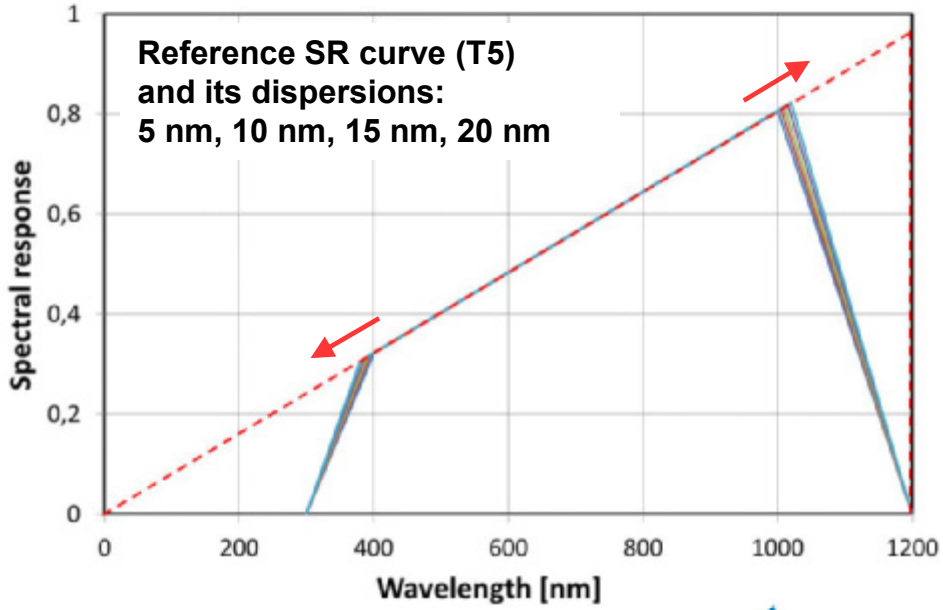
- **Xenon spectra:** High SPC values >95%, SPD value is considerably decreased by use of optical filters
- **LED spectra:** SPC and SPD values largely depend on the number of colors, upper range limit: 1100 nm

Parameters SPD and SPC can be used as additional quality indicators !

Informative Annex – Tool for PV device specific spectral evaluation

- Provides a procedure to analyze spectral impacts on measurement uncertainty.
- **Robustness for spectral mismatch error** is studied for an assumed spread of SR curves, which shall represent a production tolerance or SR changes due to degradation effects
- **Reference SR curves** (T1 .. T5) are defined for major PV technologies (4 points: A, B, C, D)
- **Dispersion SR curves** are generated by SR variation of the reference SR curve in steps of 5 nm in the lower and upper wavelength range (shift along line EQE=1).





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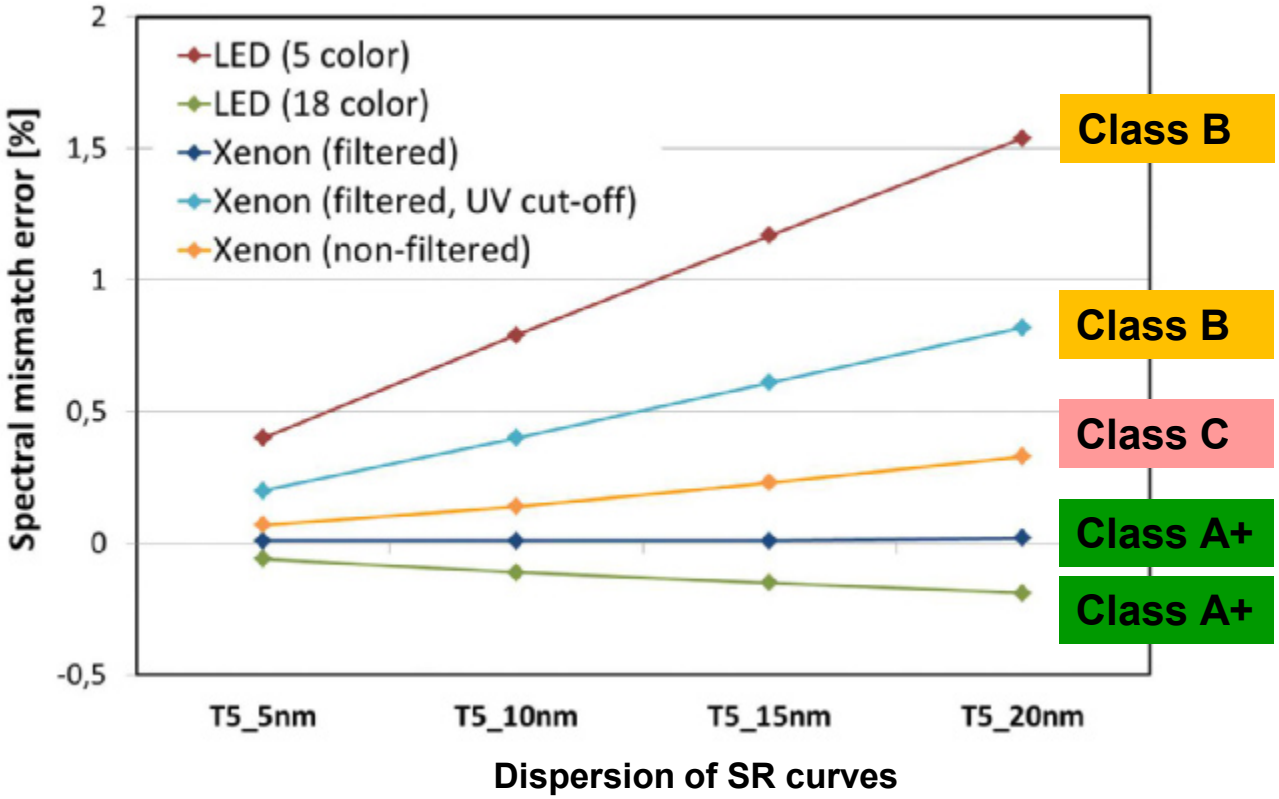
Precisely Right.

Informative Annex – Tool for PV device specific spectral evaluation

- Spectral mismatch error reference SR curve and modelled SR curves is plotted as a function of the wavelength dispersion.

- Device specific evaluation delivers a ranking of solar simulators regarding robustness for spectral mismatch error, if the SR of the test device is unknown.



A high spectral class not necessarily reduces uncertainties, which are related to SR variations (i.e. caused by production tolerances or change of materials) **!**

TÜVRheinland®
Precisely Right.

Summary

- **IEC 60904-9** ⇨ Defines the methodologies for classification, but not which class shall be used for which application.
- Specific focus on **revision of spectral classification:**

  a) **Extension of wavelength range** to 300 nm – 1200 nm ⇨ higher sensitivity to SR variations

  b) **Limited significance of spectral class** ⇨ Definition of new parameters to quantify the absolute difference between solar simulator and AM1.5 spectral irradiance distribution

     SPC – AM1.5 spectral coverage
     SPD – AM1.5 spectral deviation

  c) **Informative Annex** ⇨ Evaluate the impact of spectrally related production tolerances

Spectral evaluation beyond the letter grade

- **New class A+** addresses advances in solar simulator technology and allows for reduction in the uncertainty of secondary reference device calibration
- Revision of IEC 60904-9 is ongoing ⇨ CDV is currently circulation for comments
- IEC 60904-9 shall be used in combination with a **Technical Report IEC TR** (under consideration), which deals with best practice recommendations for PV module power measurement.

Acknowledgements

- **Members of the IEC 60904-9 revision team:**
  - Bengt Jaeckel, Fraunhofer CSP, Germany
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  - Jin Hao, Jinkosolar, China
  - Lifang, Jinkosolar, China
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  - Stefan Winter, PTB, Germany
  - Stefan Roest, Eternalsun, Netherlands
  - Tom Betts, CREST, UK
  - Tony Sample, Joint Research Center, Italy
  - Werner Herrmann, TÜV Rheinland, Germany
  - Yoshihiro Hishikawa, AIST, Japan
  - Zeng Xiangchao, Gsola, China

ANSI/CSA C450 Seq B Variations

CFV Solar Test Laboratory, Albuquerque NM, U.S.A.

Colin Sillerud, Jim Crimmins, Kyumin Lee

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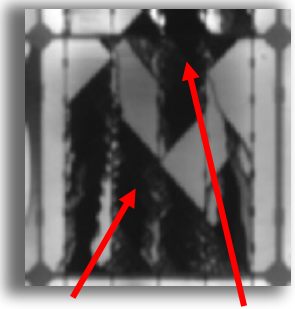
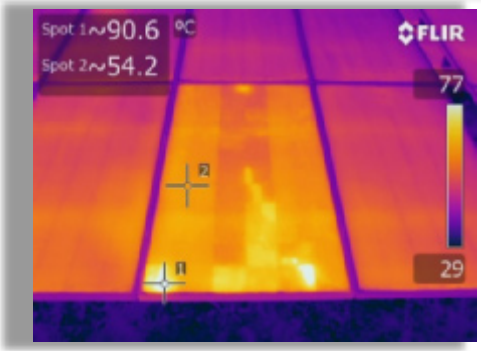
Motivation

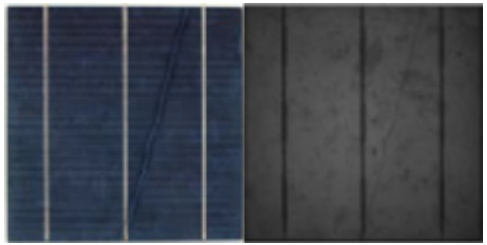
- Cell cracks in PV modules are considered to be problematic for several reasons:
  - Cell cracks can cause isolated power regions which result in power loss in the module.
  - Cell cracks can cause hot spot behavior due to uneven current flow through the active regions of the cell.
  - Cell cracks provide a path for moisture through the backsheet to the front of the cell surface, which can cause corrosion or “snail trails”, although this problem has been largely mitigated.



Electroluminescence image showing electrically isolated cell sections



Infrared image showing hotspots on electrically isolated cell sections

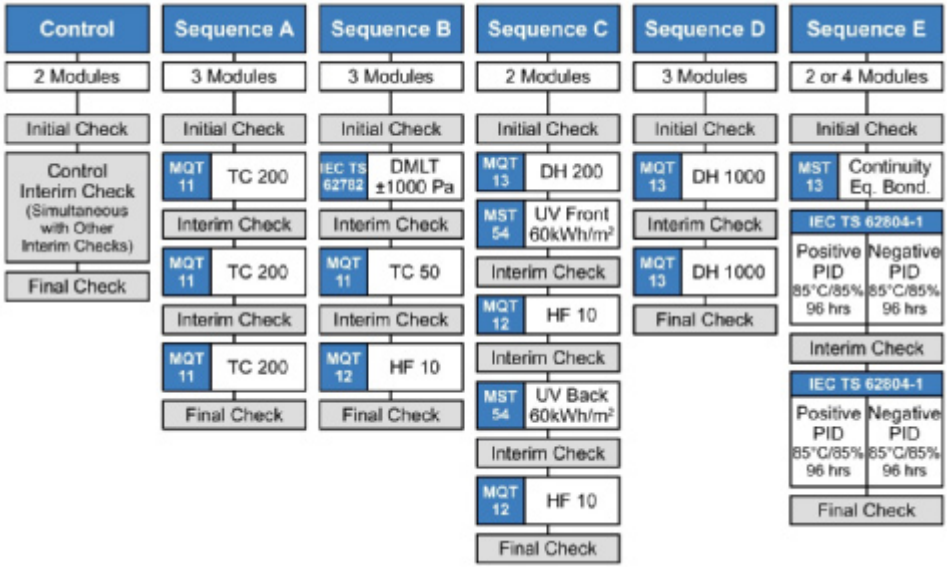


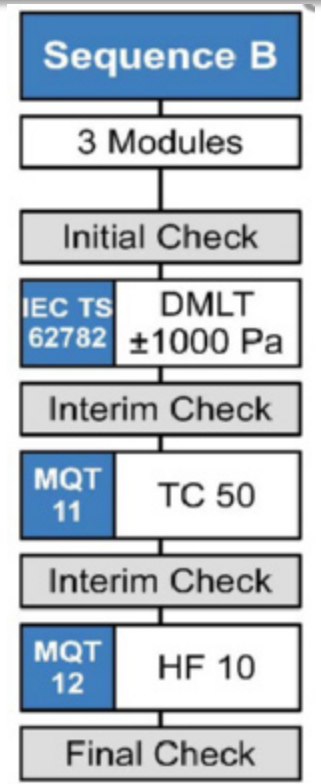
Visual and EL images show a snail trail tracing a crack

Motivation

- There is no standard test for crack susceptibility in PV modules.
- Reliability tests (CSA ANSI/C450, PVEL PQP, etc.) typically use DMLT (Dynamic Mechanical Load Testing) followed by environmental chamber stresses (TC50/HF10/HF20, etc.).
- Empirical lab evidence suggests that the DMLT testing, while it cracks cells, is not effective at producing electrically isolated cell regions which are sometimes seen in the field, and are problematic.
- Empirical lab evidence also suggests that the environmental chamber stresses after DMLT do not necessarily propagate or isolate cracks, but instead typically cause independent degradation modes.
- This project intends to investigate those observations.

Project Motivation – ANSI/CSA C450 Seq B





- First public extended module testing protocol – published November, 2018.
- Sequence B based on NREL Qualification Plus - checks for crack susceptibility

Design of Experiment

- Dynamic MLT = repeated minor loading events
  - Standardized with IEC TS 62782:2006.
  - Intended to mimic stresses encountered during installation and operation
  - Usually followed by TC50 and HF10 to “amplify” the mechanically induced cracks
  - DMLT: ±1000 Pa, 1000 cycles, 6 cycles/min per IEC TS 62782:2016
- Static MLT = major loading event
  - Has been a part of IEC 61215 from inception.
  - +/-2400 Pa corresponds to wind pressure of 130 km/hr with a safety factor of 3 for gusty winds (61215:2005)
  - Static MLT: (+2400 Pa for 1 hr, -2400 Pa for 1 hr) x3 per IEC 61215-2:2016
- During its lifetime, a PV module is likely to experience both major and minor loading events.

Design of Experiment

How will the results vary if we try different combinations of mechanical stresses?

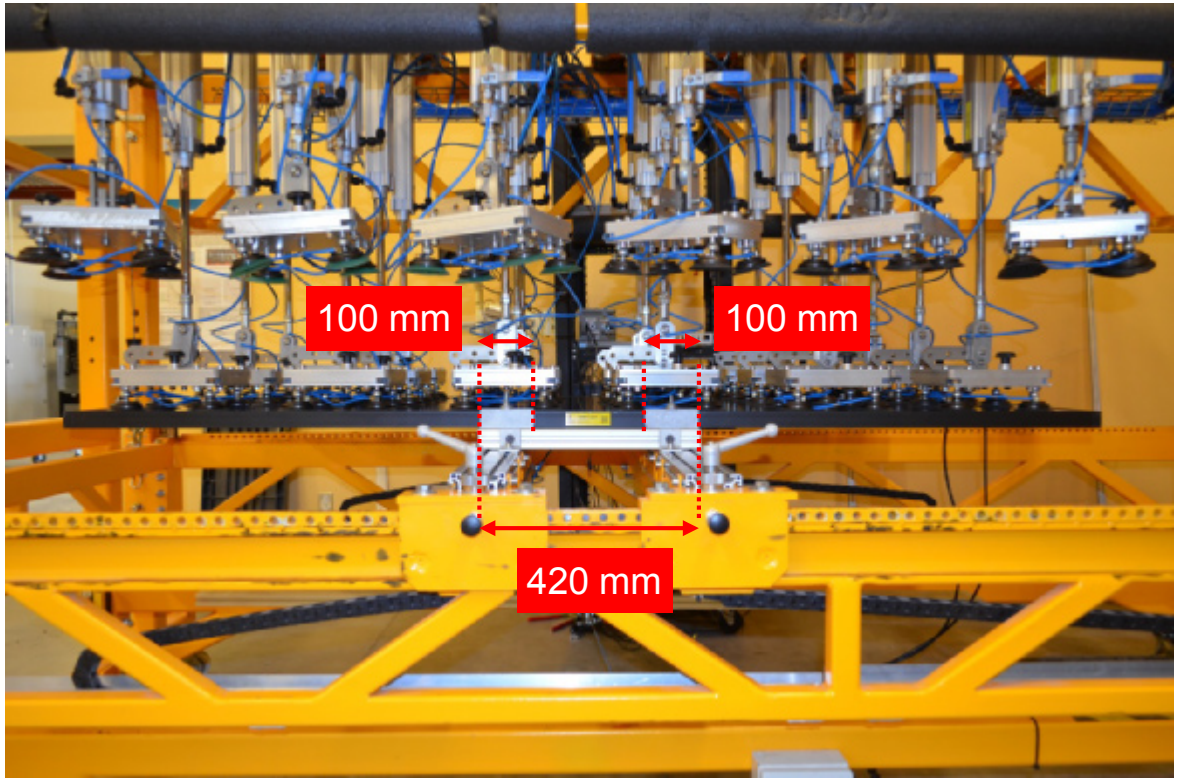
Leg 1 (Baseline)	Leg 2 (Static MLT)	Leg 3 (SMLT+DMLT)	Leg 4 (No MLT)
Stabilization	Stabilization	Stabilization	Stabilization
DMLT	Static MLT	Static MLT	TC50
TC50	TC50	DMLT	HF10
HF10	HF10	TC50	
		HF10	

Current C450 Seq B

- STC I-V and EL after each step.
- 2 module types (A and B), 2 samples per module type per leg

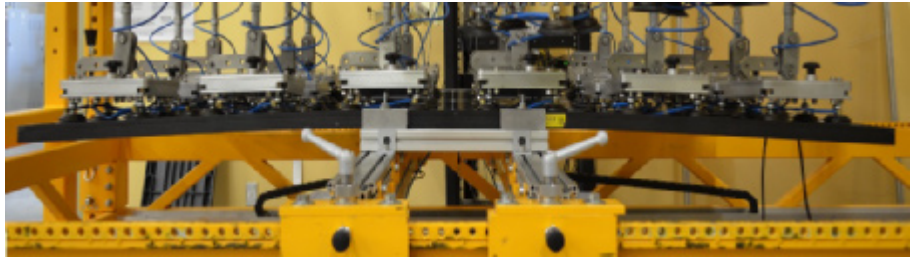
DMLT + Static MLT Setup

- We used a “center-clamping” setup that is more representative of single-axis-tracker installations.
- Our MLT machine pushes down and pulls up on the module with pneumatic cylinders and vacuum suction cups.

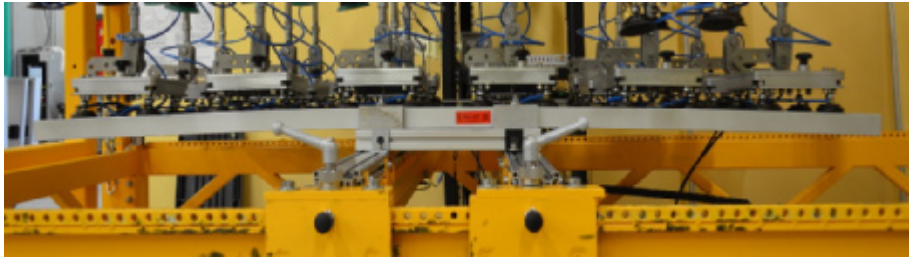


Tested Module Types

Module Type A	Module Type B
• Cell Type: 5BB Mono-PERC • Cell count: 72 • Frame Thickness: < 35 mm • Power Class: 350 W • Glass with Backsheet • Prone to cracking, per our experience	• Cell Type: 4BB Mono-PERC • Cell count: 72 • Frame Thickness: 40 mm • Power Class: 360 W • Glass with Backsheet

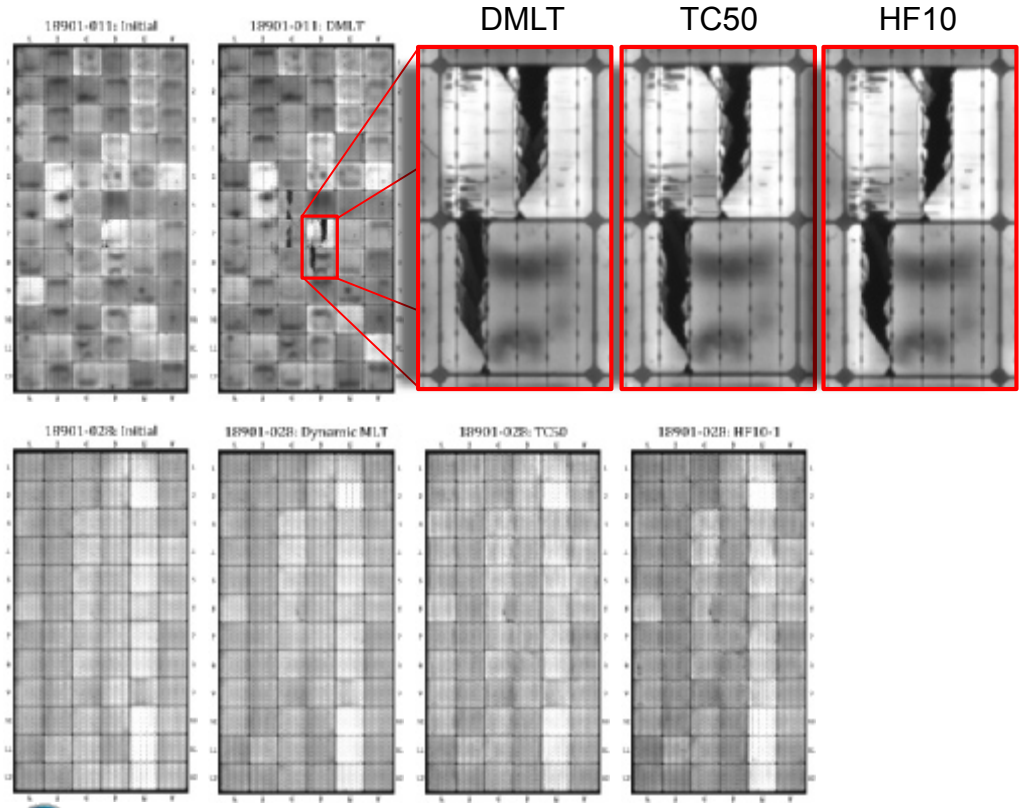


Center Point Deflection = 47 mm



Center Point Deflection = 32 mm

Leg 1 (Baseline - DMLT) - EL Results



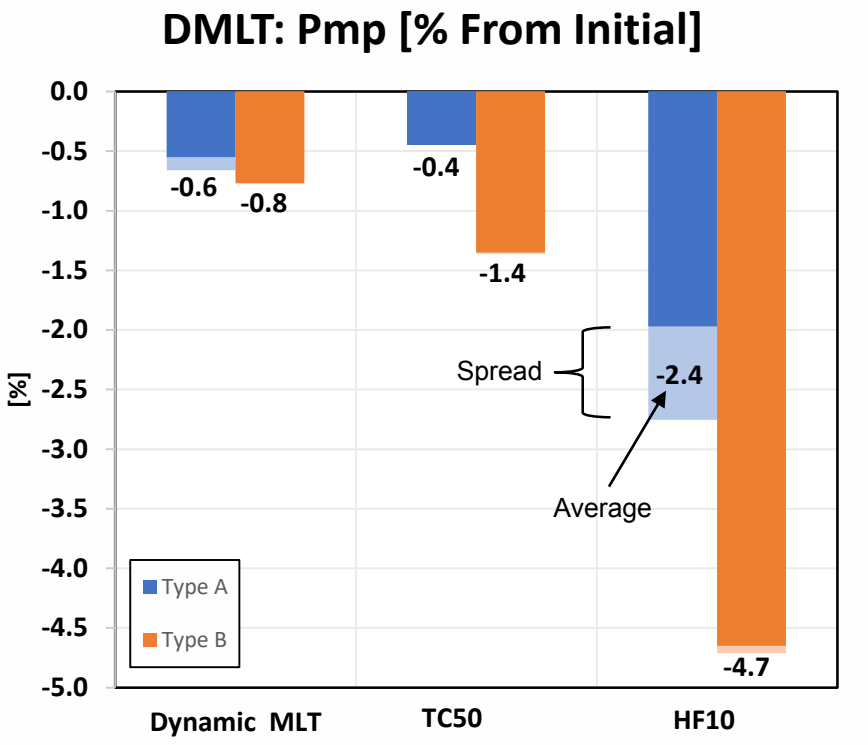
Type A (4-7 cracked cells post MLT)

- DMLT creates some bad cracks in the center.
- Some areas that are cracked become electrically isolated after DMLT.
- Electrical isolation is slightly enhanced by TC50 and HF10

Type B (2-3 cracked cells post MLT)

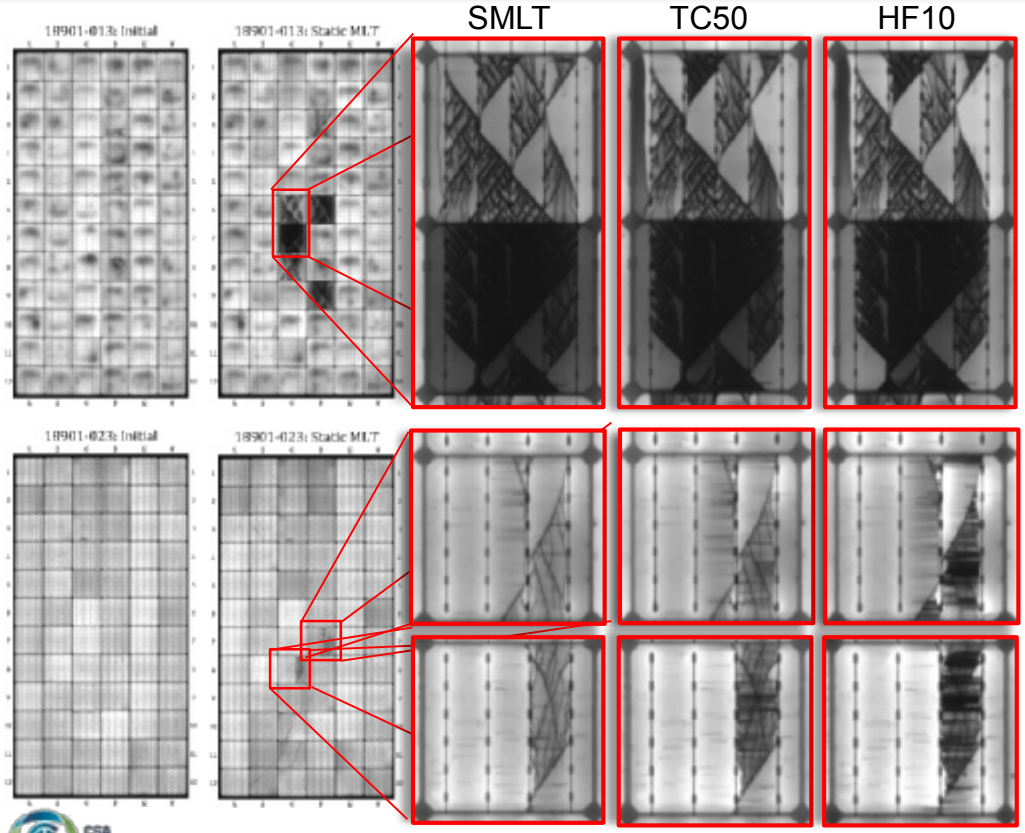
- DMLT caused virtually no cracking.
- Environmental stress enhances cell-to-cell mismatch

Leg 1 (Baseline - DMLT) - Pmp Results



- Despite the difference in EL images, both module types show similar power losses after DMLT (< 1%).
- TC50 caused negligible power change on either type.
- HF10 creates significant power loss on Type B.
  - Type A: 1.6-2.4%
  - Type B: 3.4%

Leg 2 (Static MLT) - EL Results



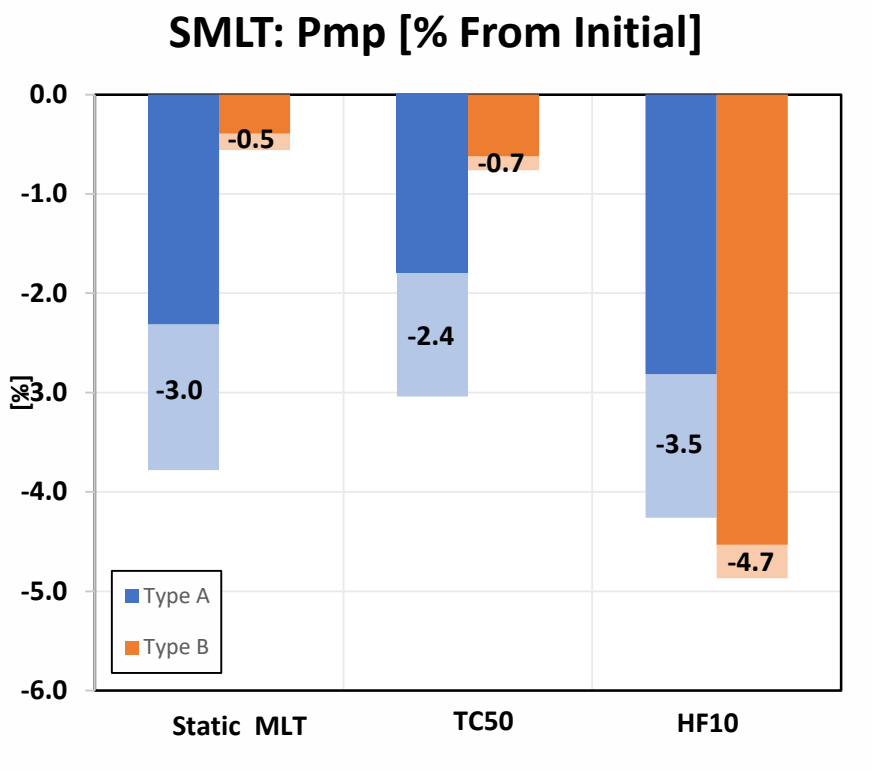
Type A (7-16 cracked cells)

- Static MLT creates more cracks than DMLT, but the broken pieces are initially still interconnected.
- Following chamber stress, some cracked portions become electrically isolated.

Type B (2-11 cracked cells)

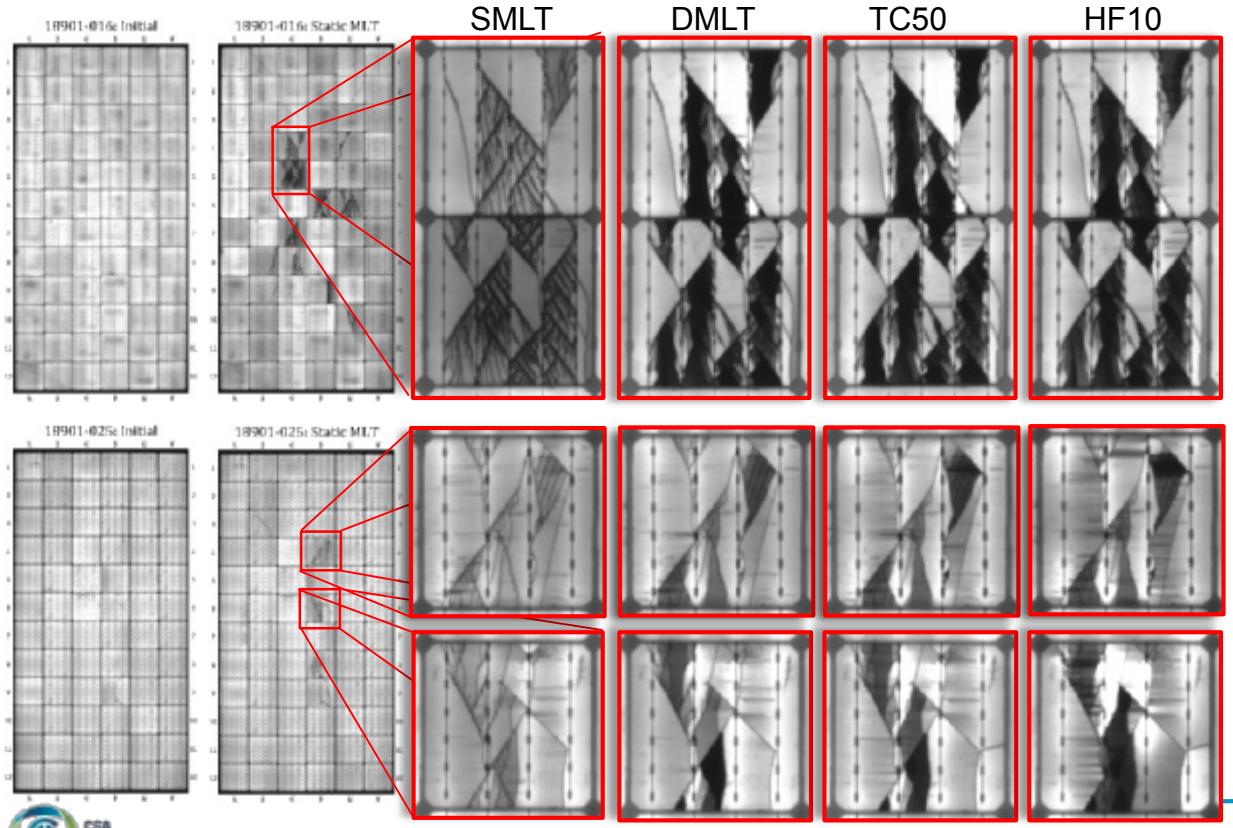
- Again, static MLT creates more cracks than DMLT, but still minor on this type.
- Electrical contact is retained after MLT.
- Chamber stress electrically isolates some of the cracked portions.

Leg 2 (Static MLT) - Pmp Results



- The increased cracking on Type A led to ~ -3% Pmp change following MLT.
- Type B showed negligible power change from mechanical stress.
- TC50 impact was negligible on both types.
- Type B degraded significantly following HF10, leading to similar total power losses for both types.
  - Type A: 1.0-1.2%
  - Type B: 4.0%

Leg 3 (Static + Dynamic MLT) - EL Results



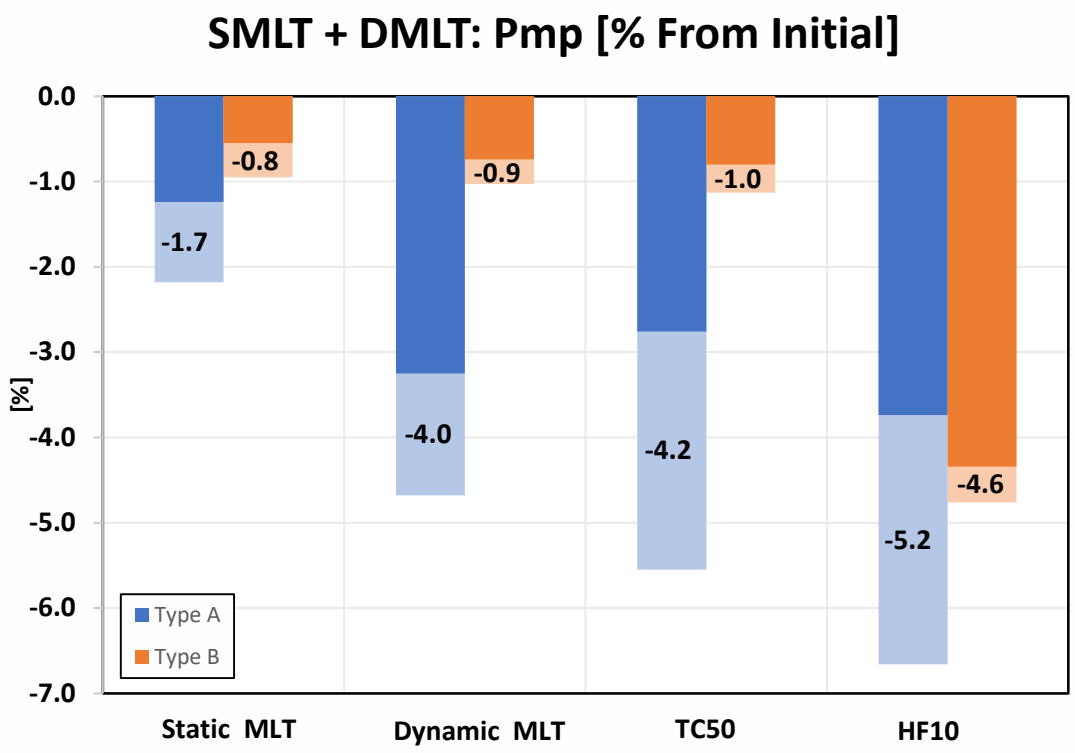
Type A (12-13 cracked cells)

- SMLT creates non-isolated cracks; DMLT isolates them.
- Little impact from follow-up chamber stress

Type B (7-11 cracked cells)

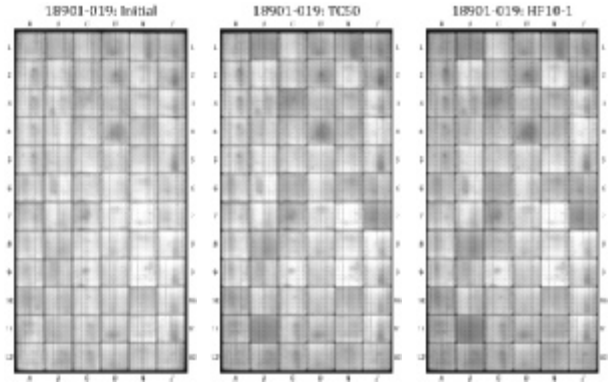
- Less cracked cells
- Slightly less isolation from DMLT, but still significant isolation occurs
- Further isolation resulted from environmental testing.

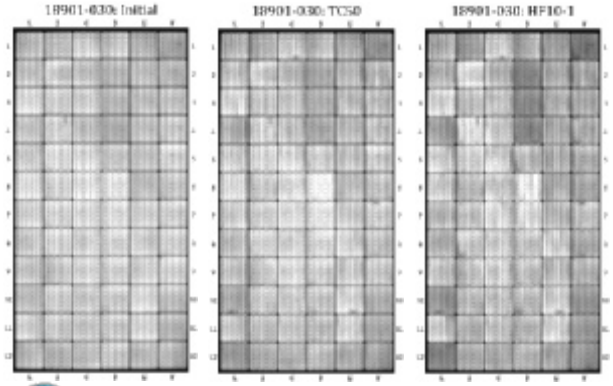
Leg 3 (Static + Dynamic MLT) - Pmp Results



- Type A showed 3-5% power loss following SMLT/DMLT.
- Type B showed 1% power loss following SMLT/DMLT.
- TC50 impact was negligible
- The final power loss was similar between types because Type B degraded more from HF10.
- The incremental degradation from HF10 was:
  - Type A: 1.0%
  - Type B: 3.6%

Leg 4 (No MLT) - EL Results





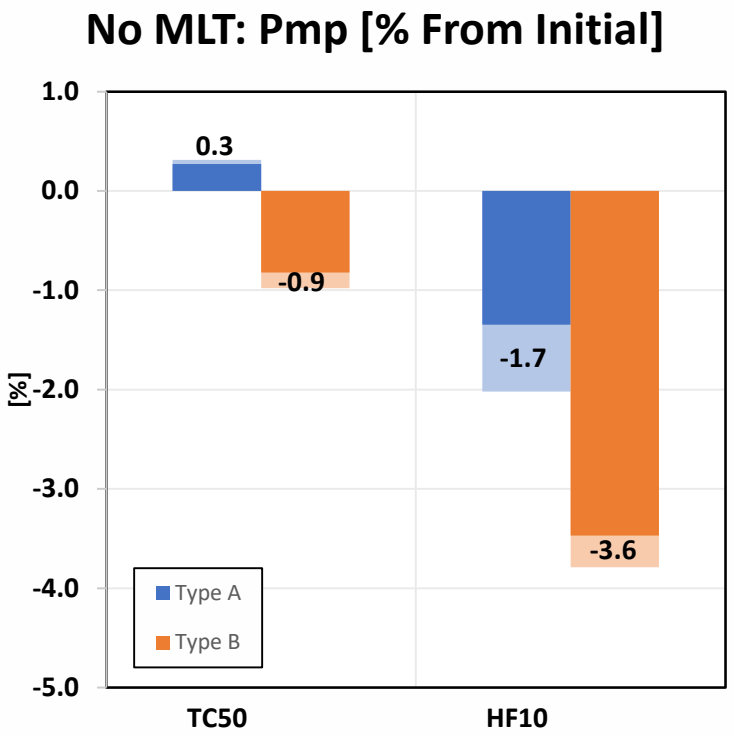
Type A

- No visible crack formation
- Same slight increase in cell mismatch

Type B

- No visible crack formation
- Same slight increase in cell mismatch

Leg 4 (No MLT) - Pmp Results



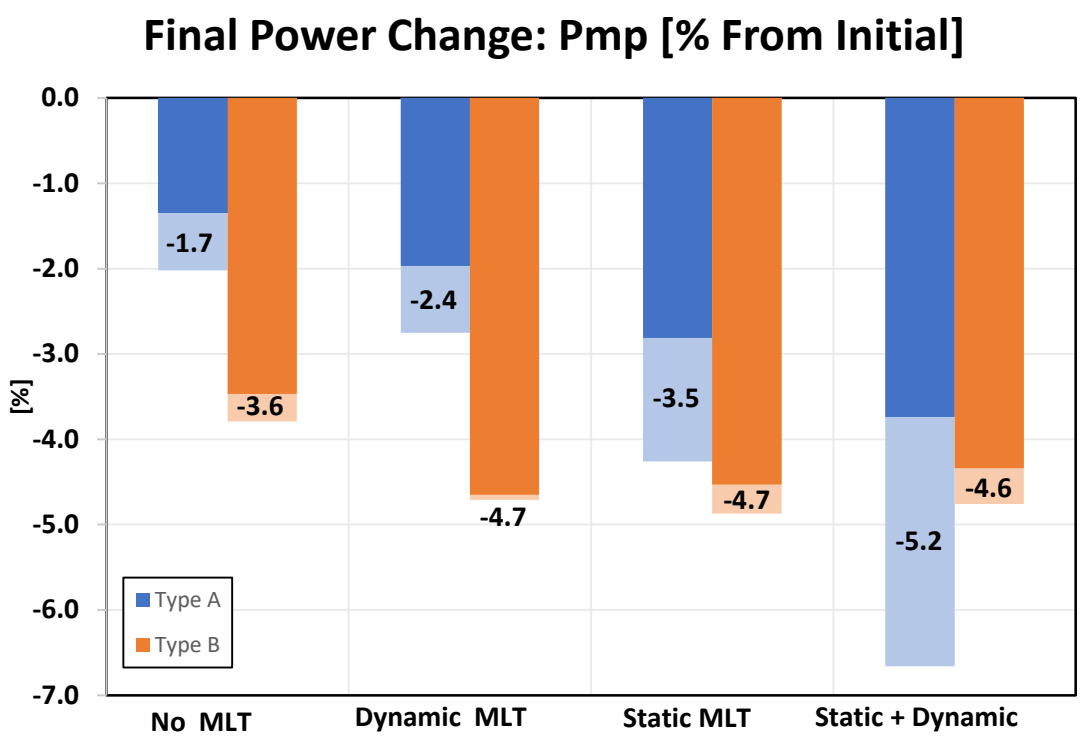
- TC50 showed negligible ΔPmp
- Type B modules degraded more significantly from HF10 stress than the Type A modules.
  - Type A: 1.6-2.3%
  - Type B: 2.6-2.8% series

Type	Isc [%]	Voc [%]	Imp [%]	Vmp [%]
A	-0.94	-0.17	-1.29	-0.40
B	-1.96	-0.37	-2.11	-1.56

Type	FF [%]	R-ser [%]
A	-0.57	**7.31**
B	-1.34	**17.60**

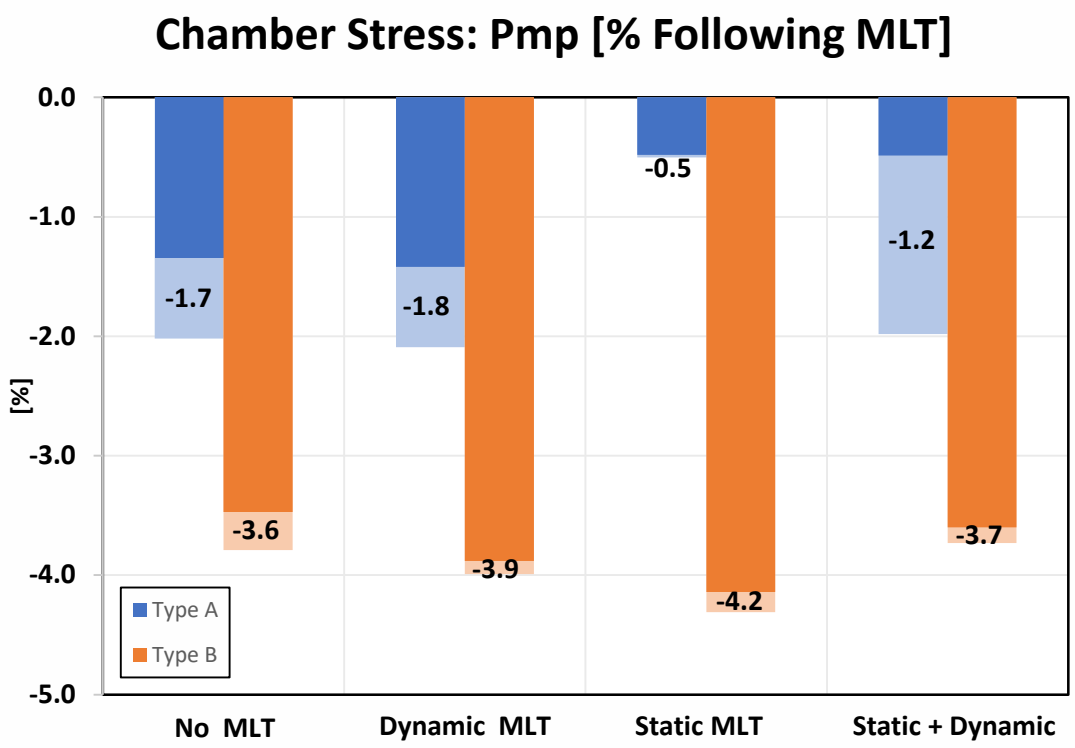
- Type B modules may have weaker solder bonds

Final Pmp Change of All Legs



- Type A, being more susceptible to cracking, exhibited increased power loss with increased mechanical stress.
- Type B, being more robust, incurred the same ~ 1.0% Pmp drop with all mechanical stresses.
- The remaining Pmp drop of 3.6-3.7% was mostly due to HF10 inducing non-crack related failure modes.

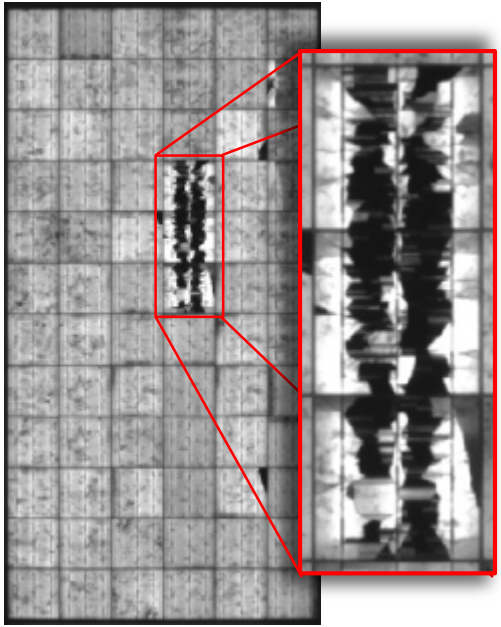
Pmp Change from Chamber Stress



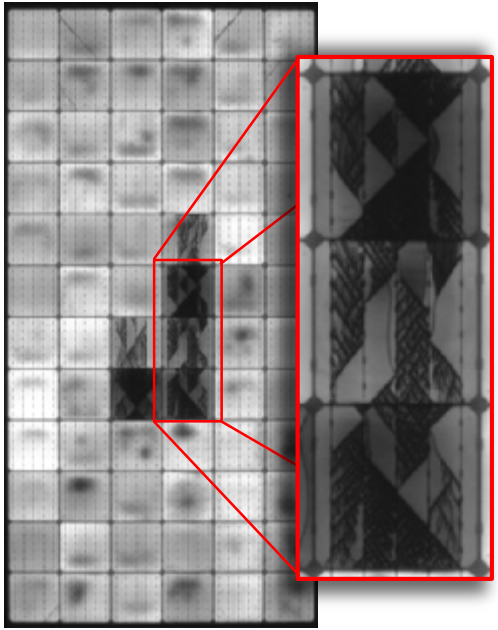
- Type A exhibited an average Pmp change of -1.3% resulting from chamber stress.
- Pmp on Type A increased following TC50 on the SMLT leg.
  - TC50 may “heal” non-isolated cracks.
- Type B exhibited an average Pmp change of -3.9 % resulting from chamber stress.

Comparison with Fielded Modules

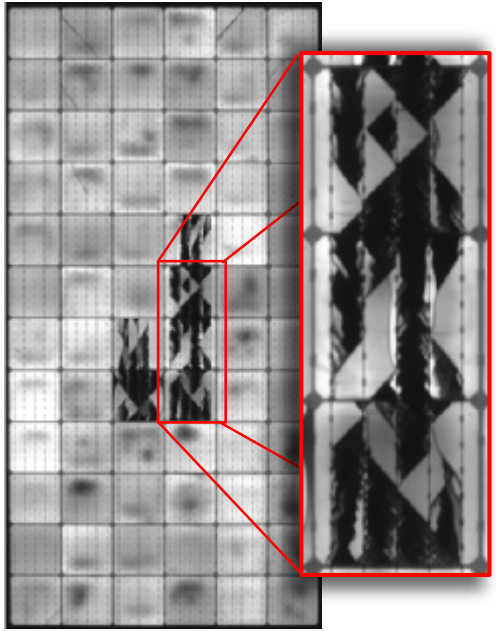
Fielded Module



SMLT



SMLT + DMLT



Conclusions

- This study has a very small sample size but confirms empirical lab testing observations.
- Neither DMLT or SMLT alone appears to be very effective at producing electrically isolated cell regions in PV modules.
- SMLT+DMLT appears to be an effective method of producing isolated cell regions in PV modules.
- Typically used environmental stresses (TC50/HF10/HF20, etc.) may not propagate cracks or isolate cell regions, but may instead activate independent module degradation modes such as solder bond degredation.
- Further work may be needed on cell crack susceptibility test legs in extended module testing protocols.

CSA Group

Photovoltaic & Advanced Materials

February 27, 2019

Assessing PV backsheet durability using multiple UV sources and test structures

2019 PV Reliability Workshops, Lakewood, CO

William Gambogi, Technical Fellow

Outline

- Outer layer backsheet failures in the field (PA and PVDF)
- Inner layer backsheet failures in the field (PET)
- Assessment method for backsheet inner and outer layers
- UV sources considered
- Exposure methodology
- Introduction of clear Tedlar® PVF
- Test results for white backsheets and clear backsheets
- Module-based test methods for assessing inner and outer layer backsheets
- Conclusions

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Field examples of outer layer backsheet failures

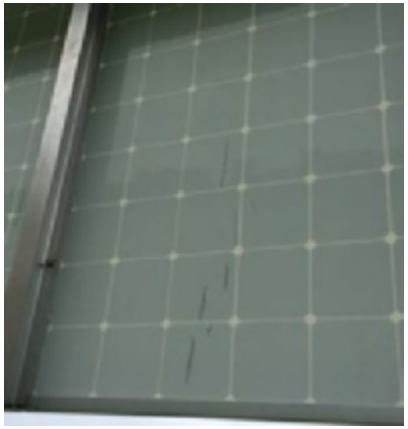
Polyamide

Italy Site 1: large crack tripped inverter, 4 years in field

Italy Site 2: large cracks, exposed busbars, 4 years in field

China Site: 100% modules, cracks over entire surface, 4 years in field

PVDF



Canada site 1: large MD crack, 4 years in field

Canada site 2: PVDF cracks led to delamination- 6 years

China Site 1: 80% modules, cracks over cell gaps, 6 years in field

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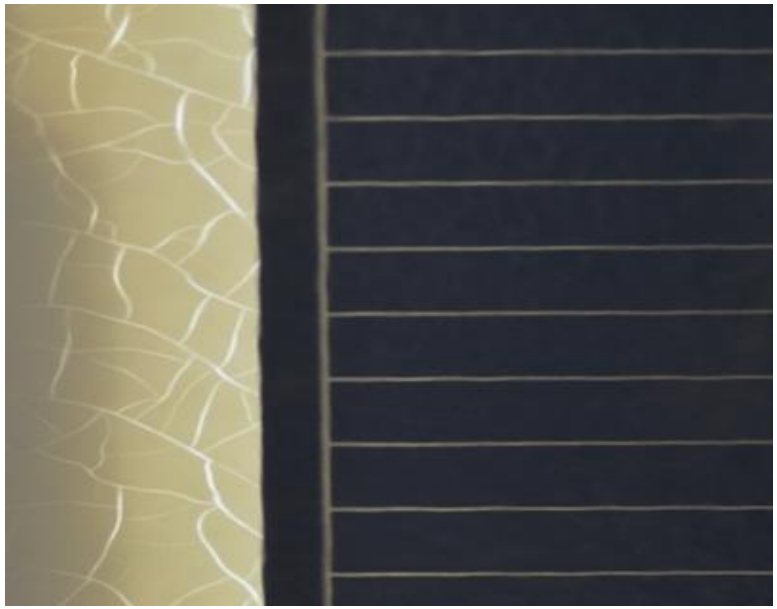
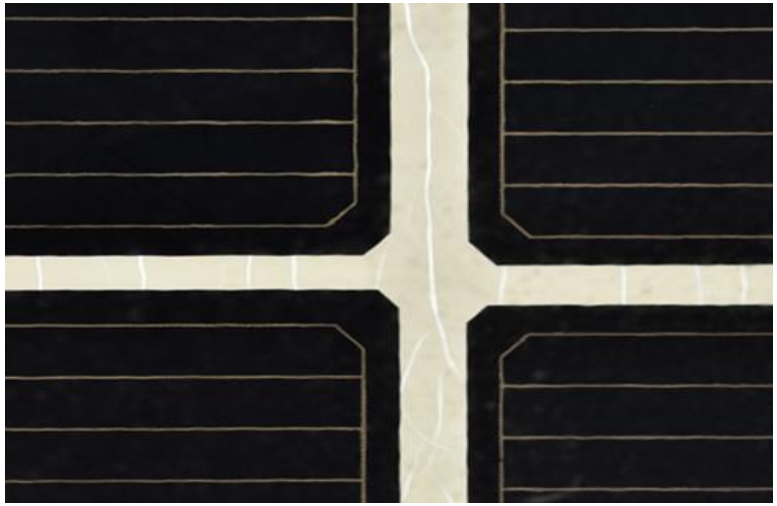
Field examples of inner layer backsheet failures

Initial year of operation	2012
• Service Time	6 years
• Location	North America
• Mounting configuration	Ground mount
• Date of inspection	2018
• Backsheet:	PET
• Technology	poly-crystalline-Si
• Plant size	30+ MW
• Climatic conditions	Arid





- PET backsheet inner layer cracked all over module in spaces between cells and around edges
- Significant power loss

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Test Method for Assessing Inner and Outer Layer Durability

- Evaluate inner and outer layer durability using commercially available UV sources (UVA, filtered xenon, filtered metal halide)
- Assess inner layer using appropriate filtering (glass/UV-transmissive encapsulant/UV-absorbing encapsulant) to avoid wavelengths not present in the outdoor environment
- Avoid sample temperatures significantly above maximum temperatures in the outdoor environment
- Assess stability of optical and mechanical properties

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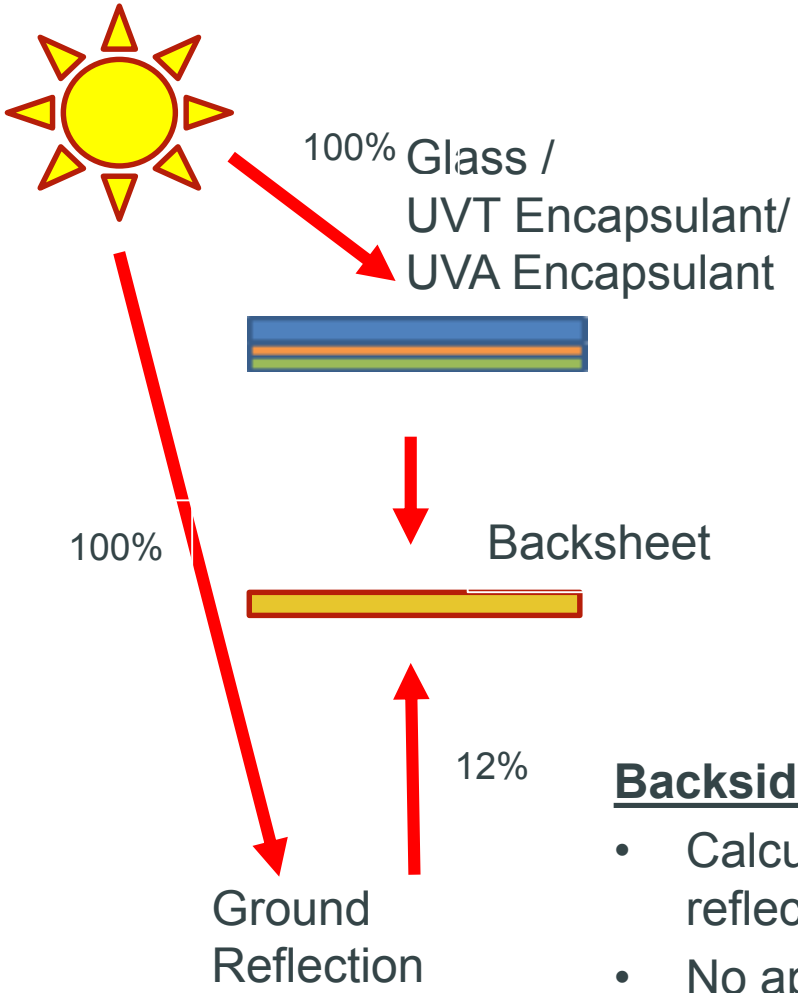
Assessment method development for inner and outer layers



Inner Layer Exposures

- Higher incident light on front glass compared to backside
- Significant Filtering by Glass and Encapsulant
- Much less short UV content
- Shorter wavelengths are more damaging to backsheet PET core
- Dose depends on wavelengths chosen

Backside Exposures

- Calculate dose for 25 years with 12% albedo (light reflected from the ground)
- No appreciable change in wavelength with reflection
- 273 kWhr/m2 for desert (300 – 400 nm)

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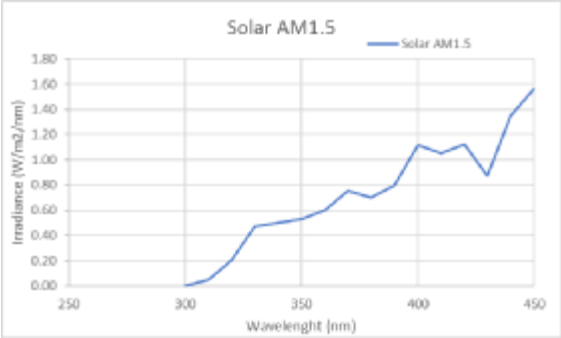
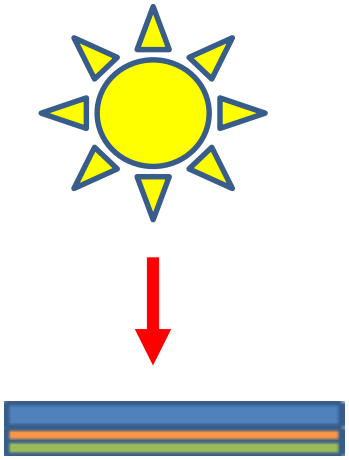
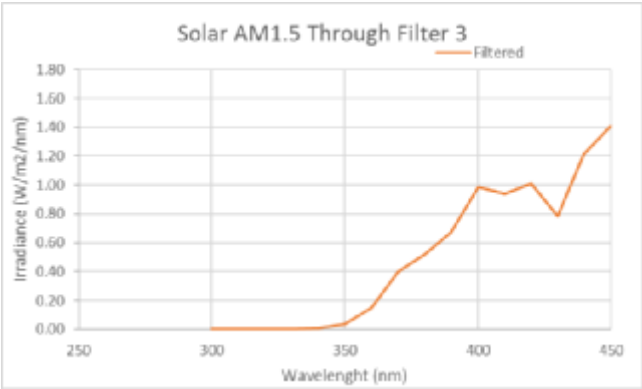
Sunlight Dose Filtered by Glass / EVA





Filter: Glass/UVT-encapsulant/UVA-encapsulant



Top Glass Sun Exposure

Sun Top Glass (nm)	Intensity (W)	Irr / 1 Yr (kWhr/m2)	Irr / 25 yr (kWhr/m2)
Full Spectrum	963.8	1797	44,913
300-400	51.7	96.4	**2,409**
300-370	27.3	51	**1,272**
300-350	14.9	27.8	**694**

Filtered Sunlight

Sun Filtered (nm)	Intensity (W)	Irr / 1 Yr (kWhr/m2)	Irr / 25 yr (kWhr/m2)	Filtered / Backside Exposure
Full Spectrum	N/A			8
300-400	22.7	42.3	**1,058**	3.8
300-370	3.9	7.3	**182**	0.67
300-350	0.3	0.6	**14**	0.05

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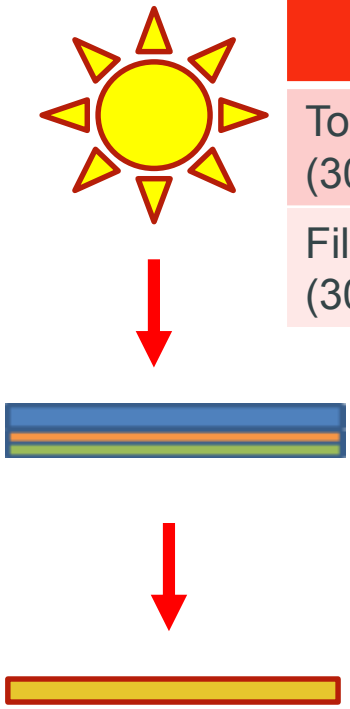
Exposure Doses and Times



Sun	Irr / 25 yr (kWhr/m2)
Top Glass (300 – 400)	2,409
Filtered (300 – 400)	1,058

MH (350nm) UV	Irr (kWhr/m2)	Equivalent Years	Hours
Top Glass (300 – 400)			
Filtered (300 – 400)	318	7.5	2,424
Direct	180	4.3	840

Filtered MH exposure of 423 kWhr/m2

- 10 year UV dose of 300 – 400 nm accelerated at 90C ST
- corresponds to longer time in field at lower temperature
- can verify longer performance with longer testing

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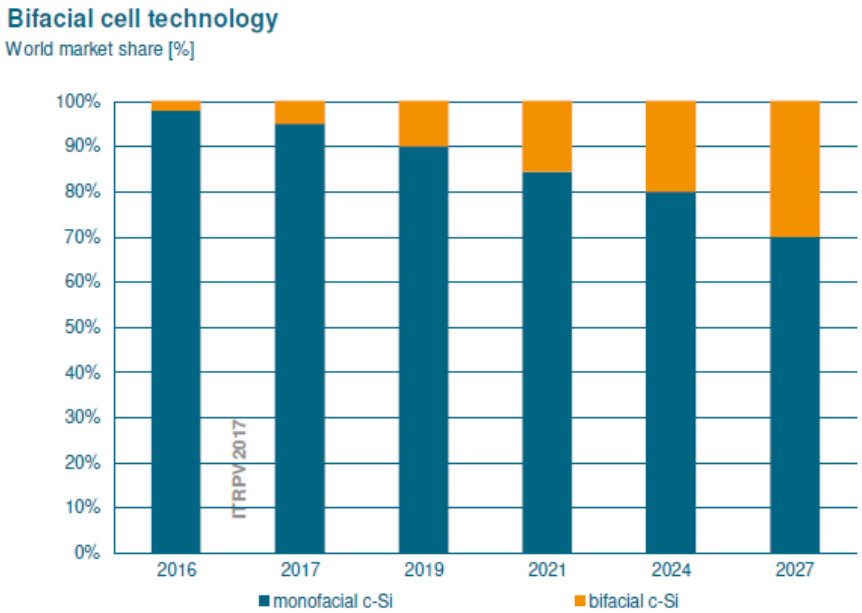
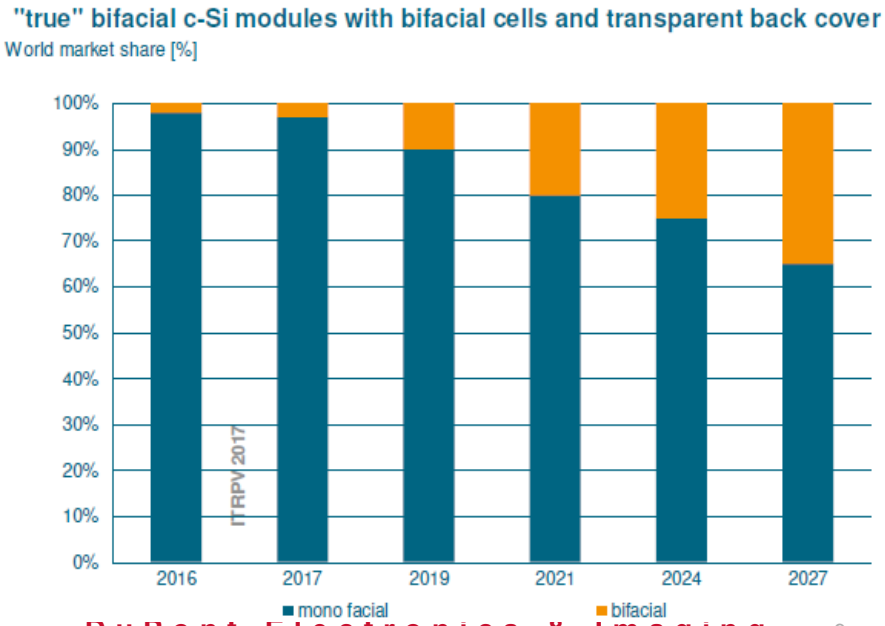
Bifacial Cell Technology is about to Achieve >20% Market Share in 5 Years (ITRPV)

Ground

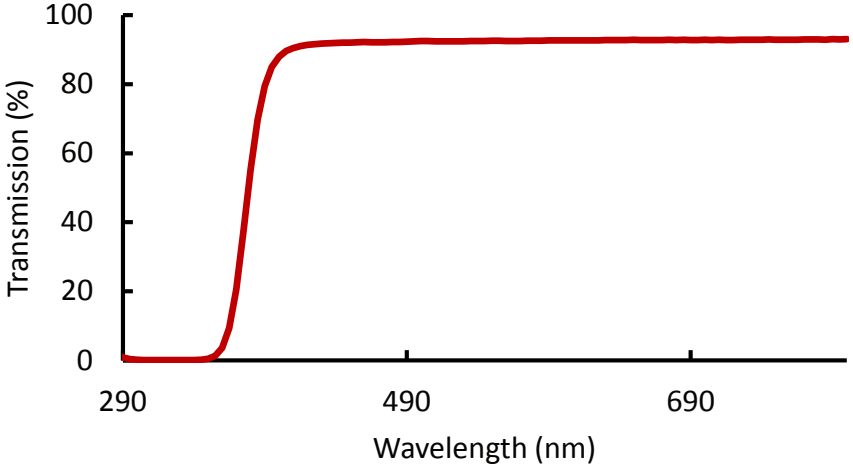
Rooftop

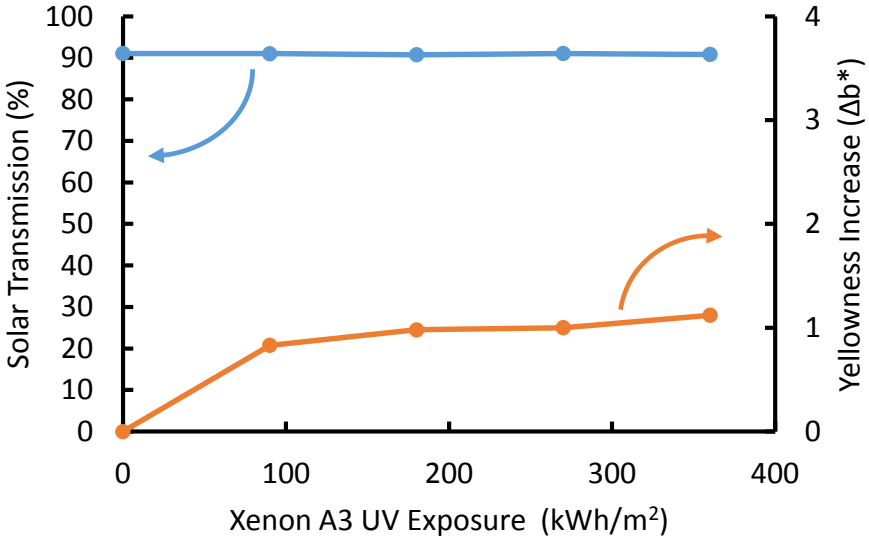
Water Surface





DuPont Tedlar® PV3001 – Transparent PVF Film





Xenon Arc Lamp, boro/boro filter
0.8 W/m²-nm @ 340 nm
90 °C BPT, 65 °C CHT

Property	Value	Method
Thickness	25 µm	Micrometer
Total Solar Transmission	91 %	ASTM E424-71
Optical Transmission	94 %	ASTM D1003
Cutoff Wavelength	370 nm	UV-VIS
Optical Haze	8 %	ASTM D1003
Color (b*)	1.6	Colorimeter
60° Gloss	83	ASTM D523
MD Elongation at Break	150 %	ASTM D882
TD Elongation at Break	140 %	ASTM D882

*Values are typical and do not represent product specifications

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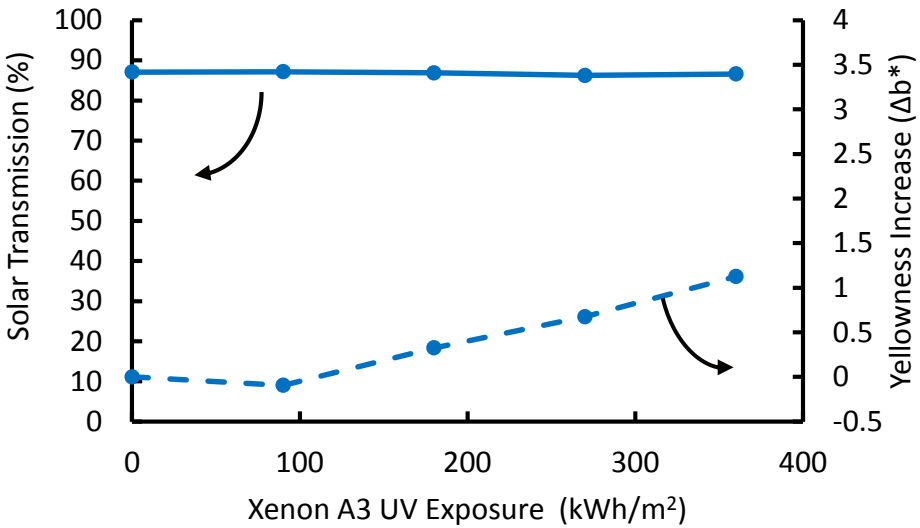
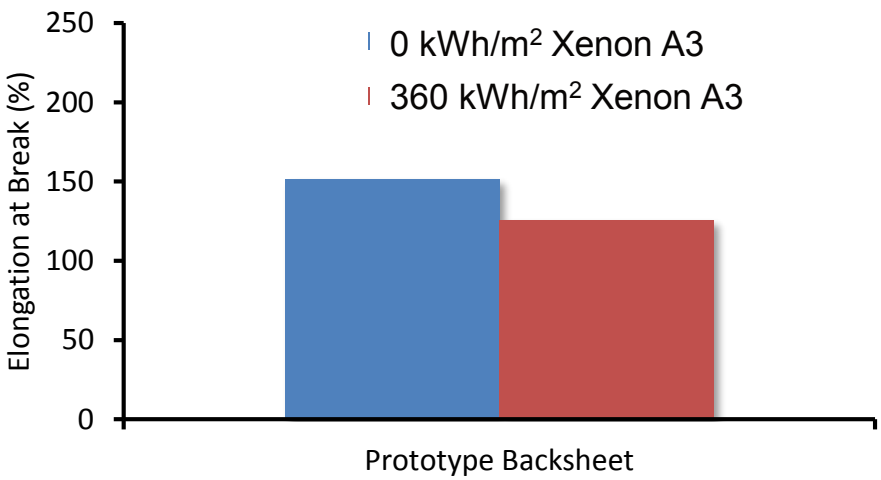
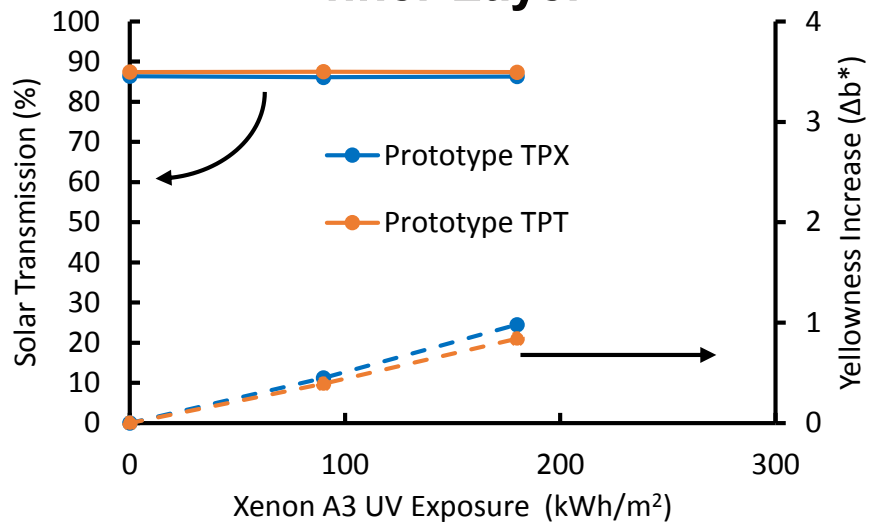
Clear Backsheets with PV3001 Tedlar® PVF

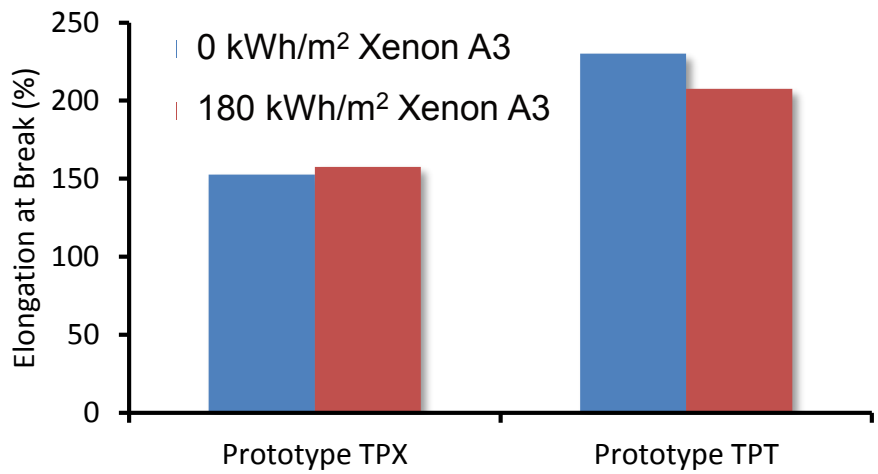
Air/Tedlar® Side





Inner Layer





Xenon Arc Lamp, boro/boro filter
0.8 W/m²-nm @ 340 nm, 90 °C BPT, 65 °C CHT

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Results – Outer Layer (color)

		MH1 b*					Xenon b*			UVA b*	
backsheet	0 hr	55 kWh/m2	110 kWh/m2	155 kWh/m2	220 kWh/m2	275 kWh/m2	55 kWh/m2	110 kWh/m2	155 kWh/m2	55 kWh/m2	110 kWh/m2
1s-PVF1 clear	3	1.9	2.1	2.2	2.2	2.4	1.8	1.9	2.0	1.9	1.9
2s-PVF1 clear	3.2	1.9	2.1	2.0	2.0	2.1	1.8	1.9	1.9	1.9	2.0
2s-PVF1 white	0.7	1.5	1.8	1.3	1.2	1.5	1.4	1.2	1.4	1.8	1.7
1s-PVF1 white	0.9	1.1	1.0	1	0.8	1.1	1	0.9	1	1.2	1.4
1s-PET1 white	1.7	4	5.2	5.2	4.8	6.1	2.2	2.9	4.9	3.6	5.2
2s-PA white	1.8	1.8	1.9	1.7	1.4	2	1.4	1.4	1.6	1.7	2.1
1s-PET2 white	2.5	4	5.1	4.5	3.7	5.9	2.6			3.9	4.1
1s-PVDF white	1.7	1.4	1.4	1.4	1.3	1.4	1.3	1.3	1.4	1.4	1.4

- Excellent stability of clear PVF backsheets
- UVA fluorescent, xenon and metal halide exposures identify yellowing issues with PET backsheets
- Higher intensity MH exposures with appropriate filtering correlates to other UV sources

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Results – Outer Layer (elongation)

	MH direct JB side			Xenon direct JB side		
JB-Side	55 kWh/m2	110 kWh/m2	165 kWh/m2	27.5 kWh/m2	55 kWh/m2	110 kWh/m2
1s-PVF1 clear	-27%	-21%	-21%	-47%	-12%	-23%
2s-PVF1 clear	-15%	-30%	-7%	-36%	1%	-17%
2s-PVF1 white	-10%	1%	9%	6%	7%	1%
1s-PVF1 white	-24%	-28%	-13%	-30%	-20%	-26%
1s-PET1 white	5%	7%	8%	-6%	10%	-4%
2s-PA white	-56%	-95%	-96%	-9%	-56%	-97%
1s-PET2 white	-28%	-42%	-21%	-29%		
1s-PVDF white	-13%	-19%	-28%	-29%	-13%	-23%

- Good mechanical properties with UV exposure
- Core PET layer typically dominates overall mechanical properties
- Drop in mechanical properties identified for PA backsheet as seen in field

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Results – Inner Layer (color)

		MH b*			Xenon b*	
Exposure from source		241 kWh/m2	482 kWh/m2	941 kWh/m2	241 kWh/m2	482 kWh/m2
Exposure at backsheet inner layer	initial	106 kWh/m2	212 kWh/m2	423 kWh/m2	106 kWh/m2	212 kWh/m2
1s-PVF1 clear	1.5	2.1	2.5	3.5	2.2	2.5
2s-PVF1 clear	1.6	1.8	2.4	3.4	2.0	2.4
2s-PVF1 white	0.7	1.8	1.8	1.3	1.6	1.8
1s-PVF1 white	0.5	0.5	0.4	0.9	0.7	0.8
1s-PET1 white	2.0	6.1	5.9	29.5	5.3	7.4
2s-PA white	1.9	2.0	1.6	2.9	2.2	3.5
1s-PET2 white	1.4	5.3	6.1	9.7		6.3
1s-PVDF white	-0.3	0.7	1.2	4.4	2.1	4.5

- Commercial white and clear backsheets tested using filtered metal halide and xenon exposure
- White backsheets with inner layer cracking and yellowing in the field correlated

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Results – Inner Layer (elongation)

E-Side	MH1 filtered			Xenon filter	
Exposure from source	241 kWh/m2	482 kWh/m2	941 kWh/m2	241 kWh/m2	482 kWh/m2
Exposure at Bsheet inner layer	106 kWh/m2	212 kWh/m2	423 kWh/m2	106 kWh/m2	212 kWh/m2
1s-PVF1 clear	6%	1%	-40%	-35%	
2s-PVF1 clear	18%	12%	-20%	-60%	
2s-PVF1 white	-10%	-8%	7%	-1%	-13%
1s-PVF1 white	11%	-5%	-15%	22%	-17%
1s-PET1 white	-95%	-96%	-98%	-96%	-97%
2s-PA white	-93%	-88%	-98%	-96%	-98%
1s-PET2 white	1%	-46%	-97%	-49%	-98%
1s-PVDF white	**-22%**	-68%	-99%	-94%	-99%

- Commercial white and clear backsheets tested using filtered metal halide and xenon exposure
- White backsheets with inner layer cracking and yellowing in the field identified

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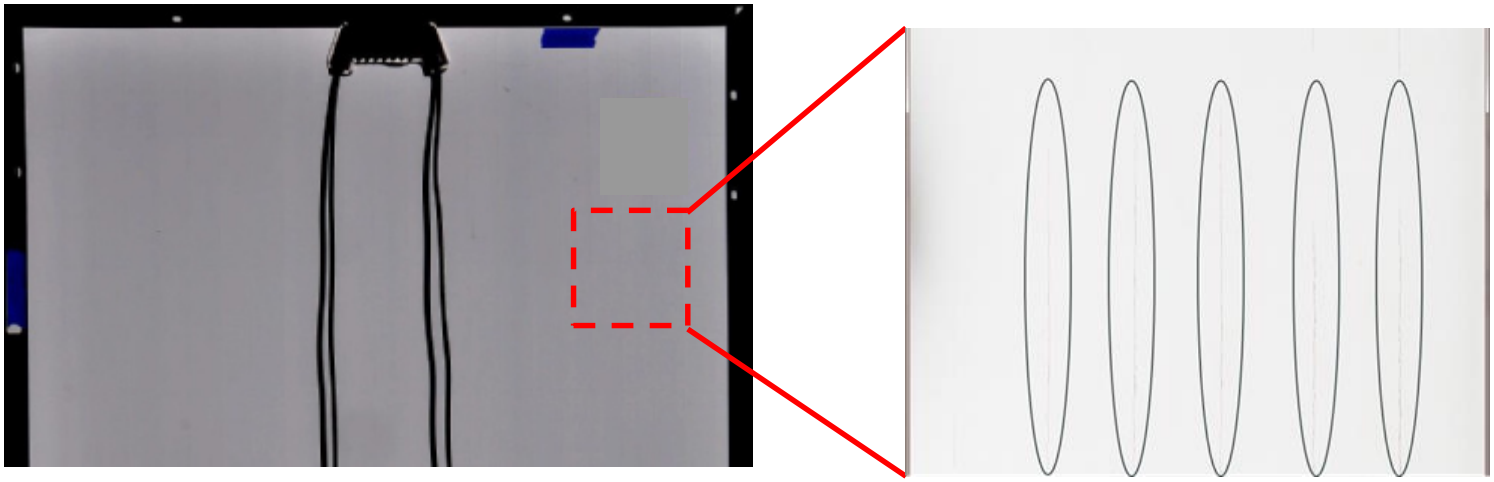
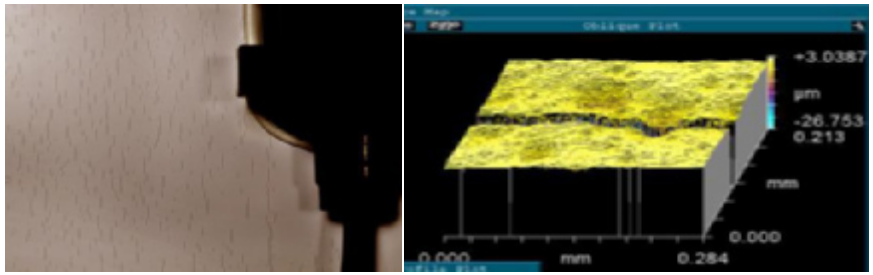
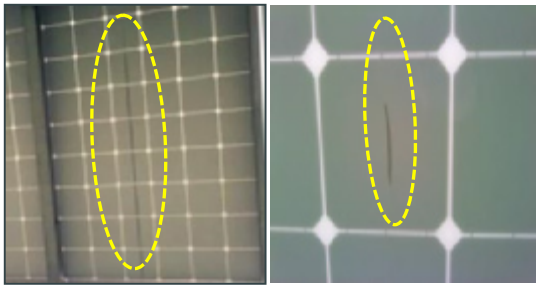
Sequential Testing (DH/UV/TC) predicts outer layer cracking



Visible cracks on backsheet over all of the bus-bar ribbons in each cell of both PVDF modules tested. All cracks are in the long (MD) direction of the module; due to low TD elongation of outer PVDF layer. Third party testing at PVEL.



PVDF backsheet cracking in minimodules in MAST



PVDF backsheet cracking in the field in 5 years, North America

Cracking in PVDF-based backsheet after MAST in full-sized modules, minimodules, and in the field

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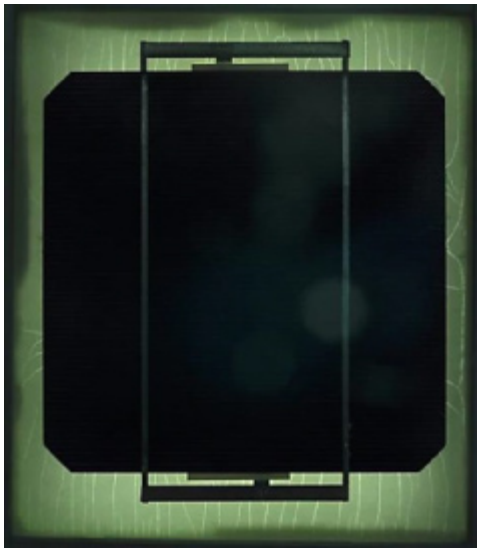
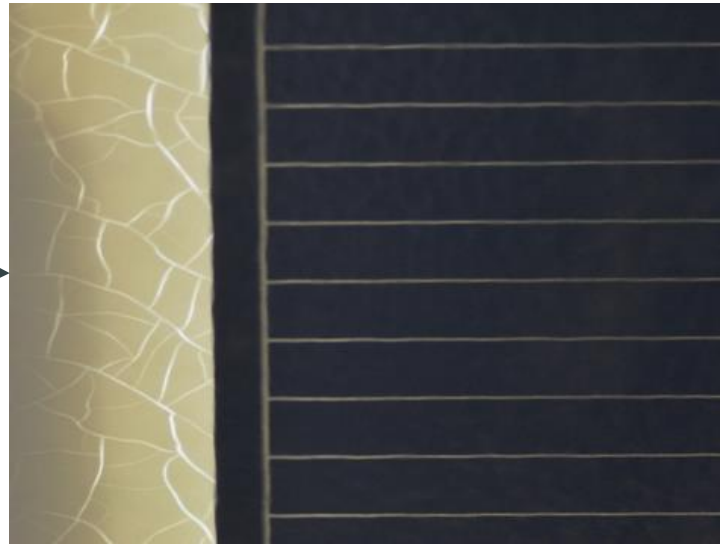
Front side weathering exposure predicts inner layer cracking



Same PET Backsheet



Accelerated Test: Front side exposure in xenon weatherometer *

Fielded module with 6 years service in North America with 30% power loss in 5 years of service, 6% linearized power loss per year

Inner Layer Cracking can result in
- **Loss of adhesion**
- **Moisture ingress**
- **Insulation failure and power loss**

* Exposure conditions: 90 °C BPT, 1.1 W/m^2–nm UV, cycle: 102 min UV followed by 18 min UV + water front spray, 3500h (~ 5y outdoor equivalent)

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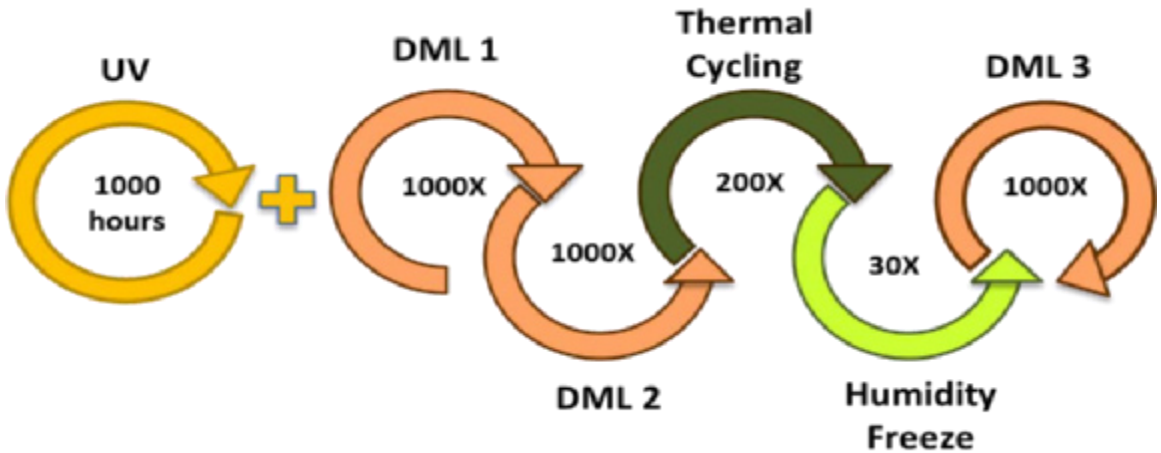
Sequential Testing Sequence of Commercial Modules using UVfront and Dynamic Mechanical Load



UV exposure: 65kWh/m^2 on the front
DML 1: 1000 cycles of ±1500 Pa of loading @ 1/6 Hz
DML 2: 1000 cycles of ±1500 Pa of loading @ 1 Hz
TC200 = Thermal Cycling, -40°C <–> 85°C, ramp and hold *per IEC62782*, 200 cycles
HF30 = Humidity Freeze, 30 cycles
Optional **DML 3**: 1000 cycles of ±1000 Pa of loading @ 4 Hz

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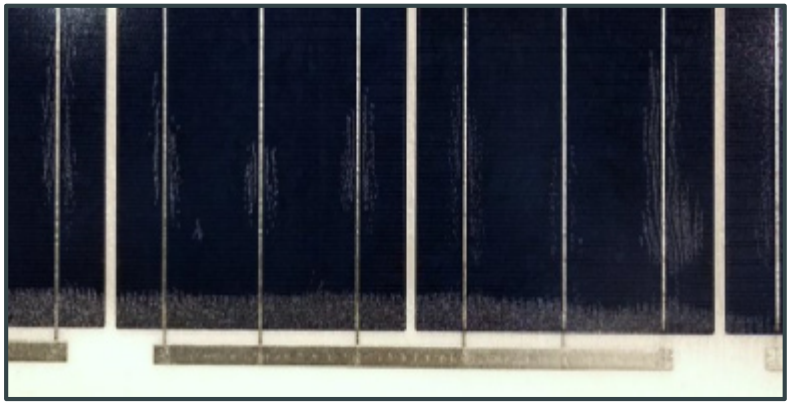
Sequential Test with Dynamic Mechanical Load

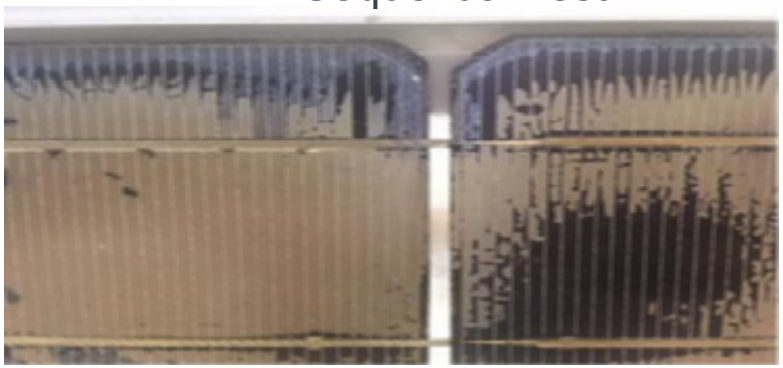
	G/G modules	G/Backsheet modules
UVA	No change	No change
DML 1	No change	No change
DML 2	Slight delamination on front	No change
TC 200	Delamination on front, encapsulant voids on back	No change
HF 30	Severe delamination on front, multiple encapsulant voids on the back	Slight yellowing along the edge, no delamination

DML 3 not performed

Third party testing at PVEL.



DML Sequential Test



Fielded Glass Module: 21 yr (JRC)

Glass-Glass modules show delamination induced by mechanical load combined with UV exposure, thermal cycling and humidity

Due to adhesion loss, internal mechanical stress and non-breathability allowing trapping of degradation products

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Conclusions

- Assessment of the durability on the inner and outer layer of PV backsheets is important to long term performance of PV modules
- Higher intensity UV sources (metal halide) can be used for assessment provided the appropriate filtering is applied
- Using a filter based on laminates of solar glass, UV transmissive encapsulant and UV absorbing encapsulant is most appropriate for assessing component durability
- Clear backsheets can be evaluated using this methodology and compared with performance of commercial white backsheets that have known field performance
- Module-based durability testing better assesses the impact of materials changes in module performance and can be compared directly with field experience

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Poster Session II (Wednesday) Poster Awards

1st Place: #62 A. Meyer, V. LaSalvia, W. Nemeth, M. Page, D. Young, S. Agarwal, and P. Stradins, "Light-induced degradation and regeneration of p-type crystalline silicon solar cells"

2nd Place: #106 P. Arularasu, "Role of humidity on the degradation of UV-cut and UV-pass encapsulants"

3rd Place: #80 B.G. Potter, M.R. Dzurick, and K. Simmons-Potter, "Effect of location-specific weather and PV degradation data on PV power prediction using NREL PVWatts"

Reduce to the Maximum

– What makes up a Reliable PV Inverter –

Presented by Daniel Clemens, Reliability Technical Manager

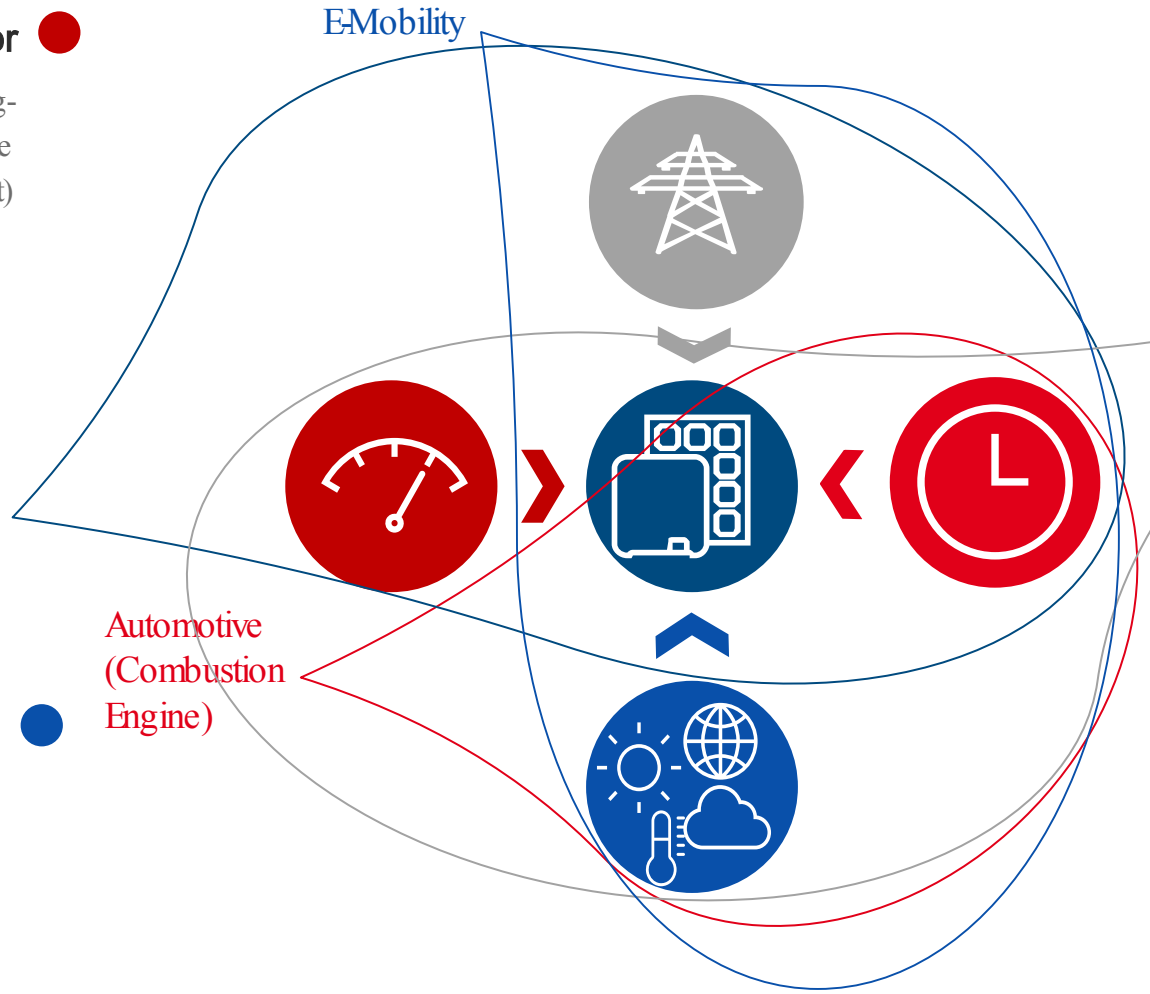
Unique Requirements for PV Inverters

High Load Factor

extremely high number of working-hours. Nowadays even at night time (Q at night)

High Voltages

Power Electronics with voltages up to 1500V



Outdoor Worldwide

The inverter needs to cope with all sorts of climates, rain, hail, dust, sandstroms, snow, elevated irradance, low/ high temperatures

Long Design Lifetime

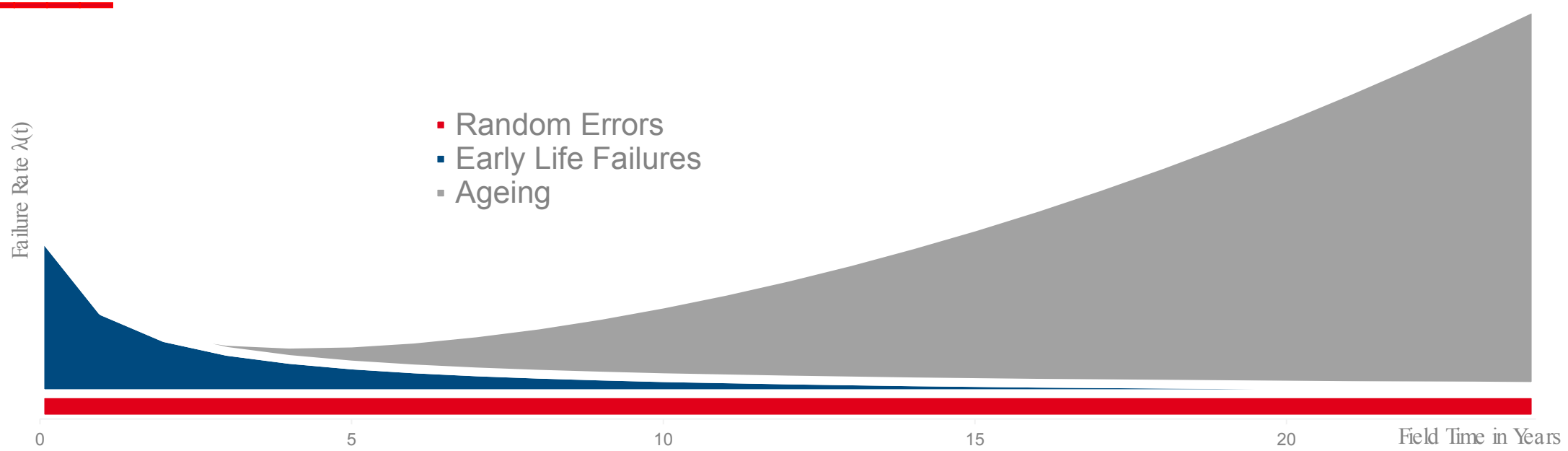
20 to 25 years standard. Tendency for 30 to 40 years

Reliability of PV Inverters

Reliability of PV Inverters is not a matter of defining a standard set of qualification tests.

It is instead a matter of the **right attitude** and **processes** along the value chain.

What leads to failures?



Random Errors

Dramatically overestimated (FIT Rate calculations are obsolete).

Cosmic Radiation is the only reported failure mechanism.

Early Life Failures

To cope with by

- Stable production process
- Effective product end test
- Incoming goods inspection

Ageing

Often referred to as "Design Failures" or "Series Failures".

Neither appear during final inspection nor during standard qualification tests.

Instead: **Acceleration of the reality necessary**

How to Compress Reality

Limited acceleration and sample size

- Operation 24/7
- Limited increase of temperature
- Limited increase of power

Essential due to cross effects

⟹ **Essential but limited**

Moderate acceleration and sample size

- Moderate increase of temperature
- Moderate increase of power

Highest acceleration and sample size

- Drastic increase of temperature
- Moderate increase of power

Ageing effects triggered most accurate

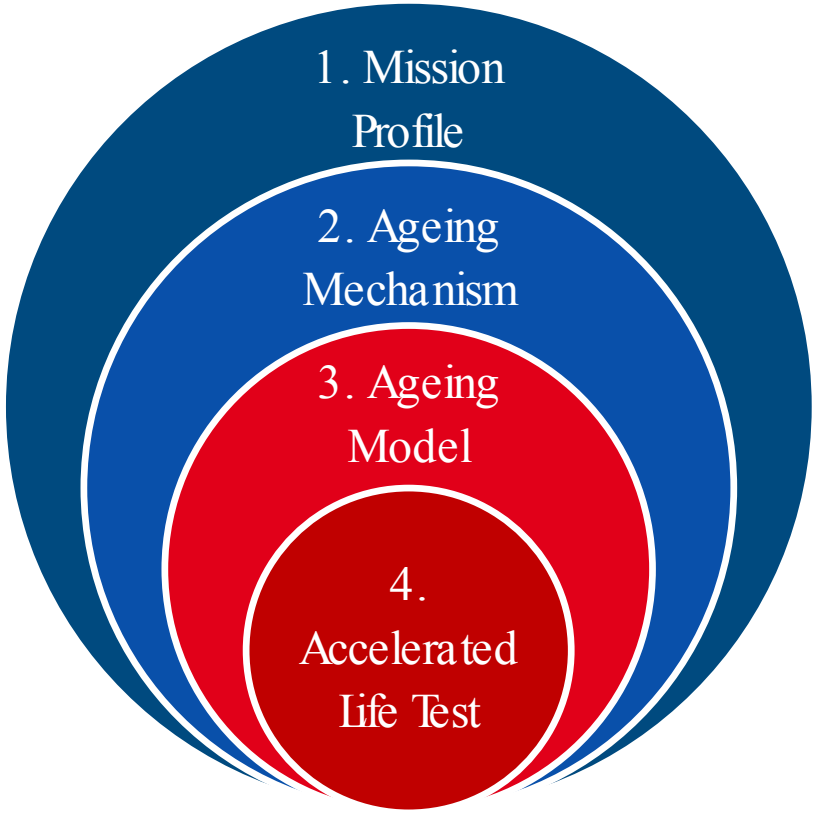
⟹ **Exactly the right test for each single failure mechanism**

Product Level

Assembly/ Board Level

Component Level

How to Compress Reality



1. Mission Profile

Information about stress level and time for each known stress type:

- Temperature / Temperature Cycles
- Humidity
- Power / Power Cycles

2. Ageing Mechanism

Explaining the actual effect (or effects) of ageing, to be obtained from

- Component Manufacturer
- Earlier Testing
- Stress Screening
- Literature

3. Ageing Model

Describes the mathematical correlation between test stress level and field stress level. Generic models (e.g. Arrhenius, Hallberg-Peck, Coffin-Manson) need to be parametrized accordingly.

4. Accelerated Life Test

Optimum: Two test levels, each tested to EOL Derive actual reliability regime.

Often only: Success Run (no failures). Derive a minimum demonstrated reliability.

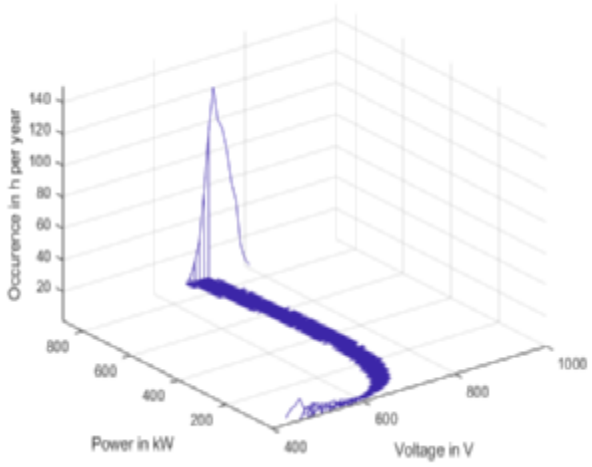
Qualification is always specific to the Mission Profile.

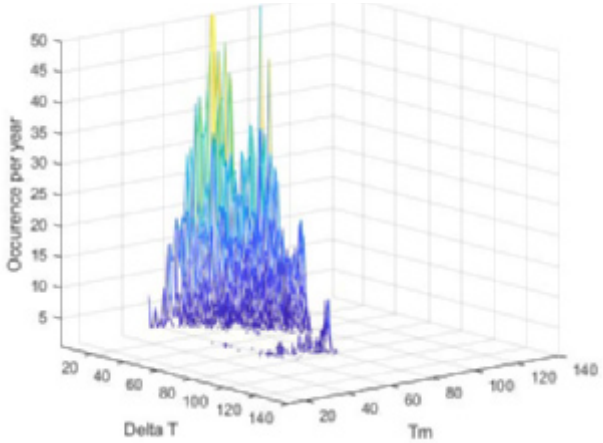
How to Compress Reality

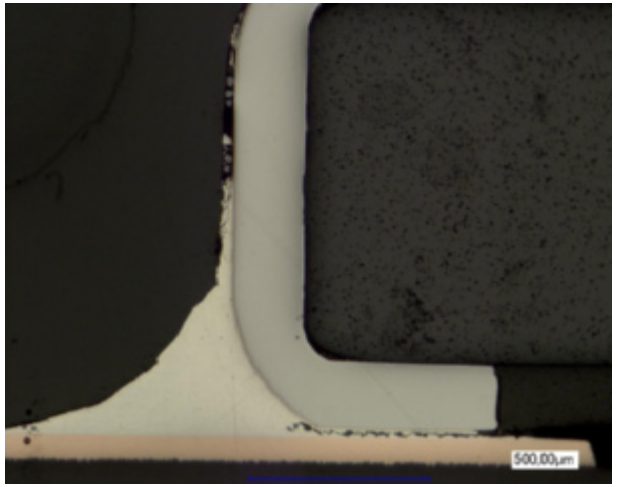
Mission Profile

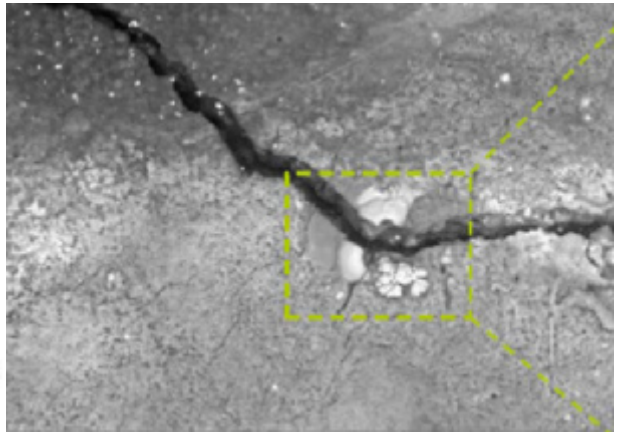
What is the “Field”?

- Expected
  - Power
  - Temperature
  - Humidity
  - Thermal and Power Cycles
- “Translate” Product Level to Component Level. Mission is defined for each component individually
- How many lines: Tradeoff between accuracy and practicability









Ageing Mechanism

What might happen?

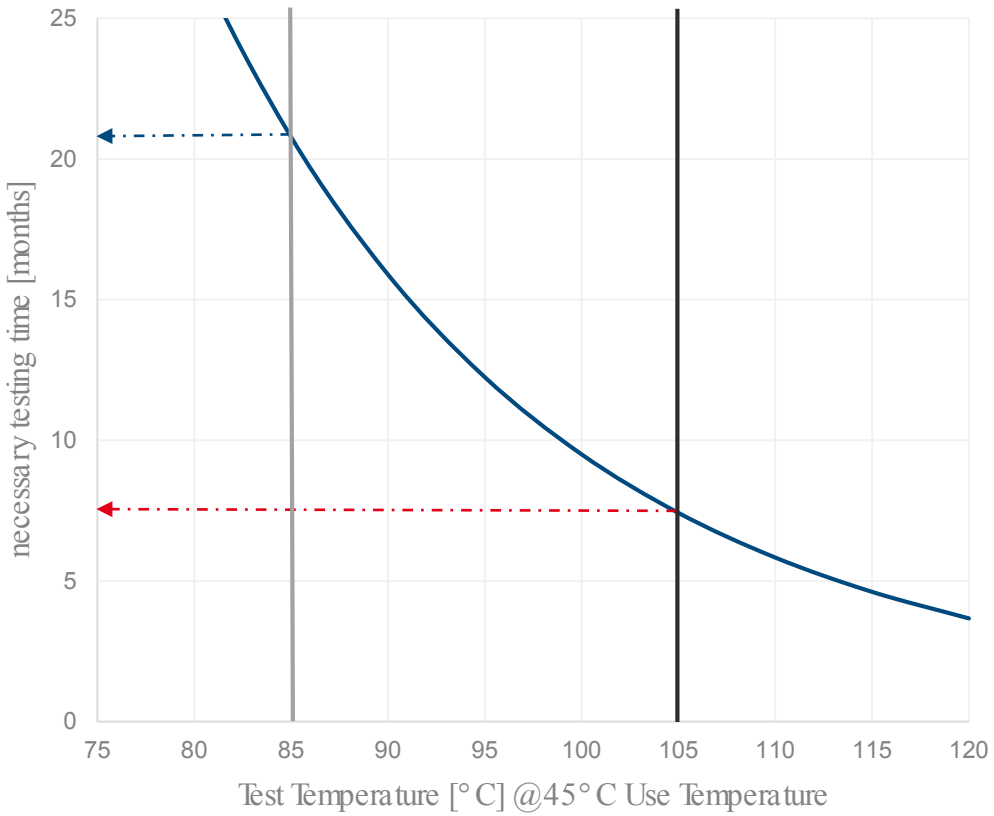
- Manufacturers often have no knowledge.
- Existing information is outdated.
- Screening tests may help.
- Ask manufacturers for commitment to the process.
- Give guidance to manufacturers.

How to Compress Reality

Ageing Model

What is the Acceleration?

- Models exist only for few components.
  - Little research in this field, engineers followed the MTBF model too long.
  - SMA cooperates with component manufacturers and research institutes to gain ageing models for more components.
  - "Robustness Validation" has been included in the AEC-Q100:
- Manufacturers will be forced to work on the topic.



Accelerated Life Test

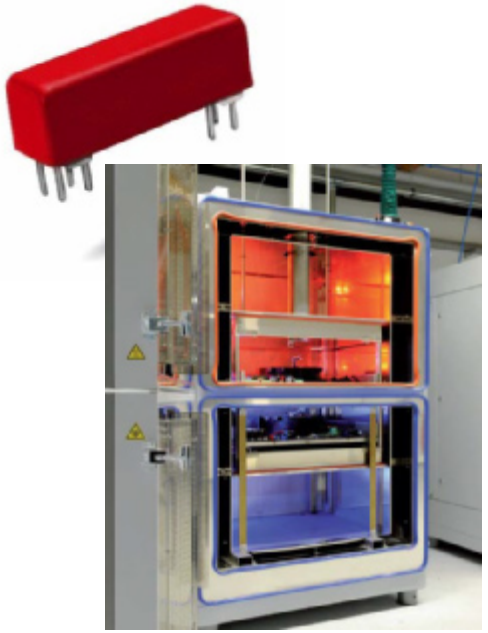
Perform Lifetime Tests!

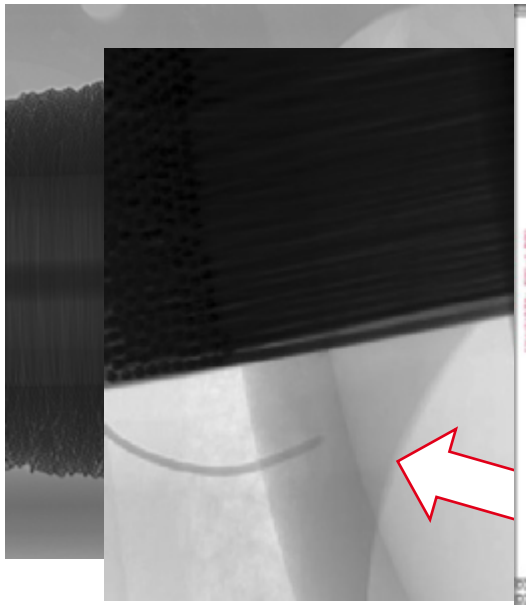
- Time-consuming (despite acceleration) resulting in conflicts with time-to-market.
- Impose a risk of false failures (due to the acceleration)
- **Do not believe in MTBF.**

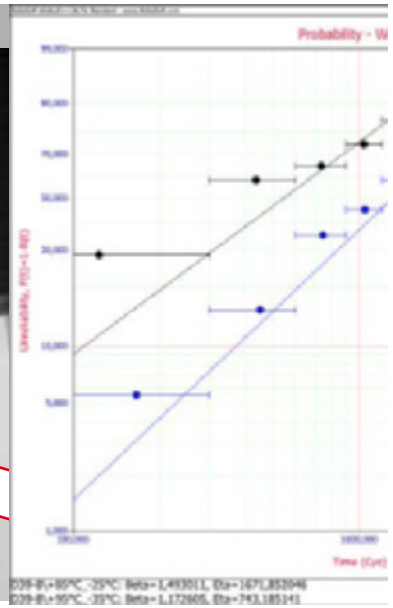
Keep tests simple:

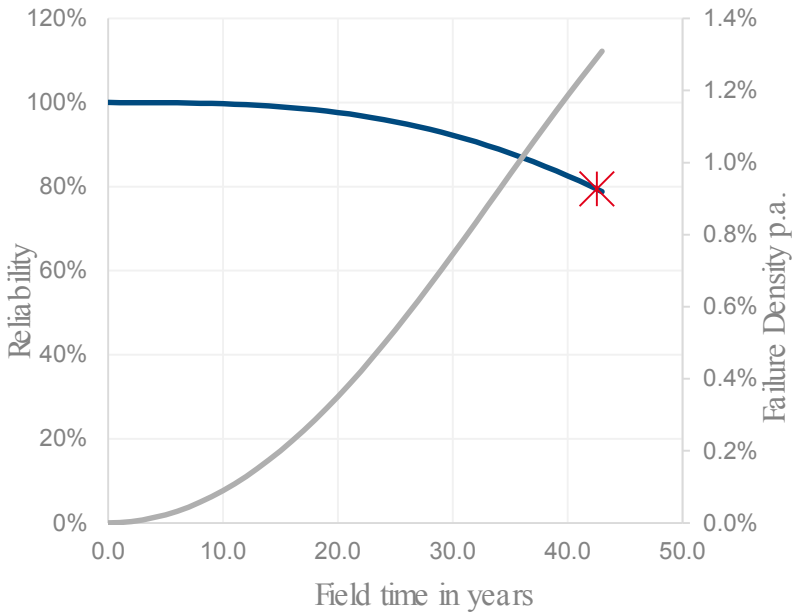
- **Only a single ageing mechanism per test (unlike HALT/HASS)**
- Test only what is really needed (even go below component level)

Reliability Testing: Relay Failures









Relay failure in Shock Test

Small Signal relay failing in standard qualification test.

Failure analysis by XRay

Breaking of the coil wire established as root cause.

Testing at two stress levels

Test 1 at ΔT=110K (blue line)
Test 2 at ΔT=130K (black line)
derived Coffin-Manson Exponent: 4.4

Projection on field stress

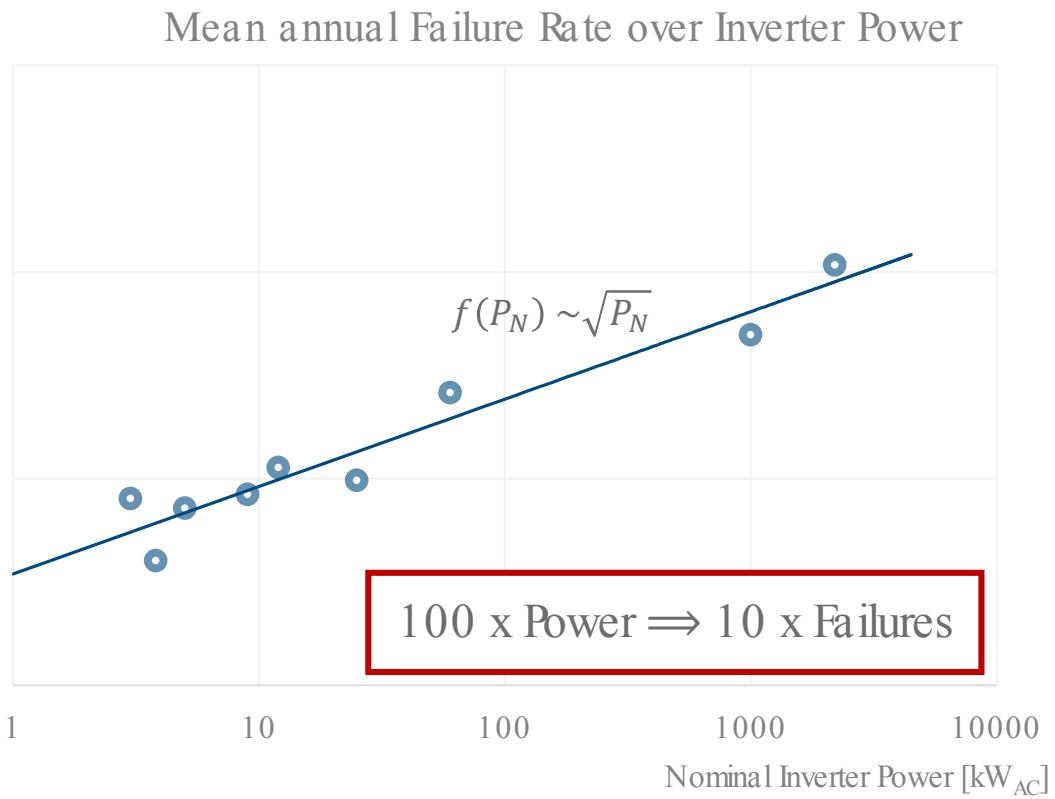
Reliability after 20 years: 97%.
Subsequent qualification of an alternative relay.

Reduce to the Maxiumum

The most reliable inverter is the only one in the installation.

The best leverage to increase inverter reliability is the reduction of parts.

Failures as function of Inverter Nominal Power



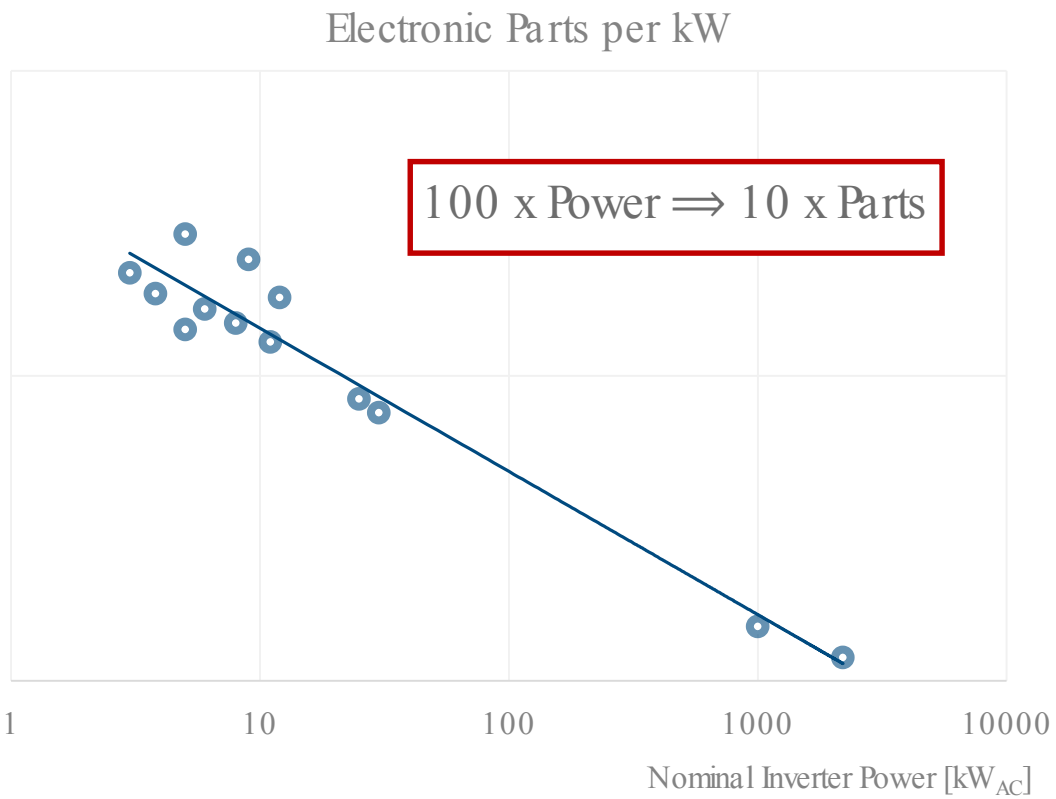
Mean annual FailureRate increases over Inverter Power

Due to an increase of complexity, large inverters generally fail more often than small inverters.

Failure Rate rises slower than Power

The failure rate rises only to the power of 0.4, approximately following the square root function.

Failures as function of Inverter Nominal Power



Mean annual number of service actions decreases with inverter power

For a constant overall power (in this case 100MW) the mean annual number of service actions decreases.

Parts will only fail, if they are designed in.

The main reason for the better performance of larger inverters is the reduced total number of components.

Effect on availability and revenue

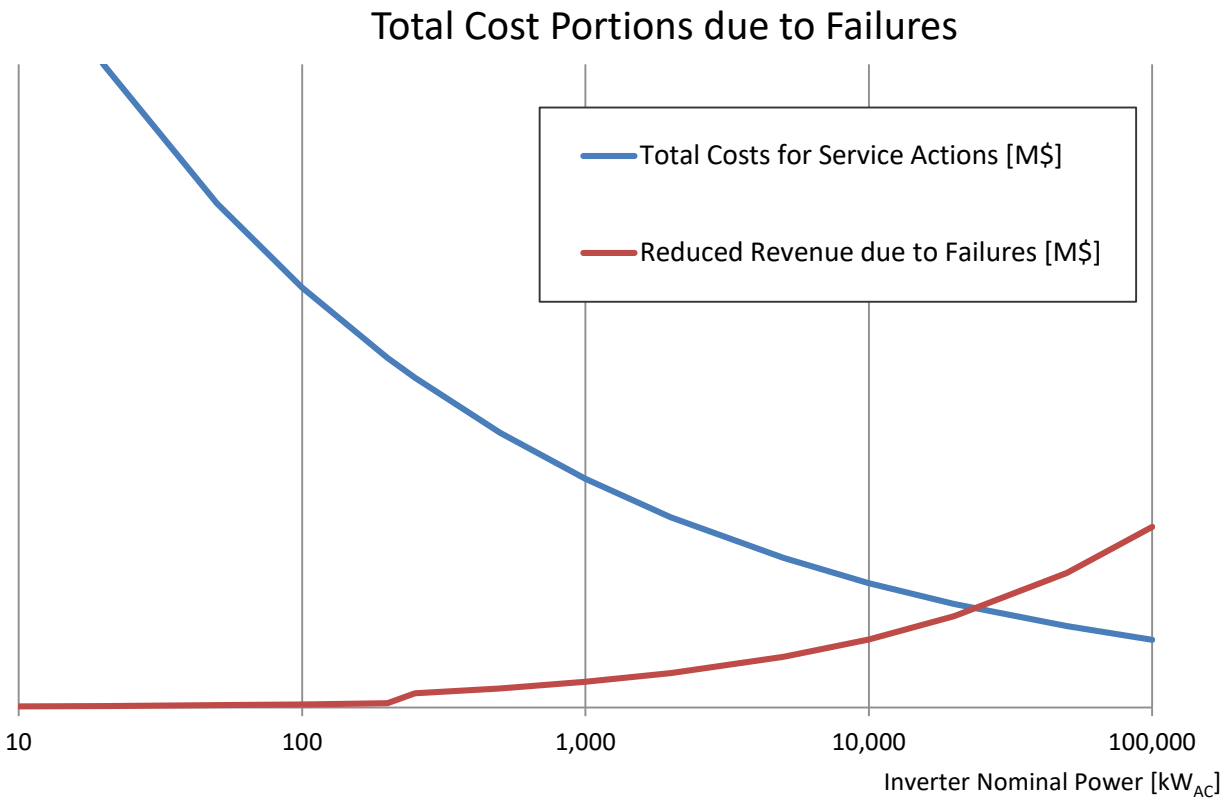
Although Downtime increases with larger inverters, the influence on revenue is much lower than the decreased number of service actions.

Failure Cost Analysis over Inverter Power

Service action costs are dominant compared to lost revenue.

Large inverters serve the lowest possible failure-related costs

The best inverter is the only one in the installation.



Reduce parts

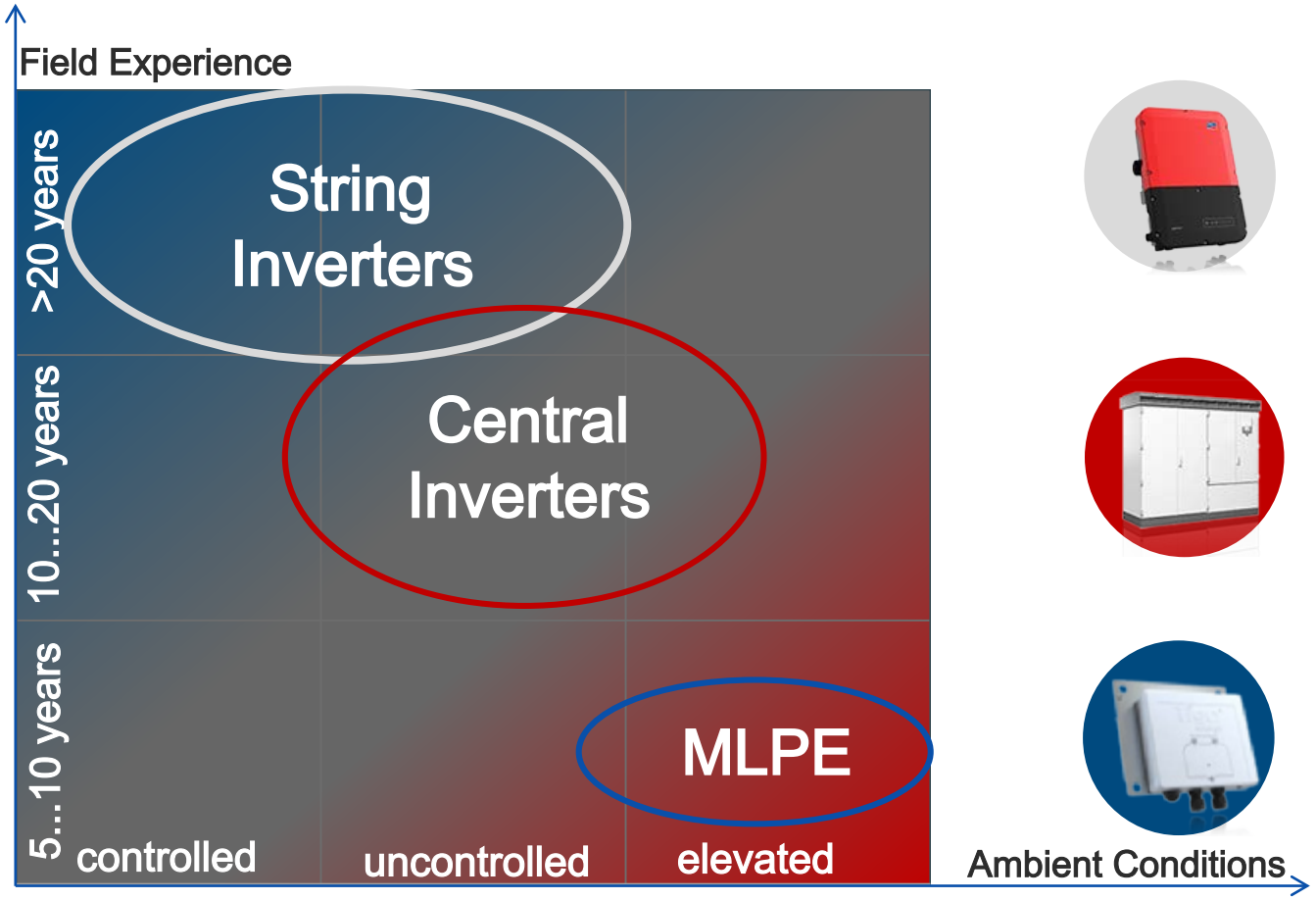
All MLPE solutions increase the number of parts in the installation.

MLPE is contradictory to reliable PV Systems.

Sample Sizes for Reliability Qualification

Inverter Type	Central – 1MW	String – 50kW	MLPE – 500W
Number of Inverters for 1MW	1	20	2000
Target Annual Failure Rate	1%	1%	1%
Number of Critical Components per Inverter	20	15	10
Total Number of Critical Components	20	300	20,000
Minimum Reliability per Critical Component (after 20 years)	99.0%	99.93%	99.999%
Required Sample Size at CL 0.6	91	1,374	91,629

A View on surrounding Conditions



Field Experience with String Inverters in Europe is up to 30 years. Installations partly indoor, partly outdoor.

Field Experience with Central Inverters is about 15 years in Europe. Usually outdoor installed

Least Field Experience with Module Level Electronics. Mounting under Modules means most severe ambient conditions

Conclusion

Standard Qualification Tests

Standard tests on system level are indispensable.

However, their evidence for reliability is limited.

MLPE

All sorts of MLPE increase the number of parts and thus reduce reliability.

MLPE runs at the challenging place in the installation

Design For Reliability

Accelerated Ageing is the way to reliable PV Systems.

All members of the value chain need to participate and bring forth the idea.

One Inverter per Installation

A large leverage to increase reliability is the reduction of parts.

Parts are reduced effectively by large inverters.

Thank you

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Methods to Optimize Maintenance in PV Plants

Starting with Inverters

Michael Bolen, Sr. Project Manager, EPRI
Sean Hackett, Engineer III, EPRI
Thushara Gunda, Staff Scientist, Sandia

PV Reliability Workshop
Lakewood, CO
2019-02-28

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What is the Electric Power Research Institute (EPRI)?

- **Mission**
  Advance *safe*, *reliable*, *affordable,* and *environmentally responsible* electricity for society through global collaboration, thought leadership and science & technology innovation

- **Members**
  450+ participants in more than 30 countries

  Generate approximately 90% of the electricity in the United States

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EPRI's Solar Generation Program (193C)

Targeted R&D addressing relevant issues to large-scale photovoltaics and concentrating solar

- ***Increase confidence in long-term plant performance and production***
  - Understand and quantify impact of upfront decisions – design through end-of-life
  - Improve accuracy, precision and capabilities of performance models (reliability, degradation)

- ***Improve operations and maintenance knowledge, capabilities, and productivity***
  - Learn from existing plants – Use operational data for budgeting, best practices, and continuous improvement
  - Increase productivity and safety of field workers

- ***Contextualize trends and innovation: Technology, Cost, Performance***
  - Subject matters experts and curated knowledge repository for tech transfer

Comprehensive, objective, actionable guidance on existing and future solar tech and life cycle

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Reliability is key to minimize and achieve LCOE targets

$$\text{Levelized Cost of Electricity} = \frac{\text{Lifetime Costs}}{\text{Lifetime Energy}}$$

(Units: $ / MWh)

Smaller upfront capital costs mean…

…other costs matter more, like OpEx…

$$= \frac{\boxed{\text{Installation Cost}} + \sum_{n=1}^{N} \frac{\boxed{\text{Annual O \& M Costs}_n}}{(1+\text{Discount Rate})^n} - \sum_{m=1}^{M} \frac{\text{Depreciation}_n}{(1+\text{Discount Rate})^n} \text{x(Tax Rate)} - \frac{\text{Residual Value}}{(1+\text{Discount Rate})^n}}{\sum_{n=1}^{N} \frac{\boxed{\text{Initial kWh/kW}}}{(1+\text{Discount Rate})^n} \text{x}(1-\text{System Degradation Rate})^n}$$

…and maintaining plant production.

Relative change in rate of return on a 1 MW PV plant		
	10% decrease	10% increase
Capacity Factor (%)	-52%	+45%
Equipment Cost ($/MW)	+18%	-18%
Fixed O&M ($/MW)	***+11%***	***-12%***
Development cost ($/MW)	+10%	-11%

Source: BNEF, "PV OM Index 2015" Sep. 2015.
Note: Assumes an initial O&M cost of $30,000/MW-yr, lifetime of 20 years, CapEx of $1.39.W, 0.7% annual degradation, 2% inflation rate, 21% tax rate, Electricity sold at $110/MWh, initial equity IRR 6.0%

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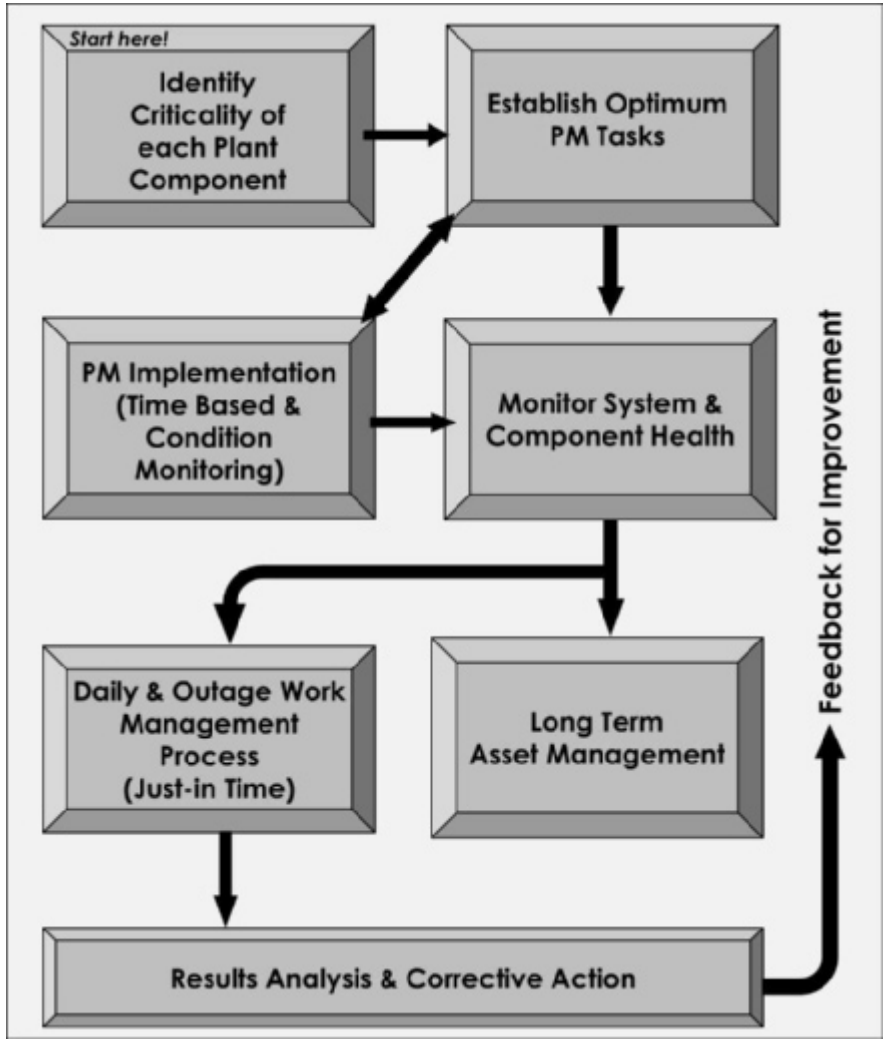
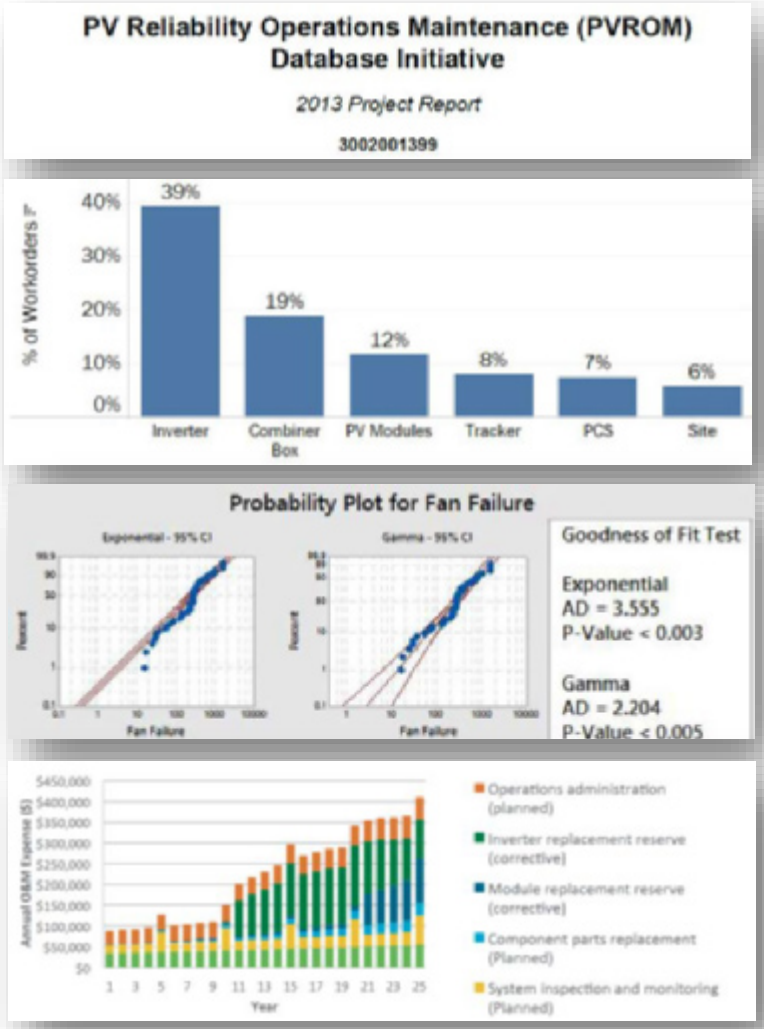
PV Plant Reliability Initiative: Parallel efforts, one goal

Established method

Equipment Reliability process



Data-driven approach



Collect

Curate

Analyze

Apply

Optimize cost versus efficacy of PV operations and maintenance

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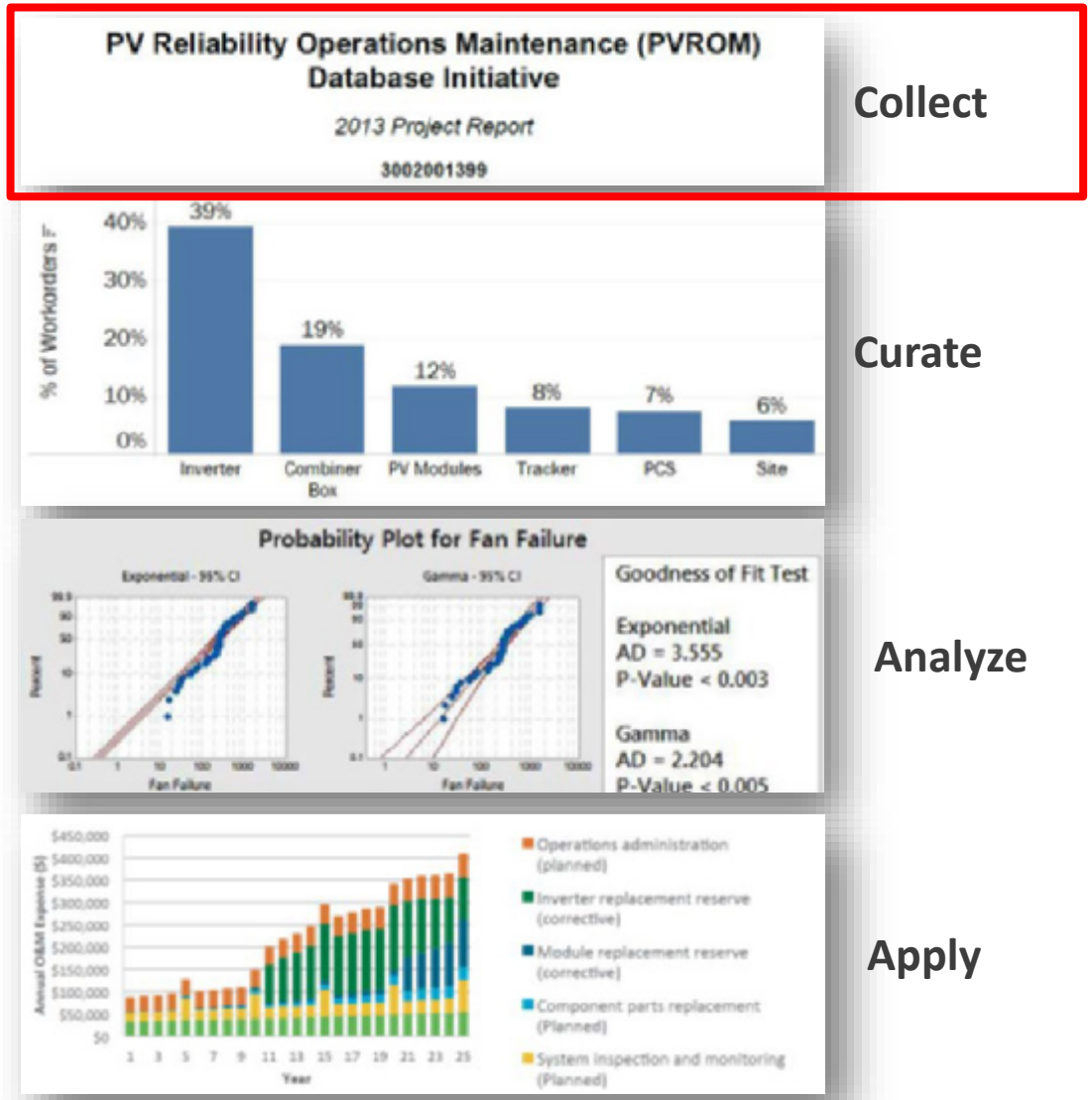
Data-driven Analysis: Approaches to intake data



Collect

Curate

Analyze

Apply

Designed for Reliability Analysis

Yes — **Somewhat** — **No**

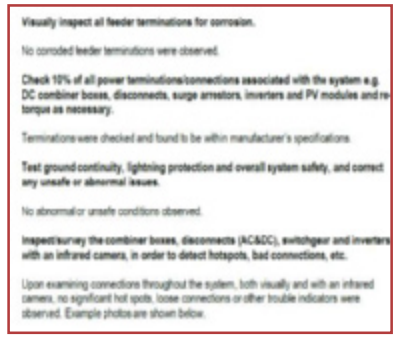
PVROM

- Highly structured series-parallel component dependencies
- Allows for less data manipulation for reliability analysis

Event Database

- Somewhat structured based on CMMS
- Data collection quality and details dependent on company

3rd Party Reports



- Monthly reports with varied level of detail
- Aggregated information often insufficient for detailed analysis

- ***Collecting raw maintenance logs from industry.***
- ***Want to share for analysis? Contact mbolen@epri.com***

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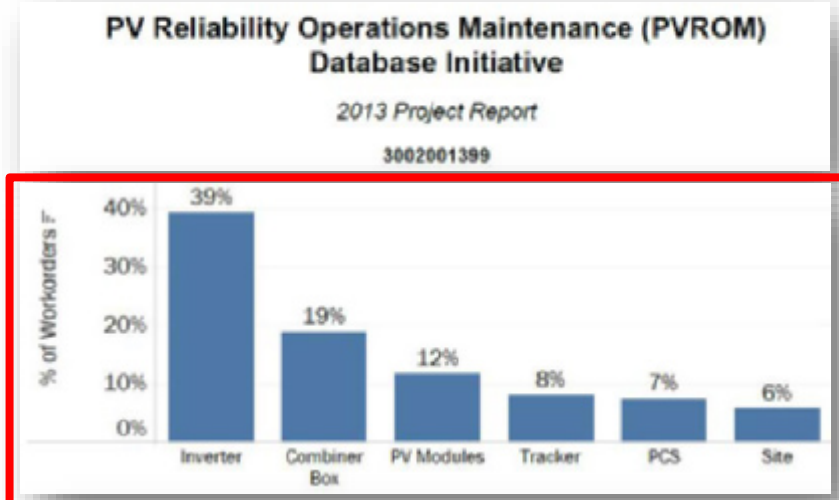
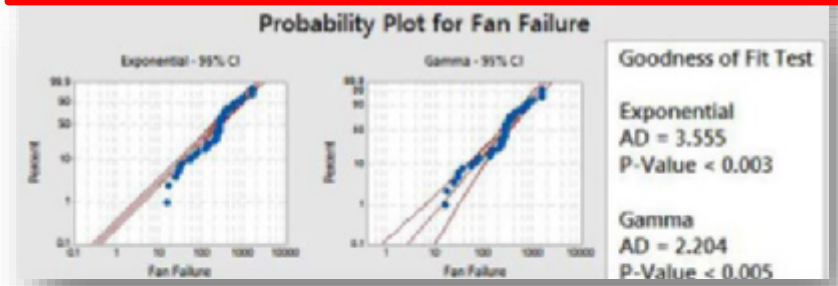
Data-driven Analysis: Categorical Consistency Desired

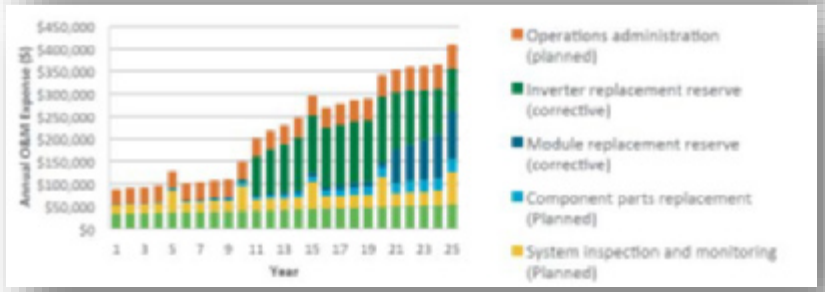


Collect

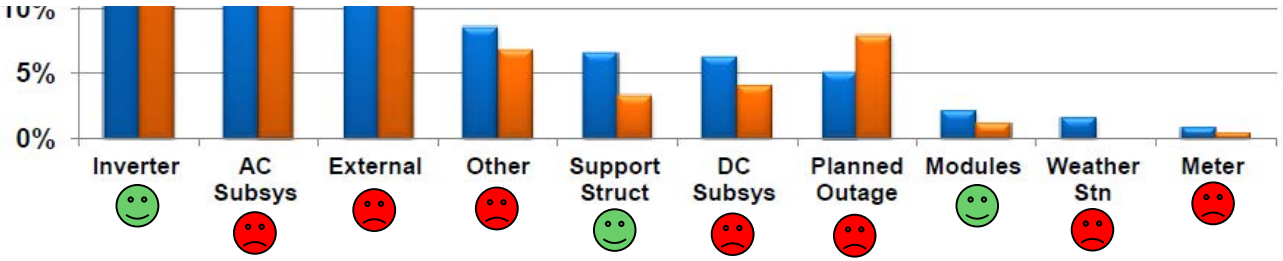
Curate

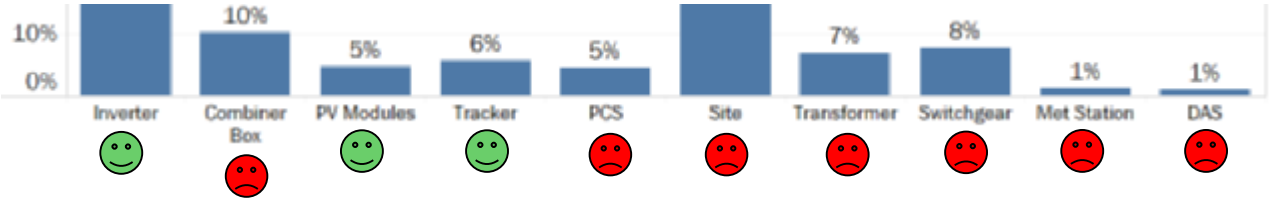


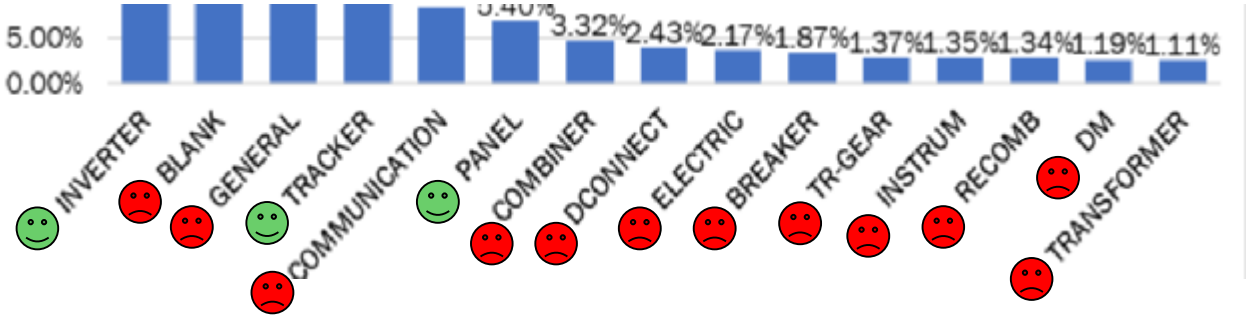
Analyze



Apply







- *Curation is a highly labor intensive part of data analysis*
- *Opportunity for industry consensus and implementation*

Images Source:
A. Golnas, "PV System Reliability: An Operator's Perspective," IEEE Photovoltaic Specialists Conference. Austin, TX: 2012.
First Solar Energy Services

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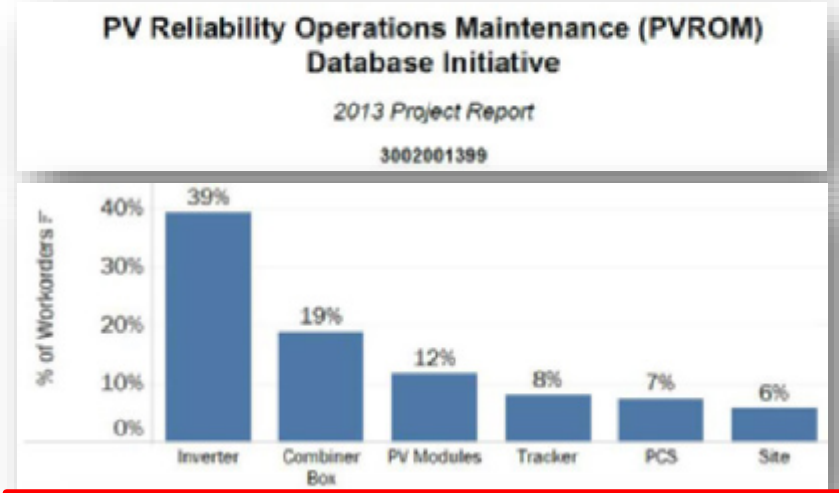
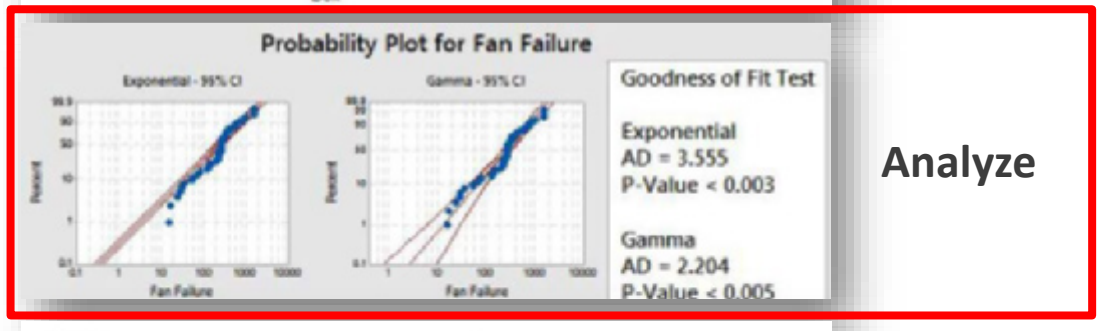
Data-driven Analysis: Example methods and metrics



Collect

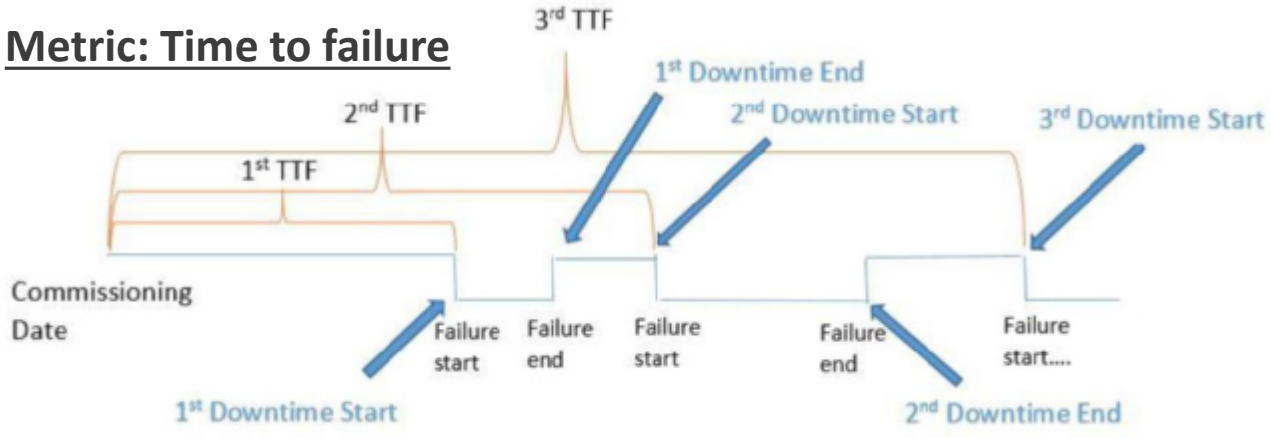
Curate



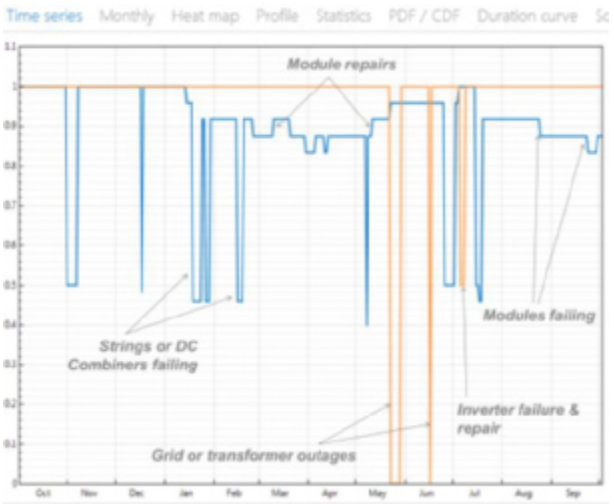
Analyze

Apply

Metric: Time to failure



Software: NREL PV Reliability Performance Model



Statistical Methods

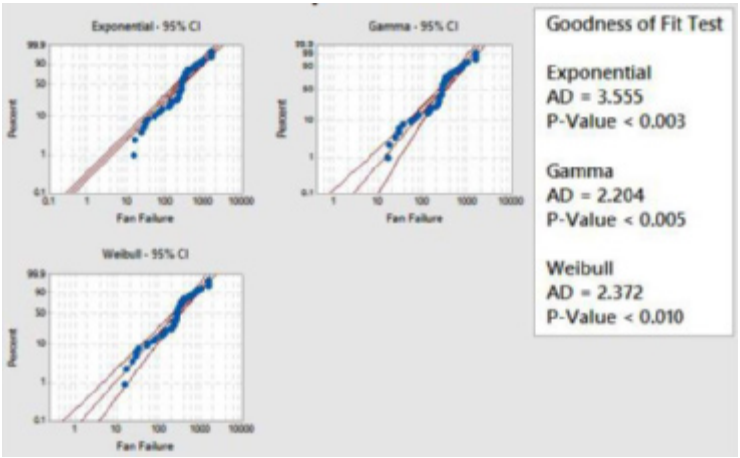


Image Sources:
J. Freeman. *Evaluating Energy Impacts and Costs from PV Component Failures.* WCPEC-7. Waikoloa, HI: 2018.
PV System Component Fault and Failure Compilation and Analysis. Sandia. SAND2018-1743. Albuquerque, NM: 2018.

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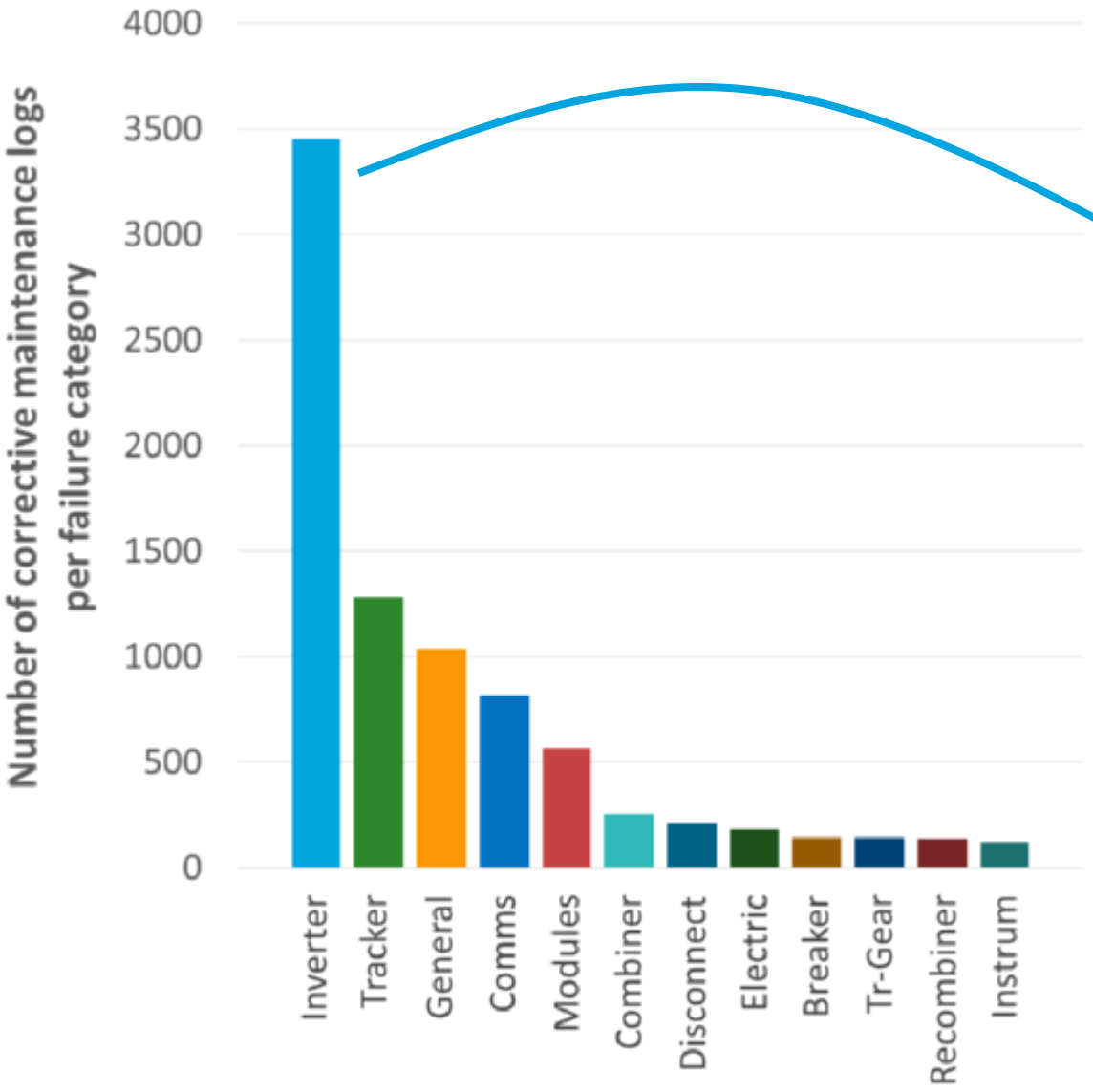
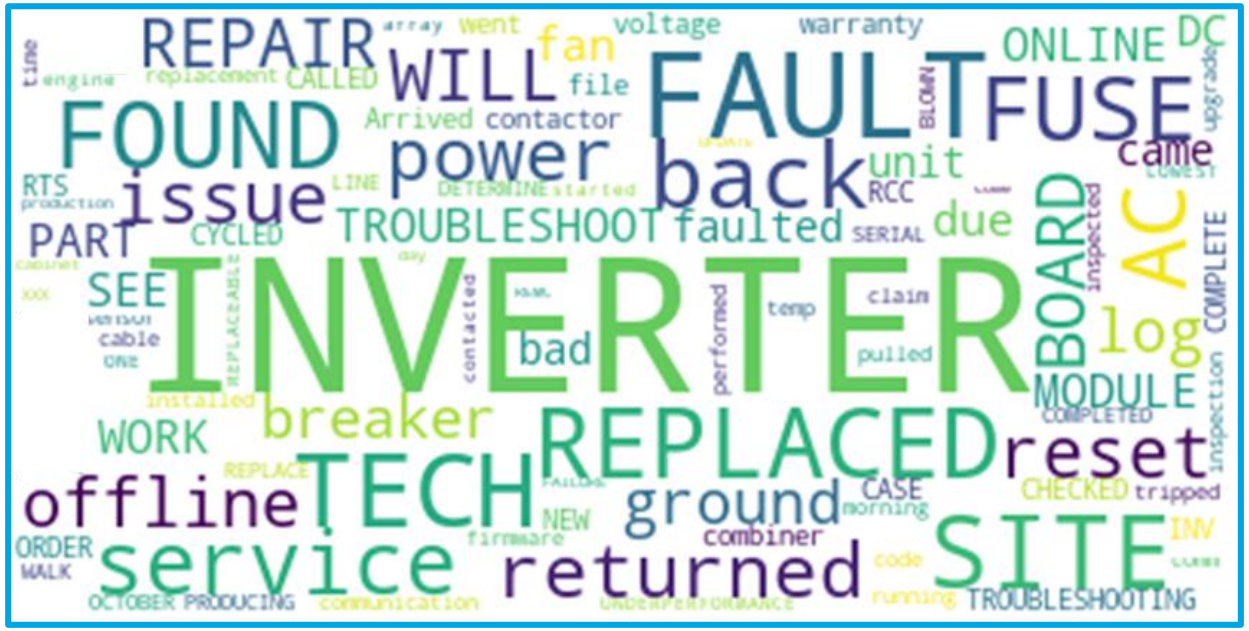
Another (simple) Analysis Method: Word clouds



Word cloud from corrective maintenance logs of ~60 large-scale plants



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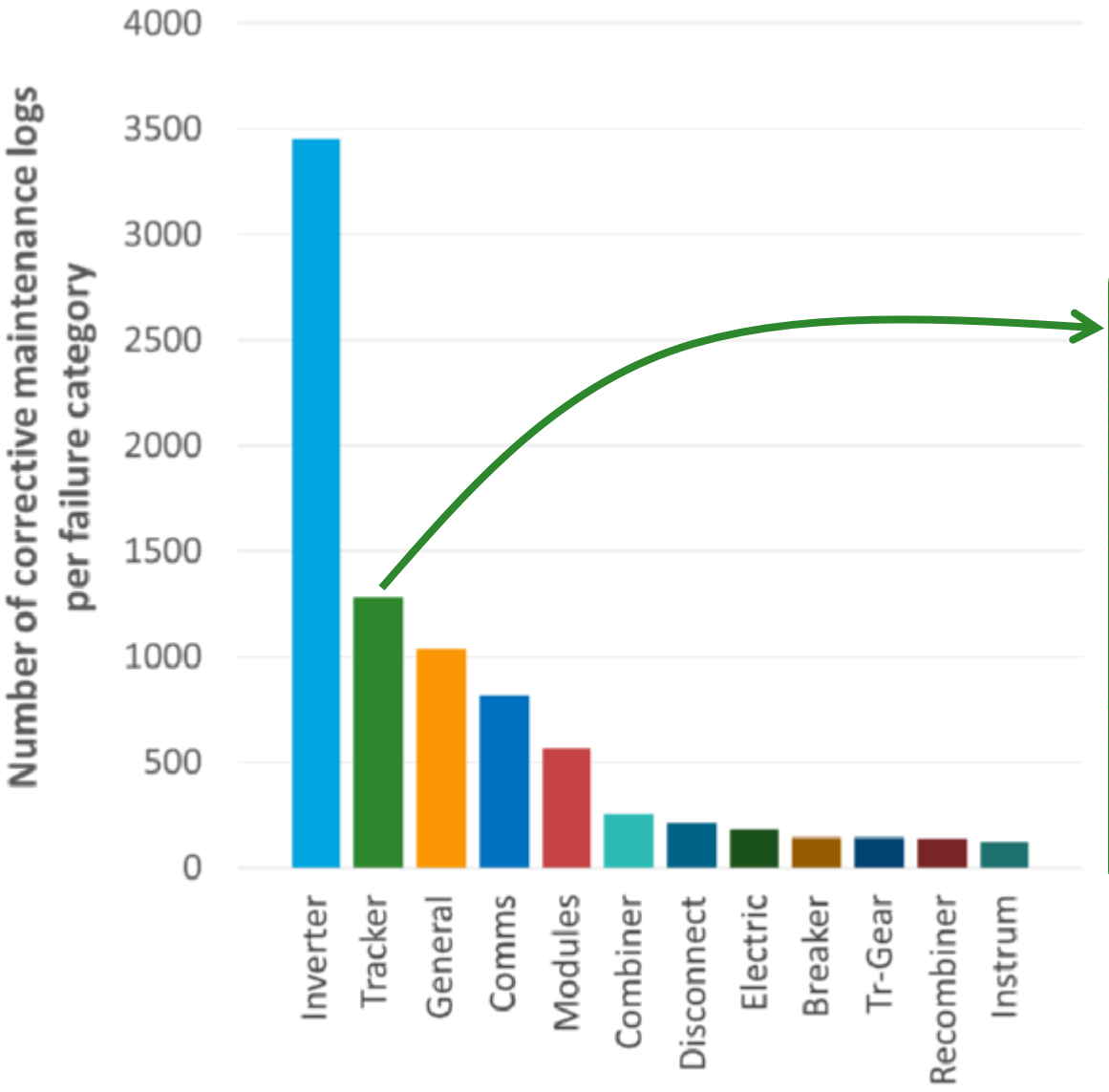
Another (simple) Analysis Method: Word clouds



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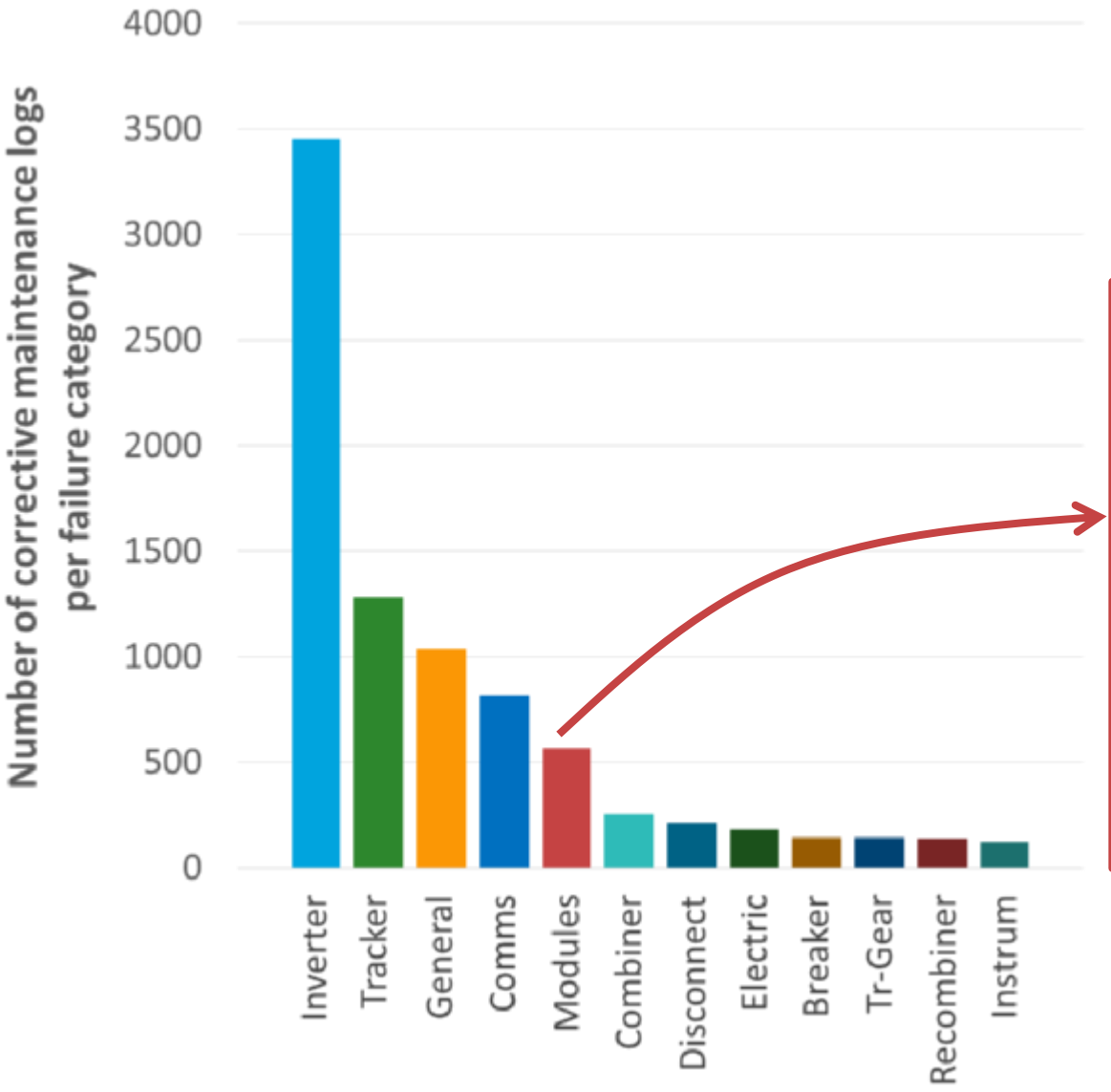
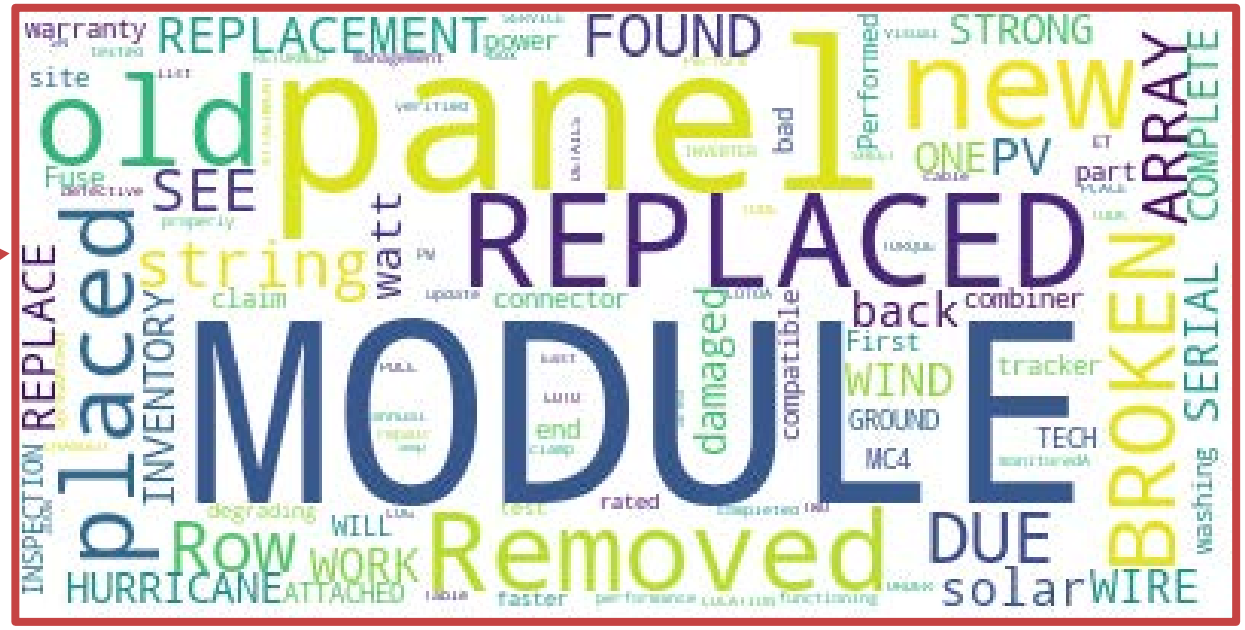
Another (simple) Analysis Method: Word clouds





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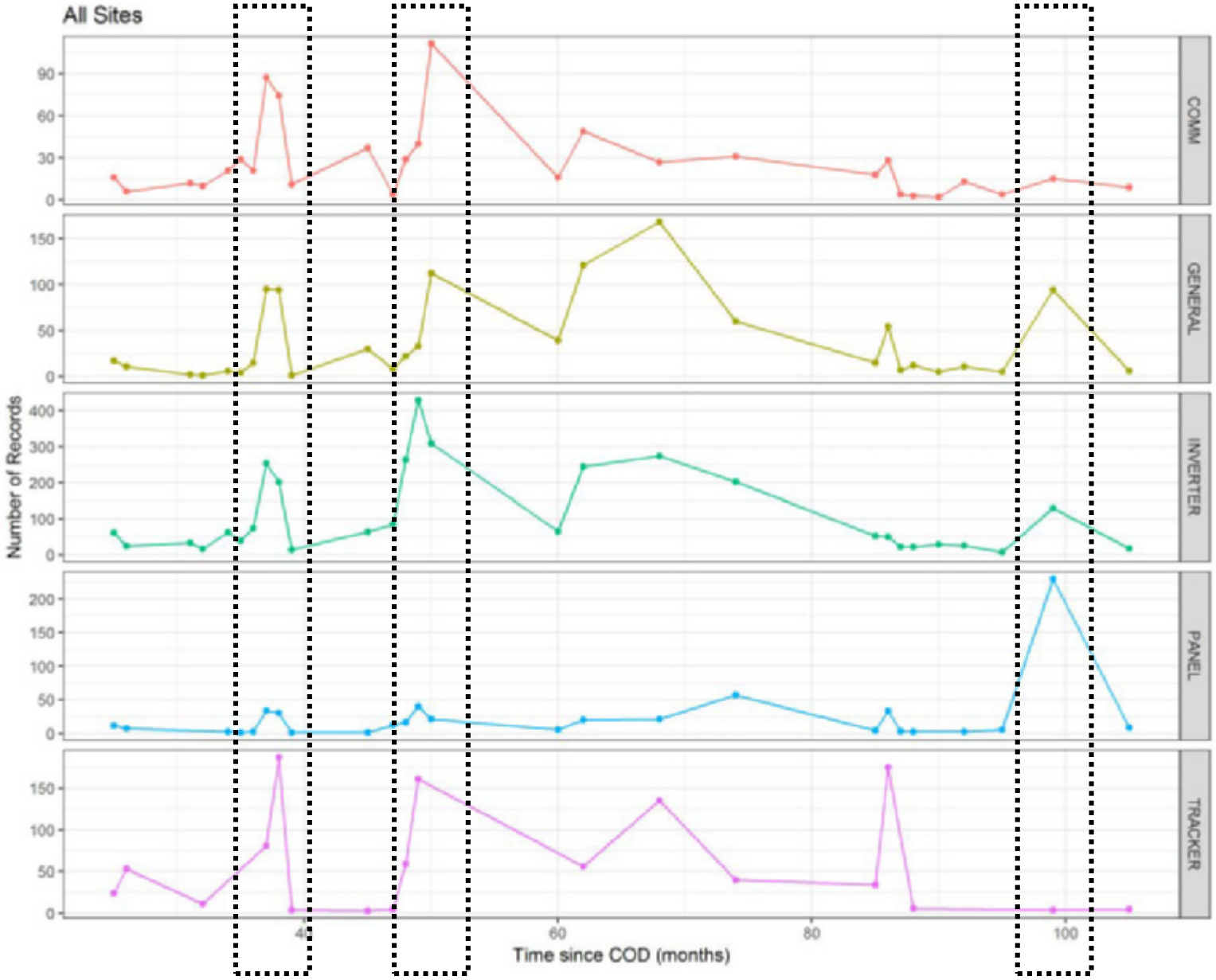
Spikes in failures at discrete points in time?

- Observed spikes in corrective maintenance logs for components
  - Months ~36, ~48, and ~96 after commercial operation date (COD)

- Root cause under investigation

- ***Anyone else seeing this phenomena?***



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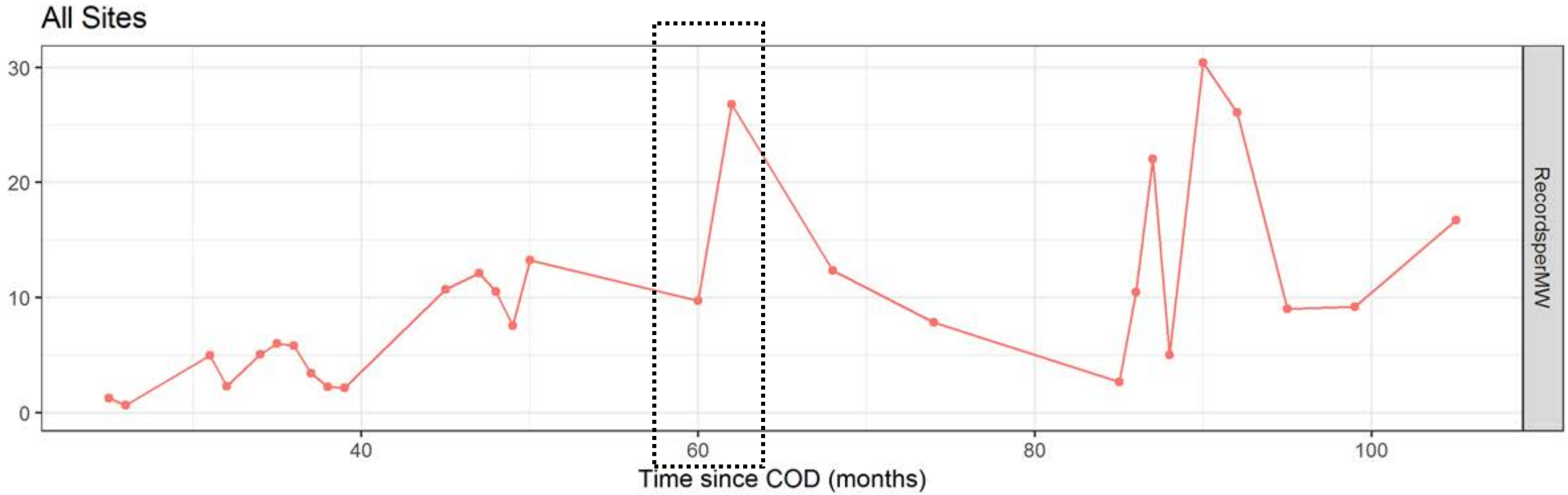
Spike in inverter failures after 5 years of operation?

- Inverter corrective maintenance logs per MW shows spike ~60 months after COD



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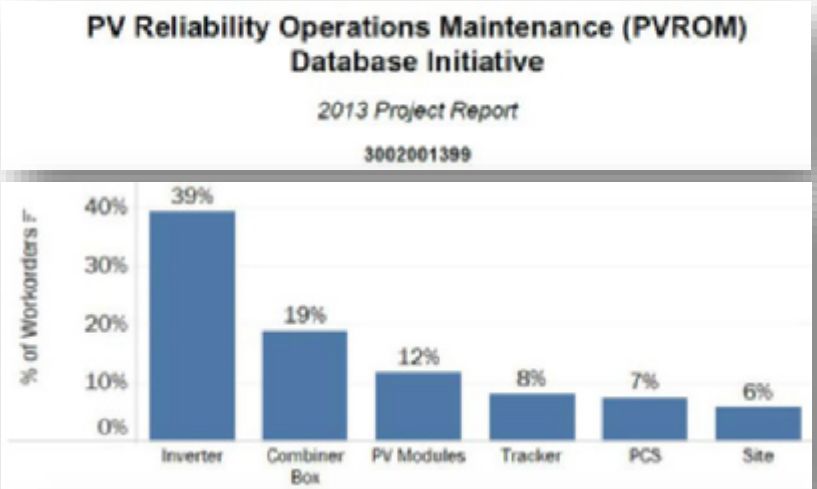
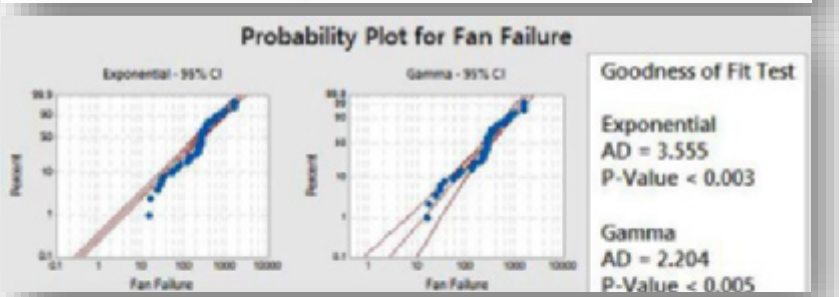
Data-driven Analysis: Examples of past ways to apply

Collect

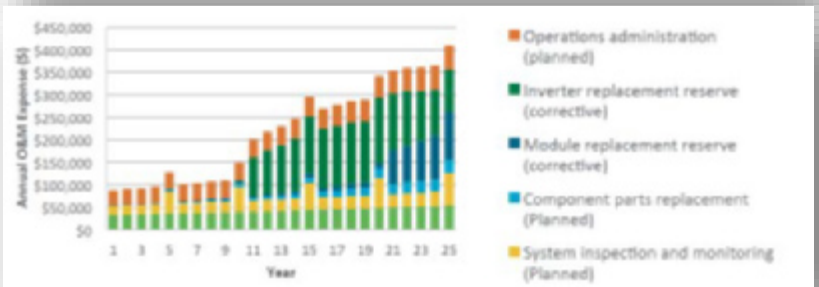


Curate

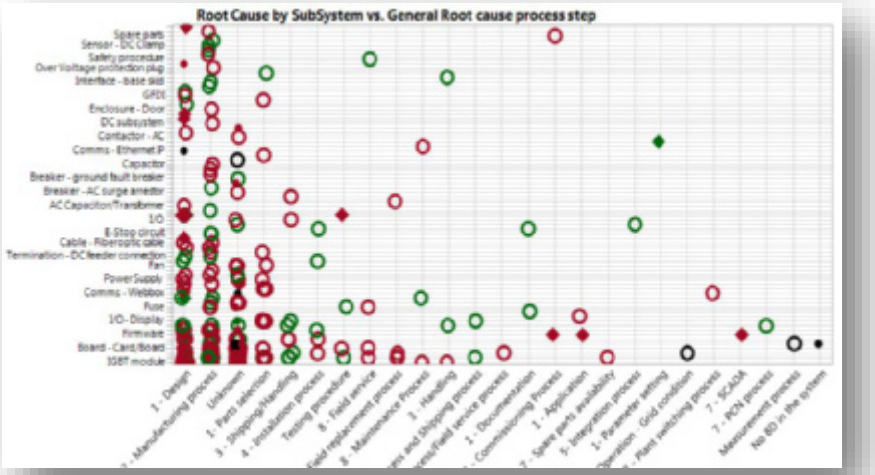


Analyze

Apply



8-D Analysis: Processes to improve at OEM

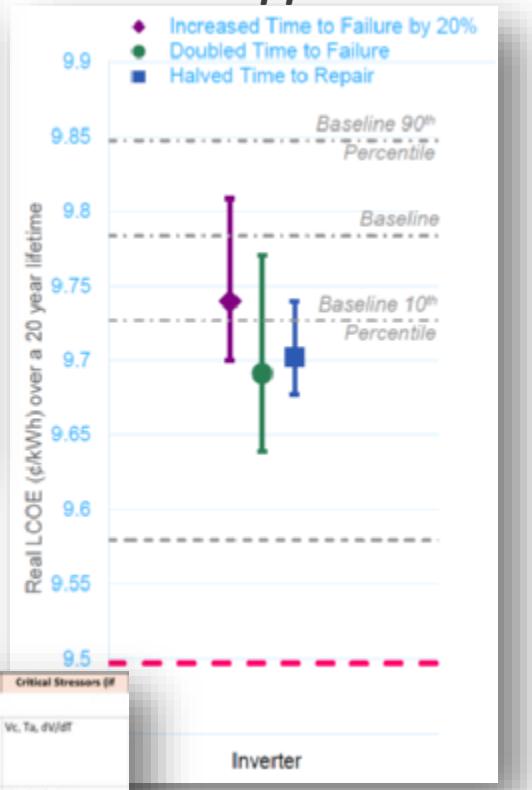


S. Lokanath. *Central Inverter Cost of Ownership & Event Analysis.* PV Reliability Workshop. Lakewood, CO: 2017.

Failure Mode Effect Analysis: Component-level stressors and failure mechanisms

Component	Potential Failure Mode(s)	Potential Failure Mechanisms(s)	Failure Mechanisms Type	Critical Stressors (if
Polymer Caps	Open Circuit	Self-heating dielectric breakdown	Overstress	Vc, Ta, dV/dT
		Heat contraction of the dielectric leading to connection instability	Overstress	Ta, ripple Ic
		fatigue induced cracks in through hole solder joints	Overstress/Wear out	Temperature cycling and vibration
		Reduction in electrode area due to oxidation as a result of moisture absorption	Wear out	Relative Humidity
	Short Circuit	Dielectric breakdown of oxide layer	Overstress	Vc, dV/dT
		Self-heating due to overcurrent	Overstress	Ta, ripple Ic
		Moisture absorption by Polymer	Wear out	Relative Humidity
	Drift in electrical parameters	Rapid increase in leakage current due to the presence of iron particles in the dielectric layer, which originate from iron salt used in polymerization process of the electrolyte	early wearout resulting from issues with manufacturing-process control	Vc, ripple Ic, Ta, Humidity
		Dielectric degradation, polymer electrolyte degradation	Wear out	Vc, ripple Ic, Ta, Humidity
Liquid Electrolytic Caps	Decrease in Capacitance and Increase in ESR	Aging of dielectric material	Wear out	Prolonged use - T and V outside of rated values

Sensitivity Analysis: Decision support tool



J. Freeman. *Evaluating Energy Impacts and Costs from PV Component Failures.* WCPEC-7. Waikoloa, HI: 2018.

P. Hacke. *PVQAT TG 11 PV Systems - Subgroup on Power Electronics.* PV Reliability Workshop. Lakewood, CO: 2018.

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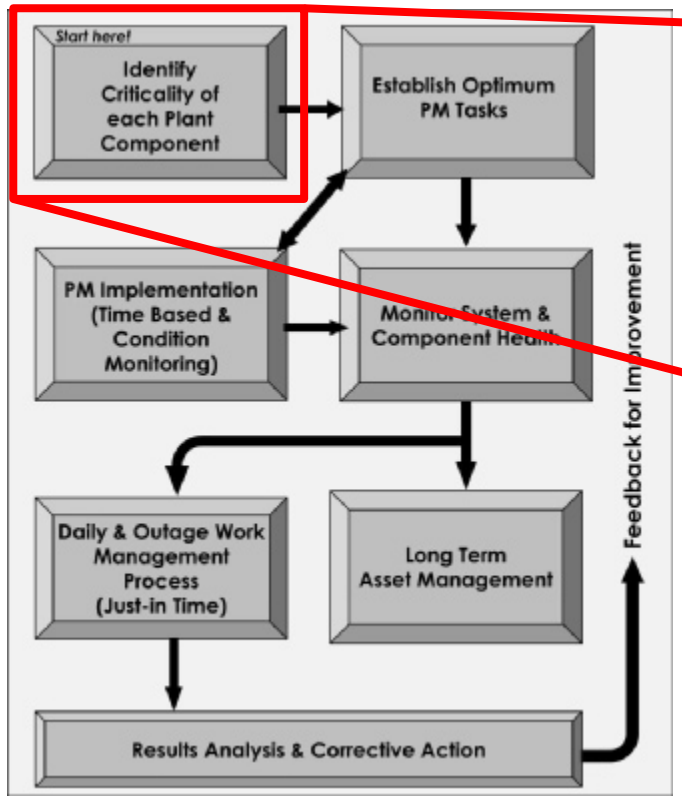
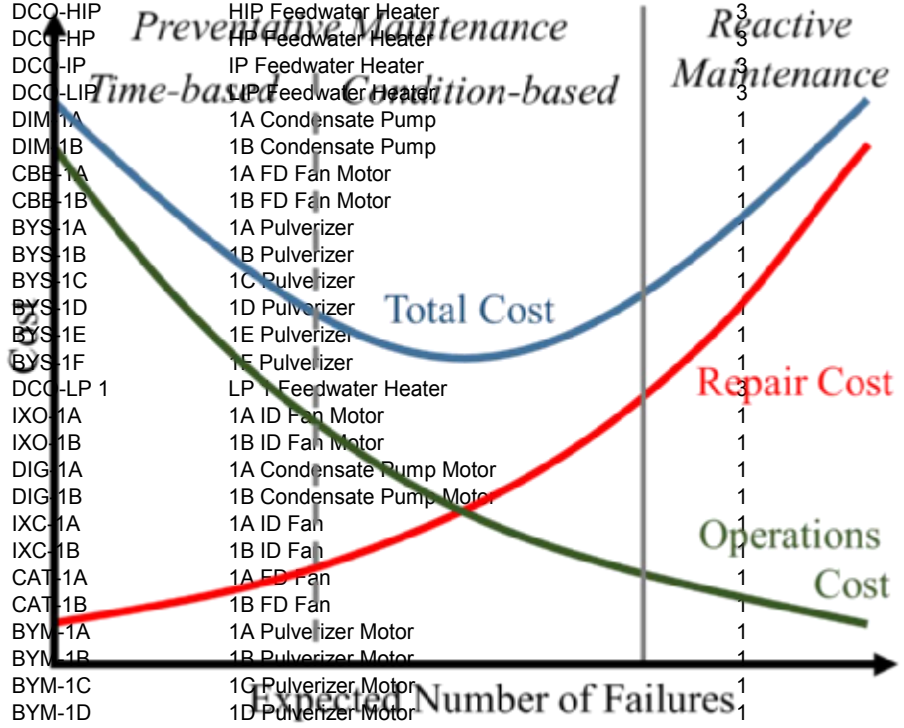
Equipment Reliability: Assess Component Criticality



Equipment Code and Spec ID	Equipment Description	Safety	Environmental	Cost	Commercial Availability	Efficiency	Operating Criticality Ranking	Asset Criticality Ranking
DXX-1A	1A Circulating Water Pump	1	1	6	5	8	11.27	102.67
DXX-1B	1B Circulating Water Pump	1	1	6	5	8	11.27	102.67
DCO-CROSSOVER	Crossover Feedwater Heater	3	1	2	3	8	9.33	88.98
CBC-1A	1A Air Preheater	1	1	3	8	1	8.72	79.42
CBC-1B	1B Air Preheater	1	1	3	8	1	8.72	79.42
PGE	Condenser (Tubes)	1	1	2	8	1	8.43	76.77
CZW	Pump, Boiler Feed	1	1	3	9	1	9.64	71.52
DXD-1A	1A Circulating Water Pump Motor	1	1	3	4	5	7.21	65.70
DXD-1B	1B Circulating Water Pump Motor	1	1	3	4	5	7.21	65.70
DCO-HIP	HIP Feedwater Heater	3	1	2	3	4	6.24	59.57
DCO-HP	HP Feedwater Heater	3	1	2	3	4	6.24	59.57
DCO-IP	IP Feedwater Heater	3	1	2	3	4	6.24	59.57
DCO-LIP	LIP Feedwater Heater	3	1	2	3	4	6.24	59.57
DIM-1A	1A Condensate Pump	1	1	4	4	1	5.92	53.90
DIM-1B	1B Condensate Pump	1	1	4	4	1	5.92	53.90
CBE-1A	1A FD Fan Motor	1	1	4	4	1	5.92	53.90
CBE-1B	1B FD Fan Motor	1	1					
BYS-1A	1A Pulverizer	1	1					
BYS-1B	1B Pulverizer	1	1					
BYS-1C	1C Pulverizer	1	1					
BYS-1D	1D Pulverizer	1	1					
BYS-1E	1E Pulverizer	1	1					
BYS-1F	1F Pulverizer	1	1					
DCO-LP 1	LP 1 Feedwater Heater	3	1					
IXO-1A	1A ID Fan Motor	1	1					
IXO-1B	1B ID Fan Motor	1	1					
DIG-1A	1A Condensate Pump Motor	1	1	3	4	1	5.29	48.21
DIG-1B	1B Condensate Pump Motor	1	1	3	4	1	5.29	48.21
IXC-1A	1A ID Fan	1	1	2	4	1	4.80	43.69
IXC-1B	1B ID Fan	1	1	2	4	1	4.80	43.69
CAT-1A	1A FD Fan	1	1	2	4	1	4.80	43.69
CAT-1B	1B FD Fan	1	1	2	4	1	4.80	43.69
BYM-1A	1A Pulverizer Motor	1	1	3	4	2	5.57	41.29
BYM-1B	1B Pulverizer Motor	1	1	3	4	2	5.57	41.29
BYM-1C	1C Pulverizer Motor	1	1	3	4	2	5.57	41.29
BYM-1D	1D Pulverizer Motor	1	1	3	4	2	5.57	41.29



Apply Preventative Maintenance (PM) only to "critical" equipment. Use Corrective (a.k.a., Reactive) Maintenance for everything else.

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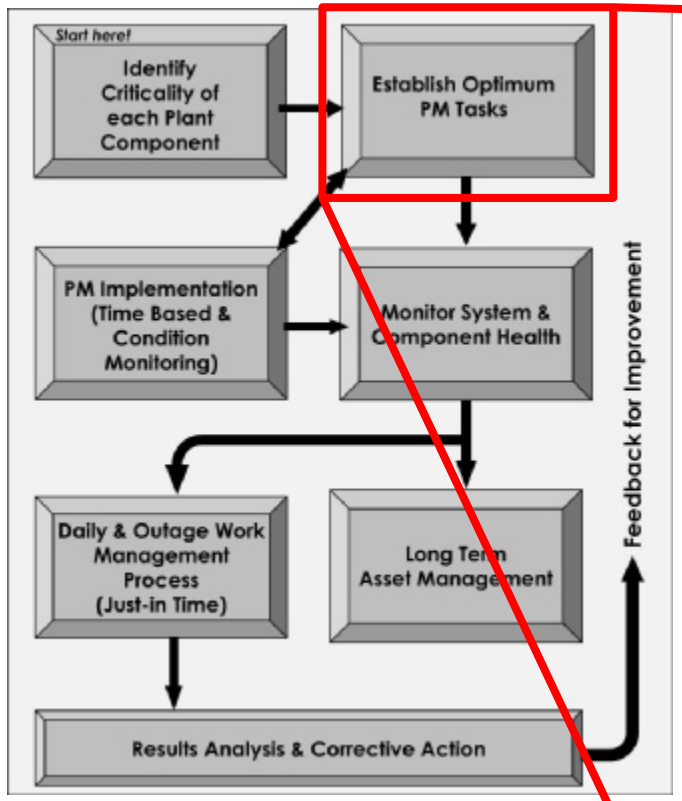
Equipment Reliability: Preventative Maintenance Basis



Developing PMBD template for inverters.

Predict impact to uptime if PM tasks and frequency are changed

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Preventive Maintenance Basis Database (PMBD)

Home | Component Templates | Saved Calcs | Groups | Reports | Help | About

You Are Here: Home > Component Templates > Tasks

Search

Tasks

DRAFT

Selected Component Template: Ready for Edits

Component Template Name:	Photovoltaic Central Inverter
Component Type:	I&C
Revision Number:	0
Revision Notes:	New Template
Equipment Type:	General

Tasks | Vulnerability | Definitions | Failure Modes | Reports

Task Name	CHS	CLS	CHM	CLM	NHS	NLS	NHM	NLM
Data Acquisition System (DAS) Monitoring	2D	NA	10D	NA	NA	NA	NA	NA
Data Analysis - Performance	1M	NA	3M	NA	NA	NA	NA	NA
DC Feeder Insulation Resistance Testing (IRT) - Inverter DOWN	2Y	NA	4Y	NA	NA	NA	NA	NA
Fan & Air Intake Filter Maintenance	3M	NA	6M	NA	NA	NA	NA	NA
Full Load Thermography	6M	NA	2Y	NA	NA	NA	NA	NA
Input & Output Conductor Terminal Torque Checks - Inverter DOWN	1Y	NA	2Y	NA	NA	NA	NA	NA
Inspect/Replace DC Surge Suppression	1M	NA	1Y	NA	NA	NA	NA	NA
Internal Component Inspection - Inverter DOWN	1Y	NA	2Y	NA	NA	NA	NA	NA
Visual Inspection - Inverter UP	1M	NA	6M	NA	NA	NA	NA	NA

Task Ranking | PM Basis

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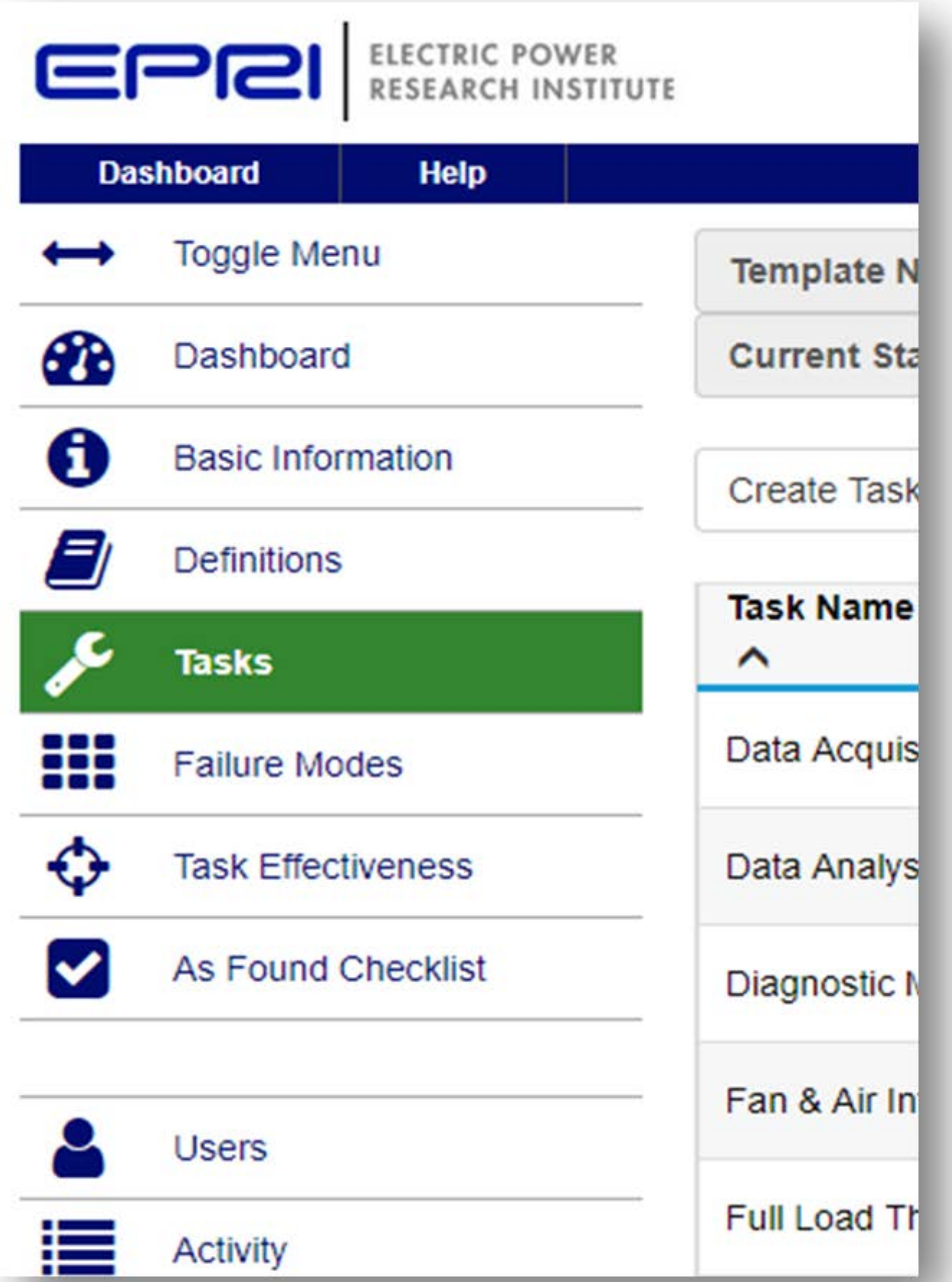
Many steps required to develop a component PM template

- Elicit experts' knowledge to built and populate component template

- Contact Sean Hackett to participate in expert elicitation
  - Email: shackett@epri.com



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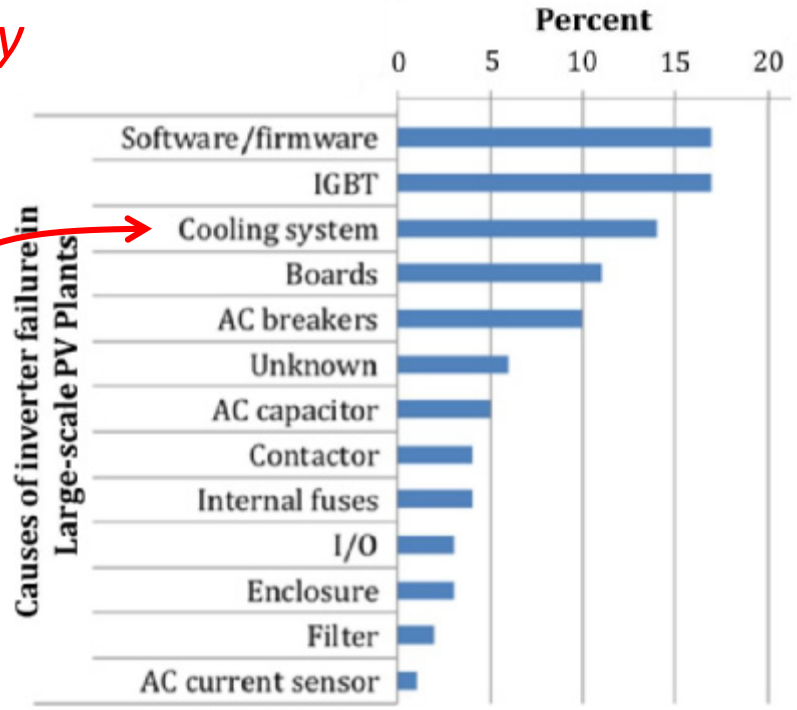
Are current inverter preventative maintenance tasks effective?

Draft list of generic PMs

	Critical			
	HI	LO	HI	LO
	Severe		Mild	
	CHS	CLS	CHM	CLM
Data Acquisition System (DAS) Monitoring	2D	NA	10D	NA
Data Analysis - Performance	1M	NA	3M	NA
DC Feeder Insulation Resistance Testing (IRT) - Inverter DOWN	2Y	NA	4Y	NA
Fan & Air Intake Filter Maintenance	3M	NA	6M	NA
Full Load Thermography	6M	NA	2Y	NA
Input & Output Conductor Terminal Torque Checks - Inverter DOWN	1Y	NA	2Y	NA
Inspect/Replace DC Surge Suppression	1M	NA	1Y	NA
Internal Component Inspection - Inverter DOWN	1Y	NA	2Y	NA
Visual Inspection - Inverter UP	1M	NA	6M	NA

Seemingly different efficacy… why?



P. Hacke, S. Lokanath, P. Williams (et al.) Renewable and Sustainable Energy Reviews, 2018

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Are current inverter preventative maintenance tasks effective?

Draft list of generic PMs

	Critical			
	HI	LO	HI	LO
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	CHS	CLS	CHM	CLM
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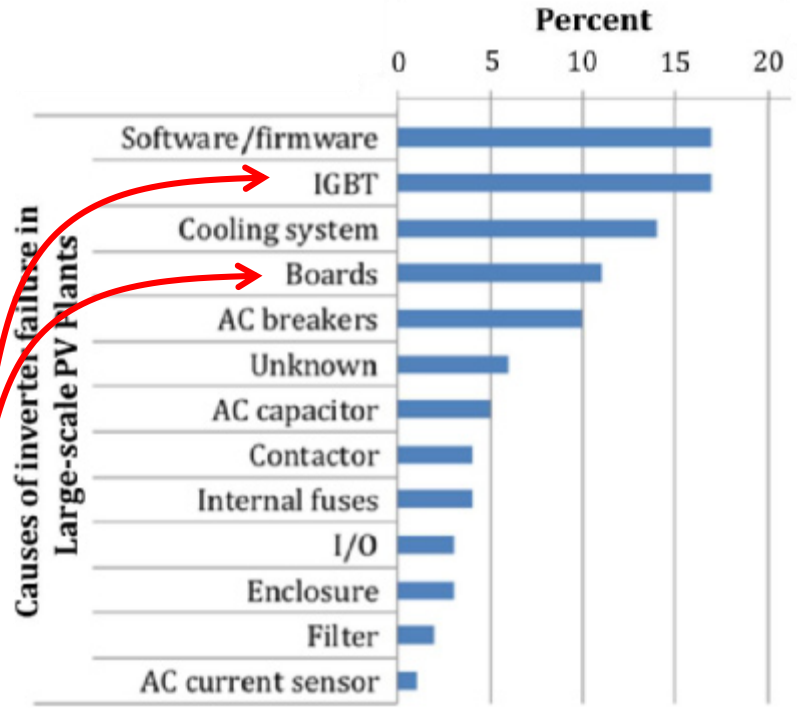
Data Analysis - Performance	1M	NA	3M	NA
DC Feeder Insulation Resistance Testing (IRT) - Inverter DOWN	2Y	NA	4Y	NA
Fan & Air Intake Filter Maintenance	3M	NA	6M	NA
Full Load Thermography	6M	NA	2Y	NA
Input & Output Conductor Terminal Torque Checks - Inverter DOWN	1Y	NA	2Y	NA
Inspect/Replace DC Surge Suppression	1M	NA	1Y	NA
Internal Component Inspection - Inverter DOWN	1Y	NA	2Y	NA
Visual Inspection - Inverter UP	1M	NA	6M	NA



P. Hacke, S. Lokanath, P. Williams (et al.) Renewable and Sustainable Energy Reviews, 2018

More PMs or sensors needed?

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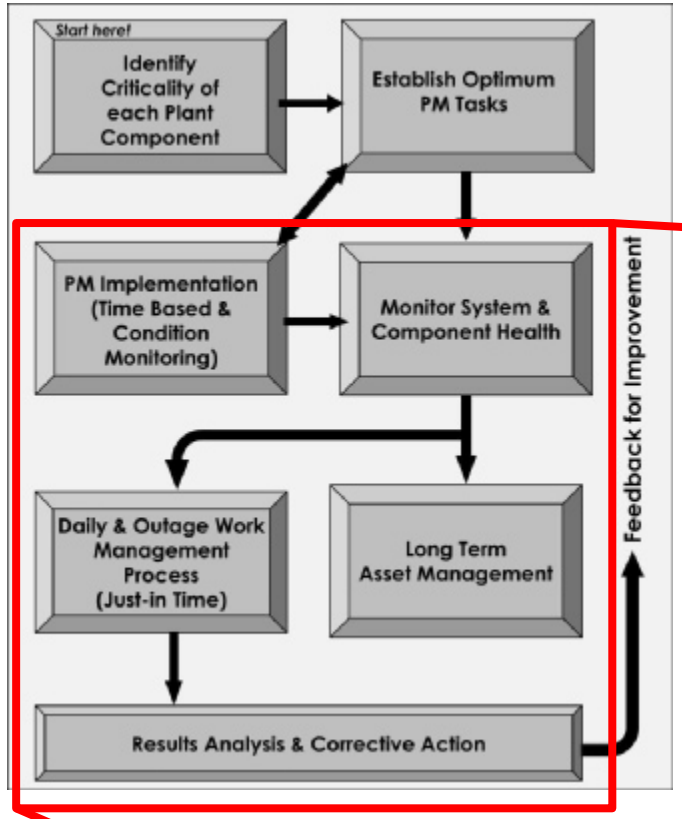
Equipment Reliability: Implement, Assess efficacy



Tracking the implementation and results of PM revisions are important to continuous improvement

Image Source: *Data Collection Practices to Facilitate Analytics of PV Plant Maintenance Logs.* EPRI. 3002009937. Palo Alto, CA: 2018.

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Multiple methods emerging to improve PV plant preventative maintenance

- Equipment Reliability
  - + Tried-and-True: Determine what equipment is critical and focus on it, Good for soliciting industry feedback
  - – Qualitative: Gives directional guidance for maintenance optimization, Generalizing results can be difficult

- Data-driven Analytics
  - + Quantitative: Results are highly quantitative, easily integrate into models and simulations
  - – Emerging: Standard failure categories needed analysis and benchmarking, Statistically significant amount of sites needed to make broad conclusions

- Next steps
  - Anyone want to contribute maintenance logs for analysis?
  - Volunteers to participate in PMBD expert elicitation meeting?
  - Anyone else seeing discrete spikes in failures over time?

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The Effect of Inverter Failures on the Return on Investment of Solar Photovoltaic Systems

Tyler Formica

Johns Hopkins University Applied Physics Laboratory

Prof. Michael Pecht

Center for Advanced Life Cycle Engineering (CALCE)
University of Maryland

NREL PV Reliability Workshop 2019

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Introduction

- This presentation is based on my M.S. research funded by the Center for Advanced Life Cycle Engineering (CALCE) at University of Maryland. These 2 publications provide a more in-depth look at the topics presented in this presentation:
  - "Return on Investment Analysis and Simulator of a 9.12 Kilowatt (kW) Solar Photovoltaic System," Tyler Formica and Michael Pecht, *Solar Energy, Vol. 144, pp. 629-634, 1 March 2017.*
  - "The Effect of Inverter Failures on the Return on Investment of Solar Photovoltaic Systems," Tyler Formica, Hassan Abbas Khan, and Michael Pecht, *IEEE Access, Vol. 5, pp. 21336 - 21343, 18 Sept 2017.*

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Contents

1. Introduction and overview of power electronics in Solar PV systems
2. Return on investment analysis of solar PV systems
3. Failure studies of solar PV systems
4. Root causes of failure of solar PV inverters
5. Case study: Return on Investment simulation of a solar PV system in College Park, MD
6. Future work and conclusions

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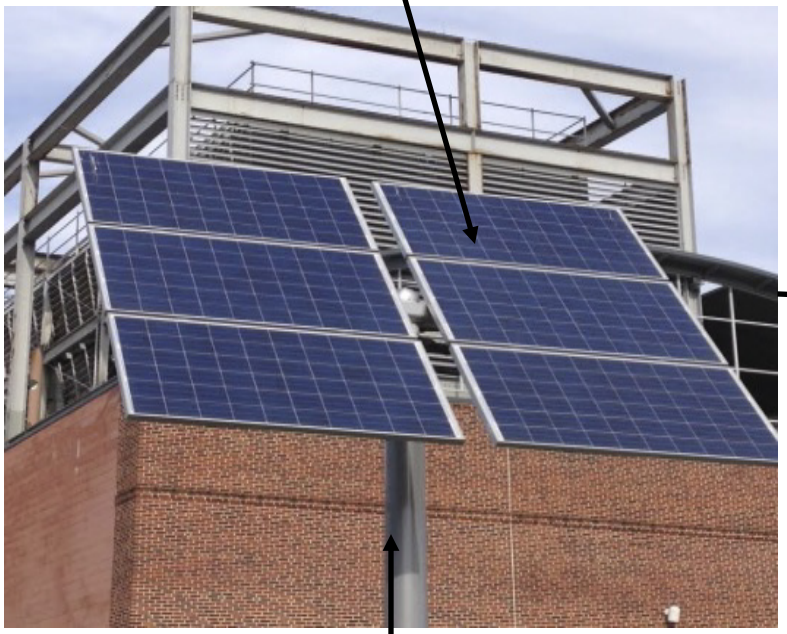
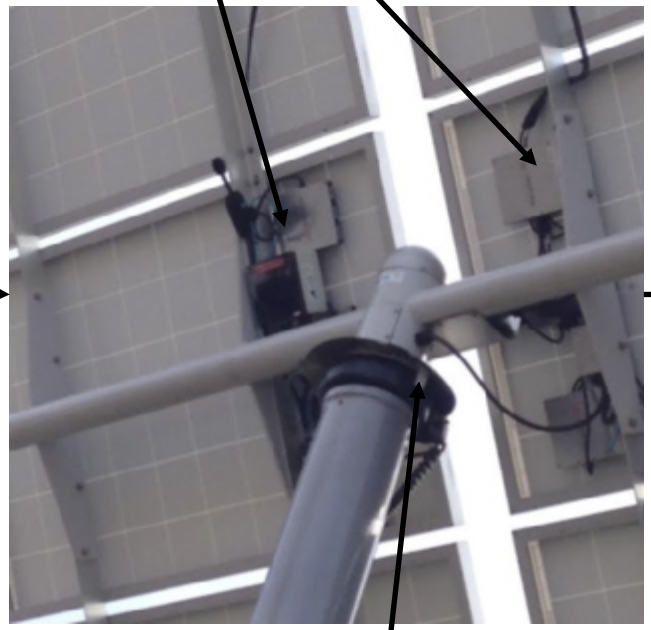
Solar PV System Key Components

PV Panel Array

Micro-Inverters





Electric Grid

Mounting Equipment

PV System Wiring

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Solar PV Industry Trends (1 of 2)

- In 2016, 14.8 gigawatts (GW) of new solar PV energy was installed in the US, a 97% growth from 2015 [1]
  - 39% of all new electricity added to the US grid was from solar electricity; more than any other source (Natural Gas: 29%, Wind: 26%)
- In the US, the total price of solar installation (modules, electronics, labor, etc.) was down 29% from 4th quarter of 2015 to 4th quarter of 2016 [1]
- According to the International Renewable Energy Agency, there is an estimated 290,761 megawatts (MWs) of solar photovoltaic energy capacity worldwide as of the end of 2016 [2]

[1] Solar Energy Industries Association, "Solar Industry Data," Solar Energy Industries Association, Date Accessed: April 05, 2017. Available Online: http://www.seia.org/research-resources/solar-industry-data
[2] Adrian Whiteman, Tobias Rinke, Javier Esparrago, Iana Arkhipova and Samah Elsaye, "Renewable Energy Statistics 2017," International Renewable Energy Agency, Date Accessed: April 05, 2017.

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Solar PV Industry Trends (2 of 2)

- GTM Research [3] estimated that the US Department of Energy Sunshot program would reach their goal of decreasing solar PV electricity in large utility-scale solar plants to below $1.00 per watt by 2020.
- In August of 2016 the price for PV modules was at an all-time low of $0.45 per watt and it will most likely continue to decrease [4]
- According to Bloomberg [5], the average cost of solar PV electricity is projected to decrease by 59% from 2016 to 2025

[3] Munsell, M., "Solar PV Prices Will Fall Below $1.00 per Watt by 2020," Greentech Media, June 1, 2016. Available online: https://www.greentechmedia.com/articles/read/solar-pv-prices-to-fall-below-1.00-per-watt-by-2020
[4] Ryan, J., "Solar Industry Braces with Looming Glut Eroding Panel Prices," Bloomberg, August 23, 2016. Available online: http://www.bloomberg.com/news/articles/2016-08-23/solar-industry-braces-as-looming-glut-threatens-to-erode-prices
[5] Habboush, M. and Carpenter, C., "Solar Power to Grow Sixfold as Sun Becoming Cheapest Resource," Bloomberg Technology, June 22, 2016. Available online: https://www.bloomberg.com/news/articles/2016-06-22/solar-power-to-grow-sixfold-as-sun-becoming-cheapest-resource

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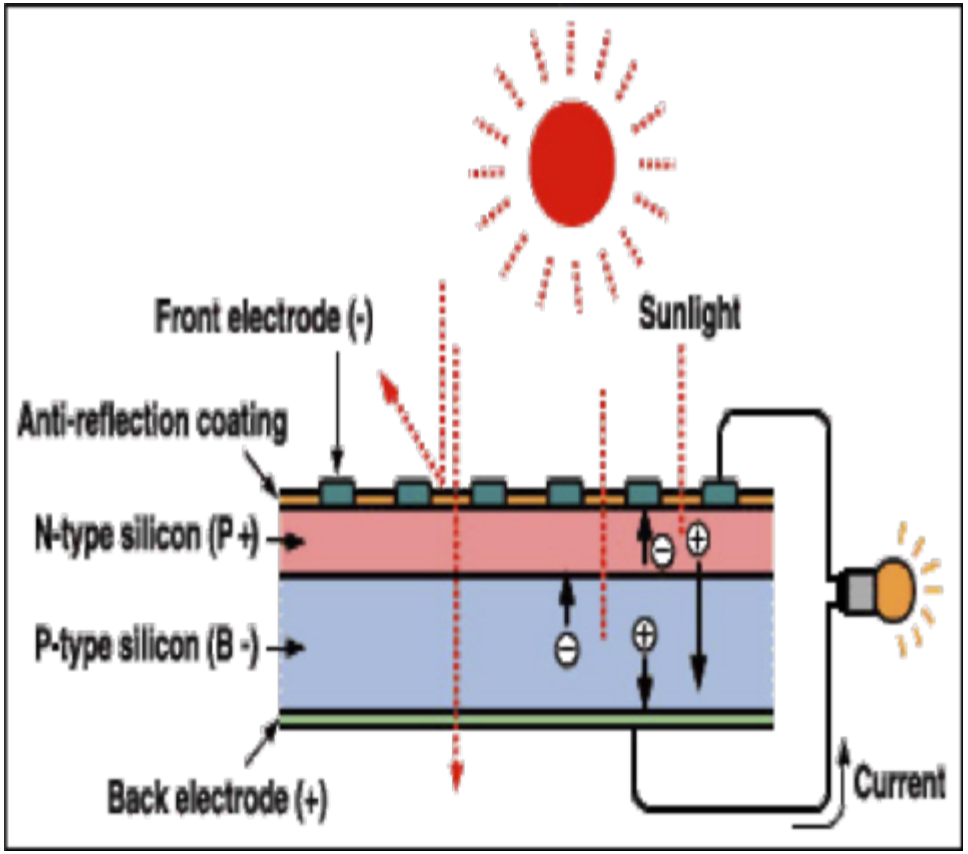
The Solar PV Energy Conversion Process: The Role of Solar Cells

- Solar cells are installed in solar modules
- Solar cells consist of semiconductor materials, most often silicon doped with impurities such as phosphorous and boron to create a P-N junction (doping with phosphorous creates N-type silicon and doping with boron creates P-type silicon)
- Photons eject electrons in the atomic bonds of these cells, thus creating a direct current



P-N Junction in a Solar Cell
http://thesolarcell.blogspot.com/2008/06/most-commonly-known-solar-cell-is.html

[6] Knier, G., "How do Photovoltaics Work?" National Aeronautics and Space Administration, 2002.
[7] Florida Solar Energy Center, "How PV Cells Work," University of Central Florida, Florida Solar Energy Center (FSEC), 2014.

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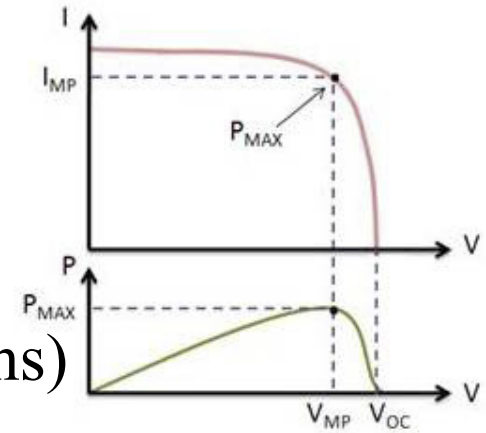
DC-DC Converter Stage: MPPT

- An inverter uses software to employ maximum power point tracking (MPPT); a process which finds the optimal input impedance of an inverter to match the power load-line of the PV modules [8]
- Since irradiation and temperature change the power load-line, algorithms (mostly hill climbing algorithms) are used to find optimal input impedance:
  - Perturb & Observe Method: Changes voltage to find the optimal voltage that maximizes the power
  - Incremental Conductance: Measures incremental changes in current and voltage [9]
- Capacitance/Inductance is used to reduce ripple voltage thus reducing oscillation of voltage around MPP [10]



MPPT Power Tracking [8]
V=Voltage
P=Power
I_{MP}=Maximum Current Point
P_{MAX}=Maximum Power Point
V_{MP}=Maximum Voltage Point
V_{OC}=Open-Circuit Voltage

[8] Flicker, J. and Kaplar, R., "Reliability of Power Conversion Systems in Photovoltaic Applications," Reliability of Power Electronic Converter Systems, IET Power and Energy Series, Shuhung Chung, H., Wang, H., Blaabjerg, F. and Pecht, M. G., Stevenage Herts, United Kingdom, The Institution of Engineering and Technology, 2016, pp. 391-414.
[9] Xiao, W., Elnosh, A., Khadkiker, V., and Zeineldin, H., "Overview of Maximum Power Point Tracking Technologies for Photovoltaic Power Systems," IECON 2011 - 37th Annual Conference on IEEE Industrial Electronics Society, IEEE. Nov. 7-10, 2011.
[10] Mandal, A., "Commonly Used Algorithms for MPPT," Test Blog 2, Technical Discussions, Date Accessed: June 27, 2016.

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Grid-Tied and Off-Grid Solar PV Systems

- Grid-Tied solar PV systems are PV systems that are connected to an electric grid and therefore must convert direct current (DC) to alternating current (AC)
  - Can access electricity from the grid when PV panels are not producing. Users can receive credits by feeding more electricity to the grid than electricity received, known as net metering
- Off-Grid solar PV systems operate without being tied to the utility grid
  - If your system is over 100 yards from the utility grid an off-grid system may be more cost-effective due to transmission line costs which are at least $174,000 per mile [11]. Off-grid systems must have a battery and battery bank, which adds to the start-up costs and increases energy loss.

[11] Maehlum, M., "Grid-Tied, Off-Grid and Hybrid Solar Systems," Energy Informative, Aug. 13, 2013.

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Converting DC Current to AC Current for Use in the Electrical Grid

- Inverters must abide by power, voltage, and frequency standards specific to regions (such as the IEEE 1547 in North America) [8]
- IEEE 1547 states that inverters must contain anti-islanding software to disconnect from the grid in the event of a grid outage in less than 2 seconds [12]
  - Algorithms are used to track grid measurements. P&O is also used for monitoring islanding by sending signals to the grid and tracking voltage and current
- Advanced inverters called "smart inverters" can also monitor the efficiency of the PV system and report underperforming modules or underperforming inverters
- The AC current is then sent to the electrical grid

[8] Flicker, J. and Kaplar, R., "Reliability of Power Conversion Systems in Photovoltaic Applications," Reliability of Power Electronic Converter Systems, IET Power and Energy Series, Shuhung Chung, H., Wang, H., Blaabjerg, F. and Pecht, M. G., Stevenage Herts, United Kingdom, The Institution of Engineering and Technology, 2016, pp. 391-414.
[12] Xue, Y., Divya, K., Griepentrog, G., Liviu, M., Suresh, S., and Manjrekar, M., "Toward Next Generation Photovoltaic Inverters," 2011 IEEE Energy Conversion Congress and Exposition, Sept. 2011.

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Cost-Analysis of Solar PV Systems

- Before paying the start-up costs of investing in a solar PV system, commercial and residential users should have an understanding of whether they can expect to profit and when they can expect their investment to break-even
  - **Return on investment (ROI)**: A financial measurement calculated by adding the total earnings from an investment and dividing by the costs
  - **Payback Period**: The amount of time it takes for an investor to recoup all start-up costs in the investment and break-even. Once the investment hits the payback period, an investor will start to profit

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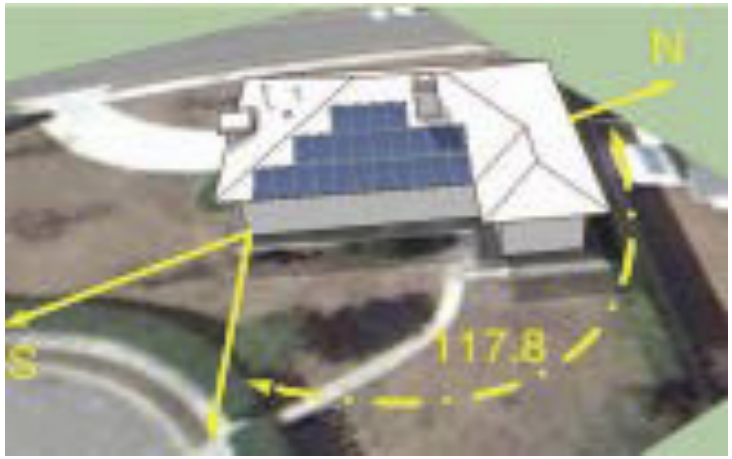
Solar PV System Return on Investment Literature

- Yang D. et al. compared the return on investment of a residential solar PV system in Gainesville, Florida installed by a contractor to a self-installed systen
- Yang, D. et al. used Suntech STP280-24Vd panels: 14.4% efficiency
- Assumed a 95.5% efficiency for the PV inverters
- Assumed monthly energy usage in household is 900kWh
- Retail electricity price in Gainesville: $0.115 per kWh

Picture: http://www.ecodirect.com/Suntech-STP280-24-VD-280W-35V-PV-Panel-p/suntech-stp280-24vd.htm



[13] Yang, D., Latchman, H. A., Tingling, D., and Amarsingh, A. A., "Design and Return on Investment Analysis of Residential Solar PV Systems," IEEE Potentials, Vol. 34, Issue. 4, July, 2015.

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Solar PV System Return on Investment Literature

Quantity	Components	Price per Component	Total Price
24	Suntech 280 Watt Panels	$ 308.00	$ 7,392.00
2	Solar Panel Cable	$ 43.46	$ 86.92
2	Fuse Holder	$ 5.40	$ 10.80
1	Grid-Tied Inverter SMA	$ 2,647.00	$ 2,647.00
2	Lightning Arrestor	$ 40.00	$ 80.00
1	Combinor Box	$ 330.00	$ 330.00
1	DC Disconnect	$ 170.00	$ 170.00
1	Mounting System	$ 2,000.00	$ 2,000.00

[13] Yang, D., Latchman, H. A., Tingling, D., and Amarsingh, A. A., "Design and Return on Investment Analysis of Residential Solar PV Systems," IEEE Potentials, Vol. 34, Issue. 4, July, 2015.

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Solar PV System Warranties

Solar PV Module Performance Warranties (25-30 years) → Covers degradation in solar PV module efficiency. Does not cover solar PV module cracks, decreased performance due to inverter failures or subsystem failures, etc.

Solar PV Module Product Warranties (10-25 years) → Covers manufacturing defects, premature wear & tear within solar PV modules

Solar PV Inverter Warranties (1-25 years) → Covers inverter failures

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Solar PV Inverter Warranties

- Warranty for central inverters typically range from 5-15 years
- For Example, SolarEdge: 12 year warranty for central inverters
- Micro-inverters generally have longer warranties: 15-25 years
- This is due to higher reliability associated with micro-inverters as they generally have lower power processing requirements for their switches and energy storage parts (e.g. central inverters are typically rated to handle 5kW or higher, each micro-inverter is generally rated to handle 200-250W [14])
- ABB Group:10-year product warranty for their micro-inverters and a 2-year product warranty for their PVS800 central inverters [15, 16]
- Enphase Energy: 25-year warranty with their micro-inverters [17]

[14] Microchip, "Grid-Connected Solar Micro-inverter Reference Design Using a dsPIC ® Digital Signal Controller" 2010-2011 Microchip Technology Inc, Aug., 2011.
[15] ABB Group, "Central Inverters PVS800 Warranty and Service Offering," ABB Group, Date Accessed: Apr. 10, 2016. Available Online: https://library.e.abb.com/public/7488c31491241476c1257d89002aca52/17267_Warranty_and_service_offering_3AUA0000133536_RevC_lowres.pdf
[16] ABB Group, "ABB Micro Inverter System MICRO-0.25/0.3/0.3HV-I-OUTD 0.25kW to 0.3kW," ABB Group, Date Accessed: Apr. 10, 2016. Available Online: https://library.e.abb.com/public/3b4b2359a4986e2685257dff005e1834/MICRO-0.25-0.3-0.3HV-Rev0.1.pdf
[17] Enphase Energy, "Enphase Energy M215 Micro-inverter 25-Year Limited Warranty – North America," Enphase Energy, Jan., 2014, Accessed Nov. 3, 2015.

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Frequency of Tickets and Associated Energy Loss for Each General Failure Area in SunEdison Solar Panel Systems

Failure Area	% of Tickets	% of kWh lost
Inverter	43%	36%
AC Subsystem	14%	20%
External	12%	20%
Other	9%	7%
Support Structure	6%	3%
DC Subsystem	6%	4%
Planned Outage	5%	8%
Module	2%	1%
Weather Station	2%	0%
Meter	1%	0%

[18] Golnas, A., "PV System Reliability: An Operator's Perspective," IEEE Journal of Photovoltaics, Vol. 3, pp. 417-418, Jan., 2013

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SunEdison Distribution of Inverter Tickets

Failure Area	% of Tickets	% of kWh lost
No-Fault Found Failures	28%	15%
Card/Board	13%	22%
AC Contactor	12%	13%
Fan(s)	6%	5%
Matrix/IGBT	6%	6%
Power Supply	5%	5%
AC Fuses	4%	12%
DC Contactor	4%	1%
Surge Protection	3%	1%
GFI Components	3%	2%
Capacitors	3%	7%
Internal Fuses	3%	4%
Internal Relay/Switch	3%	2%
DC Input Fuses	2%	1%
Other	5%	2%

[18] Golnas, A., "PV System Reliability: An Operator's Perspective," IEEE Journal of Photovoltaics, Vol. 3, pp. 417-418, Jan., 2013

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Failure Data from a 4.6 MW Solar PV Plant

- Sandia National Laboratories conducted a 5-year study of failures associated with a 4.6 megawatt solar PV plant
  - 26 arrays; each with 450 PV panels and 1 inverter

Failure Area	% of Tickets
Inverter	53%
AC Subsystem	14%
DC Subsystem	14%
Module	12%
Other (Lightning)	7%

[19] Collins, E., Dvorack, M., Mahn, J., Mundt, M. and Quintana, M., "Reliability and Availability Analysis of a Fielded Photovoltaic System," Sandia National Laboratories, May 2009.

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Failure Data from 202 PV Systems in Taiwan in a 3-Year Span

- Analyzed failure data gathered by the Industrial Technology Research Institute [20]
- Among the 202 PV systems, 62 experienced failures within the 3 years span
  - 60% inverter
  - 28% racking/mounting equipment
  - 12% panel modules
- Average MTTF (mean time to failure): 3.96 years
- Average MTTR (mean time to repair): 65 days
- Average Availability: 95.7%

[20] Huang, H.S., Jao, J.S., Yen, K.L. and Tsai, C.T., "Performance and Availability Analyses of PV Generation Systems in Taiwan," International Scholarly and Scientific Research & Innovation 5(6) 2011

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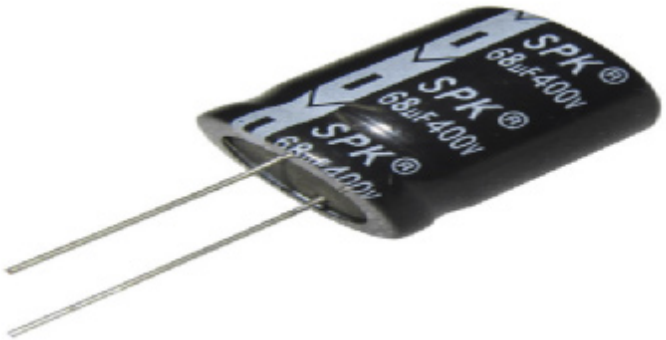
4 Components of Interest

Capacitors



Picture: http://www.nanotechetc.com/2014/02/shrinking-capacitors/101403.html

Metal-oxide-semiconductor-field-effect transistors (MOSFETs) and insulated-gate bipolar transistors (IGBTs)

Picture: http://www.calce.umd.edu/calce-enews/2012/calce-enews_june2012.html

Mounting/Racking Equipment

Picture: http://www.homepower.com/articles/solar-electricity/equipment-products/rack-stack-pv-array-mounting-options

AC Fuses

Picture: http://www.retrotechnology.com/restore/z_repair.html

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Capacitors Failures

- PV inverters use electrolytic and film capacitors
- Aluminum electrolytic capacitors have been estimated to be approximately one-third the price of film capacitors per amount of energy storage needed [21].
- Schimpf and Norum estimate the capacitance per volume ratio of electrolytic capacitors to be 20 times greater than film capacitors [22]
- Solar PV inverters with a single standard electrolytic capacitor (DC-link) are estimated to have a lifetime of about 5 years before a failure [23]. Electrolytic capacitors in solar PV inverters fail due to temperature cycling, power cycling, and high internal capacitor temperature [8, 24]

[21] Heynen, "Aluminum Electrolytic Capacitors vs Film Capacitors," Electronic Component Solutions, Date Accessed: June 02, 2016. Available Online: http://www.heynen.com/aluminum-electrolytic-capacitors-vs-film-capacitors
[22] Schimpf, F. and Norum, L., "Effective Use of Film Capacitors in Single-Phase PV-Inverter by Active Decoupling," IECON 2010- 36th Annual Conference on IEEE Industrial Electronics, IEEE, Nov., 2010.
[23] Rodriguez, C. and Amaratunga, G. A. J., "Long-Lifetime Power Inverter for Photovoltaic AC Modules," IEEE Transactions on Industrial Electronics, Vol. 55, No. 7, pp. 2594, July, 2008.
[24] Russell, M. C. and Green RaySolar, "The Promise of Reliable Inverters for PV Systems: The Micro-inverter Solution," GTM Research, June, 2010.
[8] Flicker, J. and Kaplar, R., "Reliability of Power Conversion Systems in Photovoltaic Applications," Reliability of Power Electronic Converter Systems, IET Power and Energy Series, Shuhung Chung, H., Wang, H., Blaabjerg, F. and Pecht M. G., Stevenage Herts, United Kingdom, The Institution of Engineering and Technology, 2016, pp. 398-403.

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IGBT Failures

- Fail most often due to electrical degradation in the components or mechanical degradation associated with the electronic packaging
- Short-term power cycling and temperature cycling leads to Bond wire lift-off and deterioration of the die attach [8]
- Kaplar et al. [25] stressed silicon IGBTs found in PV inverters rated for 600V and 60 amperes (A) at 25°C and 30A at 90°C
  - When IGBTs were stressed gate emitter voltage of 20V and collector emitter voltage of 2V leakage current increased
  - After 45 minute stress intervals at collector current of 61A at 100°C the gate oxide leakage current increased indicating an oxide defect which would cause an IGBT failure

[8] Flicker, J. and Kaplar, R., Reliability of Power Conversion Systems in Photovoltaic Applications, Reliability of Power Electronic Converter Systems, IET Power and Energy Series, Shuhung Chung, H., Wang, H., Blaabjerg, F. and Pecht M. G., Stevenage Herts, United Kingdom, The Institution of Engineering and Technology, 2016, pp. 398-403.
[25] Kaplar, R., Brock, R., DasGupta, S., Marinella, M., Starbuck, A., Fresquez, A., Gonzalez, S., Granata, J., Quintana, M., Smith, M. and Atcitty, S., "PV inverter performance and reliability: What is the role of the IGBT?" 2011 37th IEEE Photovoltaic Specialists Conference (PVSC), IEEE,, June 2011.

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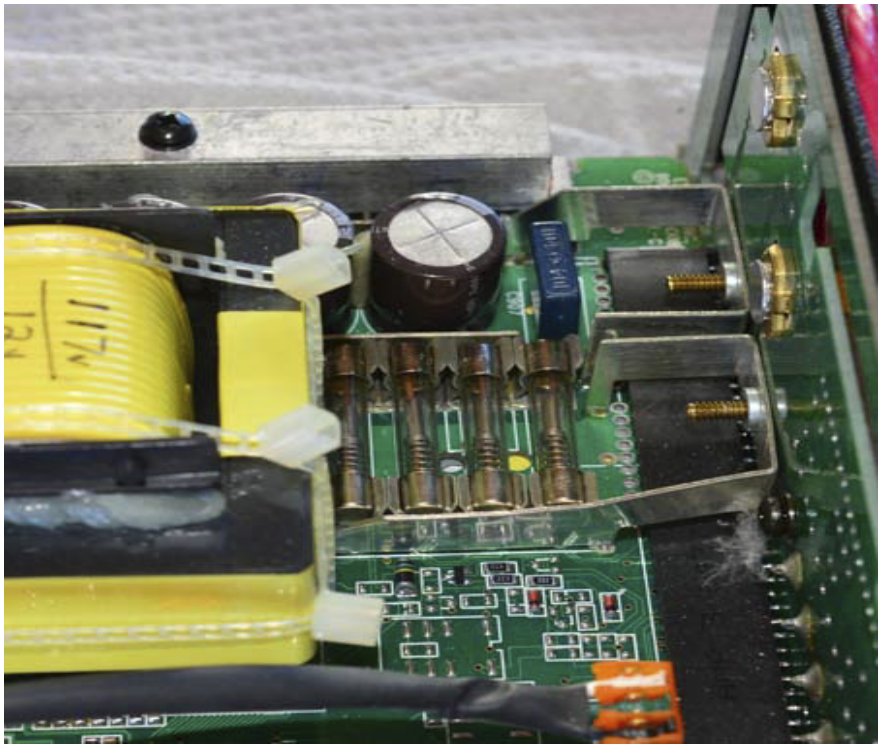
Blown AC Fuses

- An AC circuit fuse is usually located between the inverter and electric service [26]
- A blown AC fuse leads to an immediate malfunction of the solar PV system
- Blown fuses are typically caused by short circuit and inverter faults.
- Pecan Street: Studied 255 PV systems over 4 years [27]
  - 54 reported failures
  - 13 reported blown AC fuses



[26] Electrical Technology, "Fuse and Types of Fuses," Electrical Technology, Nov. 7, 2014. Available Online: http://www.electricaltechnology.org/2014/11/fuse types-of-fuses.html
[27] Pecan Street, "Minor Maintenance Issues Proving Difficult to Detect for Many Solar PV System Owners," GTM Research, Pecan Street GTM PV Maintenance Report, Vol. 2 No. 5, Feb., 2015.

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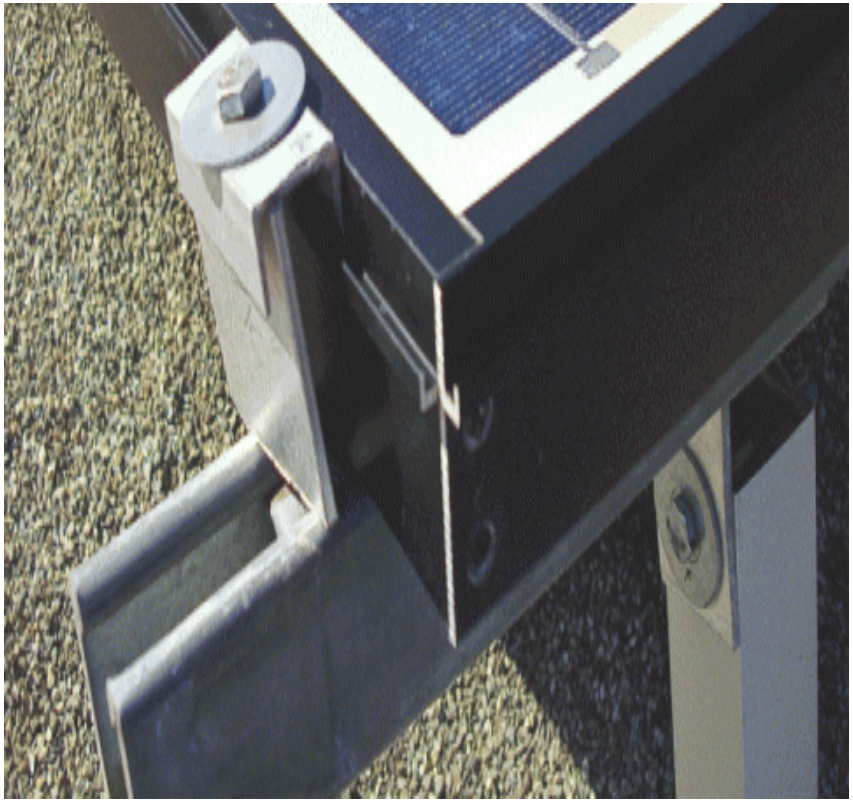
Mounting Equipment

- Poorly installed mounting systems, racking equipment used to support solar PV systems leads to failures
- The cells of the PV system can become damaged due to inexperienced installers using poor installation practices such as installing the mechanical fasteners improperly [28, 29]



Picture: http://www.homepower.com/articles/solar-electricity/design-installation/residential-pv-systems-common-code-violations

[28] Köntges, M., Kurtz, S., Packard, C., Berger, U. J. K. A., Kato, K., Friesen, T., Liu, H., and Van Iseghem, M., "Review of Failures of Photovoltaic Modules," International Energy Agency, pp. 55-63, March, 2014.
[29] O'Brien, C., "Roof-Mounted Solar Photovoltaic Arrays," RCI Incorporated, Date Accessed: February 6, 2016.

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Solar PV ROI Case Study in Maryland (1/6)

- Average electrical consumption per month in College Park:1,005 kWh
- Average electricity rate in College Park: $0.1128 per month

Quantity	Component
32	Suniva OPT285-60-4 100 Silver Mono Solar Panel
1	SolarEdge SE10000A-US-U Inverter
32	IronRidge XR100 Option D Racks per 65" X 39" Module Inc. Grounding
16	IronRidge Mounting Hardware Kit - T-Bolt 1/4" X 3/4"
1	Electrical Design Diagram
1	Square D DU222RB Safety Disconnect
1	Four Star Solar MC4 Unlocking Tool
2	Four Star Solar Dual MC4 10 AWG - 100' Cable Extension
32	SolarEdge P300 - 5NC4ARS Power Optimizer

[30] Electricity Local, "College Park, MD Electricity Statistics," Electricity Local, Date Accessed: April 8, 2016. Available Online: http://www.electricitylocal.com/states/maryland/college-park/
[31] Wholesale Solar, "8.96 kW Grid-Tied Solar PV System with SolarEdge and 32x Sunviva 280 Solar Panels," Wholesale Solar, Date Accessed: June 26, 2016. Available Online: http://www.wholesalesolar.com/1892432/wholesale-solar/complete-systems/9.12-kw-grid-tied-solar-system-with-solaredge-and-32x-suniva-285-panels

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Solar PV ROI Case Study in Maryland (2/6)

Price	Cost Calculations
$ 15,120	Price for the Components of the PV System
$12,500	Installation Cost for the PV System
$27,620	Total PV System Start-Up Before Application of State, Federal, and Local Credits
($1,000)	Maryland Residential Clean Energy Act
($5,000)	Prince George's County Solar Residential Property Tax Credit
$21,720	Total PV System Start-Up Costs After Application of State and Local Credits
($7,986)	Solar Investment Tax Credit Savings (30% of total start-up cost)
$13,634	Final Total PV System Start-Up Costs Assuming the System Qualifies for Tax Credits

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Solar PV ROI Case Study in Maryland (3/6)

- The National Renewable Energy Laboratory (NREL) [35] tracks the average solar radiation to allow PV systems' total energy output to be calculated based on conditions (size of system, efficiency of panels, etc.)
- Our inputs:
  - Total system losses (wiring, shading, degradation of cells): 14%
  - Angular tilt of 20º (degree that panels are tilted on the roof)
  - Irradiations conditions: Based on yearly data of weather conditions in Washington, D.C. from the NREL
  - Azimuth (vector from the panels to the sun projected perpendicularly on a plane) of 180º.
- These inputs projected **11,889 kWh** of electricity production per year from the PV system

[32] National Renewable Energy Laboratory, "PV Watts Calculator," National Renewable Energy Laboratory, Date Accessed: June 14, 2016. Available Online: http://pvwatts.nrel.gov/pvwatts.php

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Solar PV ROI Case Study in Maryland (4/6)

- Clean Energy Incentive Tax Credit [33]: $0.0085 per kWh for 5 years
- Utility companies pay about $160 ($0.16/kWh) for Solar Renewable Energy Certificates (SRECS) [34]
- Our system: Eligible for $1,900 SRECs per year
- Average cost of operation and maintenance [35] : $21 per kW per year

$$\text{Annual Savings} = ((E_{ut} + Cr_{pv}) * Pr_{pv}) - O\&M$$

where E_{ut} is the average price per kWh of the utility electricity ($0.1128), Cr_{pv} is the credits the PV system receives per year (Clean Energy Incentive Tax Credit and SRECs= $0.1685/kWh), Pr_{pv} is the annual production of the PV system (11,889 kWh/year), and $O\&M$ is the annual operation and maintenance costs ($190)

Total Annual Financial Gain of this System: $3,150 per year

[33] Comptroller of Maryland, "Clean Energy Incentive Tax Credit," Spotlight on Maryland Taxes, 2016. Available Online: http://taxes.marylandtaxes.com/Business_Taxes/General_Information/Business_Tax_Credits/Clean_Energy_Incentive_Tax_Credit.shtml
[34] Solar Power Rocks, "Maryland 2016 Solar Report Card," Maryland, Date Accessed: August 2, 2016. Available Online: https://solarpowerrocks.com/maryland/
[35] National Renewable Energy Laboratory, "Distributed Generated Renewable Energy Estimate of Costs," Energy Analysis, Date Updated: February 2016. Available Online: http://www.nrel.gov/analysis/tech_lcoe_re_cost_est.html

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Solar PV ROI Case Study in Maryland (5/6)

- With projected yearly savings of $3,150 and projected start-up costs of $13,364, the PV system would expect a first year return on investment of 0.2357
- With constant energy production and tax credits this system would yield a payback period of less than 5 years
- However, the reliability of solar PV systems and potential reduction of tax credits will reduce this return on investment

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Solar PV ROI Case Study in Maryland (6/6)

- Solar PV inverters are known to be the least reliable component in PV systems with a mean time to failure of 5 years [22]
  - Price of SolarEdge inverter [37] used in this case study: About $1,900. Warranty period: 12 years[38]
- Tax credits contribute significantly to the promising ROI, and the longevity of these credits is uncertain [39-41]
- The federal credit alone decreased start-up costs by $8,000
- Without state, local, and federal credits, the first year ROI in this study would be 0.114. This does not account for potential failures of components

[22] Schimpf, F. and Norum, L., "Effective Use of Film Capacitors in Single-Phase PV-Inverter by Active Decoupling," IECON 2010- 36th Annual Conference on IEEE Industrial Electronics, IEEE, Nov., 2010.
[37] Wholesale Solar, "SolarEdge SE10000A-US-U Inverter," Wholesale Solar, Date Accessed: August 5, 2016. Available Online: http://www.wholesalesolar.com/9900117/solaredge/inverters/solaredge-se10000a-us-u-inverter
[38] SolarEdge, "Single Phase Solar Inverters" SolarEdge, Date Accessed: August 5, 2016. Available Online: http://www.solaredge.com/us/products/pv-inverter/single-phase#/
[39] Hollingsworth, B., "Report: Danger of Government-Created Solar Bubble Bursting When Subsidies Expire in 2016," CNS News, Aug. 13, 2015. Available Online: http://www.cnsnews.com/news/article/barbara-hollingsworth/report-danger-government-created-solar-bubble-bursting-when
[40] Cardwell, D., "Worry for Solar Projects After End of Tax Credits," New York Times, Energy & Environment, Jan. 25, 2015. Available Online: http://www.nytimes.com/2015/01/26/business/worry-for-solar-projects-after-end-of-tax-credits.html?_r=0
[41] Kisker, S., "Now is the Wrong Time for States to Reduce Solar Incentives," Renewable Energy World, Feb. 19, 2016. Available Online: http://www.renewableenergyworld.com/articles/2016/02/now-is-the-wrong-time-for-states-to-reduce-solar-incentives.html

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Emerging Technologies to Improve Reliability of Solar PV Inverters

Micro-inverters (pictured above: Enphase M215-60-2LL-S22-IG Micro Inverter 215 Watt MC4 4MM ARRA)

Wide bandgap semiconductors (pictured above: Wolfspeed C2M™ 1200V Silicon Carbide Power MOSFETs)

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Replacing Si semiconductors with SiC and GaN semiconductors in Solar PV Inverters

- Hinata et al. [42] designed a solar PV inverter with all SiC semiconductors and achieved an efficiency of 99% (solar inverters are typically in the 93-97% range) and 50 times as many cycles to failure as an Si-based design.
  - 500 thermal cycles with parameters of -40ºC and 175ºC showed failures in the Si-based inverter and no noticeable degradation in the SiC-based inverter
  - Sintamarean et al. [51] achieved a switching frequency of 50 kHz with an SiC MOSFET based inverter compared to just 16 kHz for an Si-based MOSFET inverter

[42] Hinata, Y., Horio, M., Ikeda, Y., Yamada, R., Takahashi, Y., "Full SiC Power Module with Advanced Structure and its Solar Inverter Application," 2013 Twenty-Eighth Annual IEEE Applied Power Electronics Conference and Exposition (APEC), IEEE, Mar., 2013.
[43] Oneill, M., "Silicon Carbide Diodes Make Solar Power Systems More Efficient," EE Times, Oct., 2008, Date Accessed Oct. 30, 2015. Available Online: http://www.eetimes.com/document.asp?doc_id=1273188&
[44] Lux Research, "Reaching for the High Fruit: Finding Room for SiC and GaN in the Solar Inverter Market," Lux Research, Apr. 1, 2013. Available Online: https://portal.luxresearchinc.com/research/report_excerpt/13342
[45] Schwarzer, U., Buschhorn, S., and Vogel, K., "System Benefits for Solar Inverter using SiC Semiconductor Modules," PCIM Europe 2014; Proceedings of International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management, VDE, pp. 1-8, May, 2014.
[46] Sintamarean, N. C., Eni, E. P., Blaabjerg, B., Teodorescu, R., Wang, H., "Wide-Band Gap Devices in PV Systems- Opportunities and Challenges," Proc. International Power Electronics Conference, pp. 1912-1919, 2014.

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Micro-Inverters: Improved Reliability and Longer Warranties

- Micro-inverters promise improved reliability compared to central inverters due to lower power processing requirements for switches and energy storage elements
- Film capacitors, which are more reliable but have 1/20 the capacitance per volume ratio of aluminum electrolytic counterparts [22], can be utilized due to the lower power processing requirements [47]
- Unlike central inverters, if a single micro-inverter fails, only the module which the micro-inverter is monitoring will fail and the rest of the PV system will remain functional
- 25-year warranties associated with micro-inverters decreases replacement costs associated with central inverters that have short warranties

[22] Schimpf, F. and Norum, L., "Effective Use of Film Capacitors in Single-Phase PV-Inverter by Active Decoupling," IECON 2010- 36th Annual Conference on IEEE Industrial Electronics, IEEE, Nov., 2010.
[47] Haibing, H., Harb, S., Kutkut, N.H., Shen, Z.J. and Batarseh, I., "A Single-Stage Micro-inverter Without Using Electrolytic Capacitors," Power Electronics, IEEE Transactions on, Vol. 28, pp. 2677-2687, 2013.

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Future Research

- A study comparing the ROI of different solar PV module materials is needed. As manufacturers are racing to improve the efficiency of their modules, are these more expensive but more efficient modules more cost-effective in residential applications? Under what conditions and sizes of systems are the more efficient modules most cost-effective compared to cheaper modules with efficiencies in the 13-17% range?
- Cost-benefit analysis is needed to determine the financial benefits of wide bandgap semiconductors. As the costs of GaN and SiC semiconductors continues to decrease, research is needed to decide at what point are wide bandgap semiconductors more beneficial in solar PV inverters than Si semiconductors from a cost and reliability standpoint?

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Reliability of Electronics for Photovoltaics

Magnus Asbo

February 28,2019

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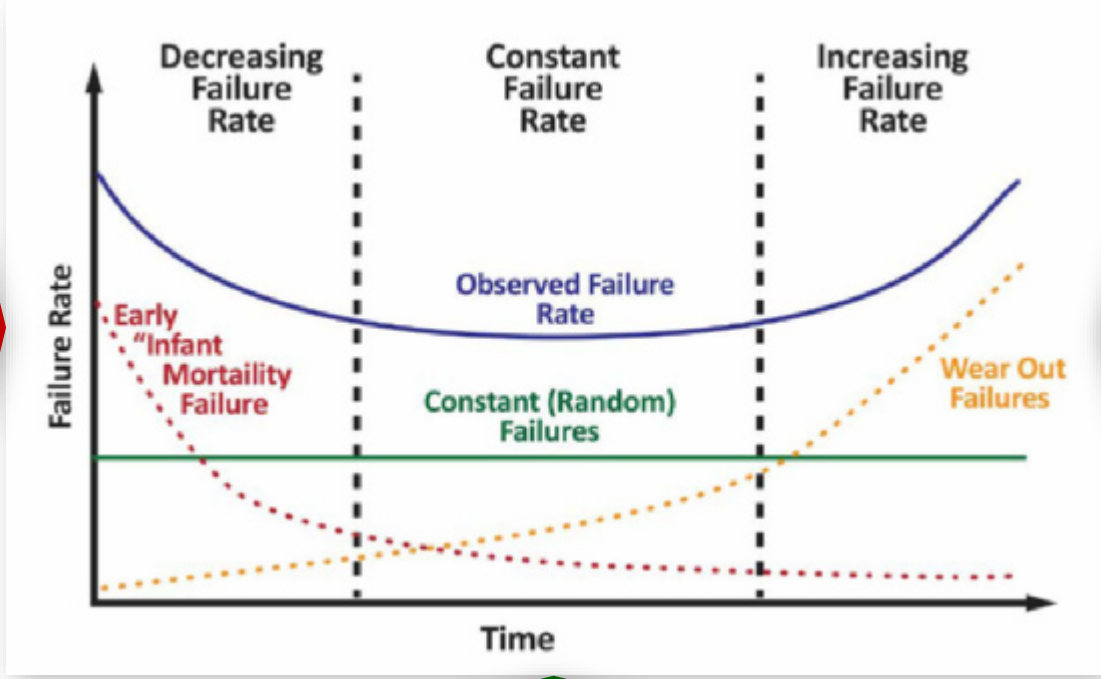
SolarEdge Reliability Approach

- The SolarEdge Reliability approach is based on the accepted bathtub reliability model

Early/Infant Failures:
- Failures that leave the factory undetected
- Production errors/mistakes

Methodology:
- Extensive testing during product manufacturing in order to eliminate early failures including burn-in test
- Extensive QC backed by a learning QA process



Wear-out failures:
- Fatigue of various components due to the impact of environmental conditions

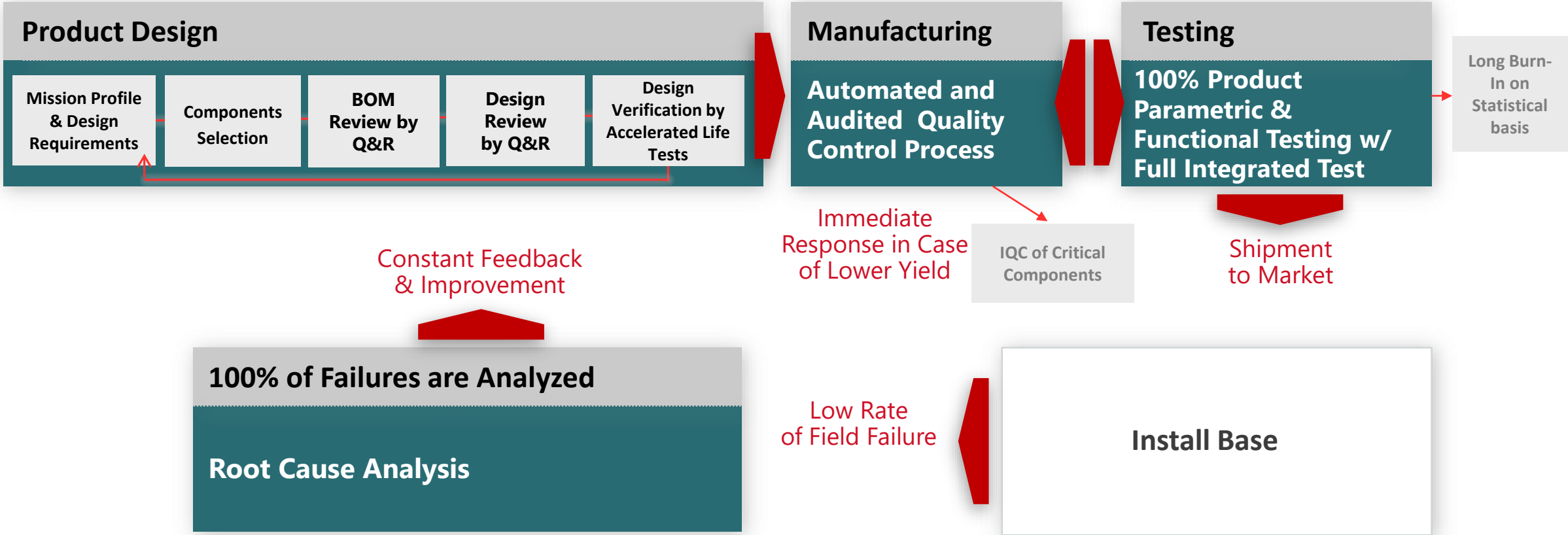
Methodology:
- Selection of components and technology according to the defined mission profile
- Comprehensive wear-out testing (functional 'envelope' testing, Burn-In, HASS) to verify wear-out period is beyond product lifetime

Constant/Random failures:
- Statistical failures of various components

Methodology:
- Design for low failure rates which is validated through component and product lifetime tests (HASS, HALT, EXTREME)

Products Reliability Life Cycle

- The reliability process is embedded into all stages of design & production



Reference Mission Profiles

- In order to design for high reliability we refer to environmental conditions in the following locations around the world as reference profiles:
  - Death Valley, CA
  - Berlin, Germany
  - Anchorage, Alaska
  - Miami, Florida
- These locations represents extreme conditions and for each location we created a reference mission profile, consisting of temperature range, irradiance levels and humidity levels. We then use these mission profiles for our accelerated life tests and to calculate the products theoretical failure rates
- For every mission profile we have derived peak, min and average annual temperature and peak, min and average power (as % of max power, based on irradiance levels)

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BOM & Design Review

- Component selection is verified by Q&R engineer to comply based on past experience & actual design parameters
- Proper de-rating in order to verify low stress on components
- Theoretical calculation
  - Finite-element thermal simulations
  - FIT calculations according to internal component lifetime tests and manufacturer data
- External reviews
  - Third-party MTBF calculation
  - Testability and Manufacturability Review

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Design Verification by Accelerated Life Tests (ALT)

- Dedicated long-term tests running until wear-out:
  - Burn-In (BI): 125°C
    - Wear out of electronic components
  - Thermal cycling (TC): -40°C/+125°C
    - To test interfaces between the electronics and the materials/mechanical parts (e.g. potting vs. coils)
    - Also tests other mechanical-electrical interfaces wear-out
  - Damp Heat (DH): 85% RH @ 85°C
    - Wear-out electronic components
    - Plastics, enclosures, potting, sealing, thermal interface materials, paints, corrosion, polymers, adhesion
  - All components are tested in accelerated life tests in order to assess their MTBF and ability to meet the mission profiles
  - Full assembled products also undergo ALT

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AFs and Qualification Tests

Test	What Mechanisms are Accelerated in the Test	Acceleration Factor Calculation (AF)	Acceleration Factor Values in SolarEdge Testing
Burn-In – Constant High Temperature (UUT at Full Power)	Aging of components, plastic materials, adhesives, coating and paint	Arrhenius equation. If activation energy is known from the manufacturer, it is used. Otherwise a rule of thumb is used: AF is doubled every 10˚C AF=Hours_Lab/Hours_field	For hot areas (Death Valley): 65 For cold areas (Berlin): 280
Thermal Cycling (UUT at Full Power)	Adhesion interfaces, solder joints, connectors	Coffin-Manson AF=Ncycles_Lab/Ncycles_field	~10
Damp Heat (Humidity/Temperature)	Plastic materials, adhesives, insulation materials	Peck's Power Law AF=Hours_Lab/Hours_field	~100

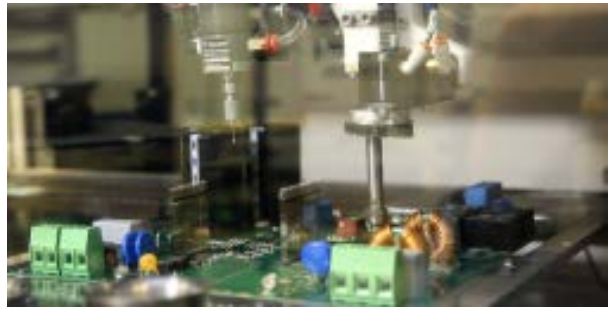
- SolarEdge minimal qualification test in BI is **2,000 hours** (equivalent to **36 years** in the field for death valley and 130 years in Berlin)
- SolarEdge minimal qualification test in TCC is **1,500 cycles** (equivalent to **41 years** in the field)
- SolarEdge minimal qualification test in DH is **1,200 hours** (equivalent to **27.4 years** in the field)

Third-Party MTBF Review

- SolarEdge products MTBF calculation was reviewed by the external third-party reliability validation company
- The process included design analysis and MTBF calculation
  - This MTBF data is also very strict since it does not take into account specific industry and product conditions
  - Therefore, the theoretical MTBF calculation will always be lower than an empirical one that is validated in our lab tests and therefore represent a worst-case extreme low
- The power optimizers MTBF as calculated by the third-party company is **1,052 years**.
- The 1ph inverter MTBF as calculated by the 3rd party company is 116.1 years
- The HD-Wave 1ph inverter MTBF as calculated by the 3rd party company is 182.3 years
- The 3ph inverter MTBF as calculated by the 3rd party company is 80.1 years

Manufacturing Sites for 2018

- Jabil site in HuangPu, China
  - 1,200 inverters and 20,000 optimizers per day
- Flextronics site in Zala, Hungary
  - 5000 optimizers per day
- Celestica site in Ordea, Romania
  - 400 inverters and 5000 optimizers per day



Quality Assurance and QC

- 140 CM QC people
- 10 CM QA people
- 30 SolarEdge QC people in China
- 20 SolarEdge QA people: 5 at Jabil, 2 at CLS, 5 at HQ
- 2 SolarEdge QA people at main suppliers, 5 QC people
- 2 debug engineers at Jabil, 1 at CLS
- 5 component engineers at HQ, 1 at CM

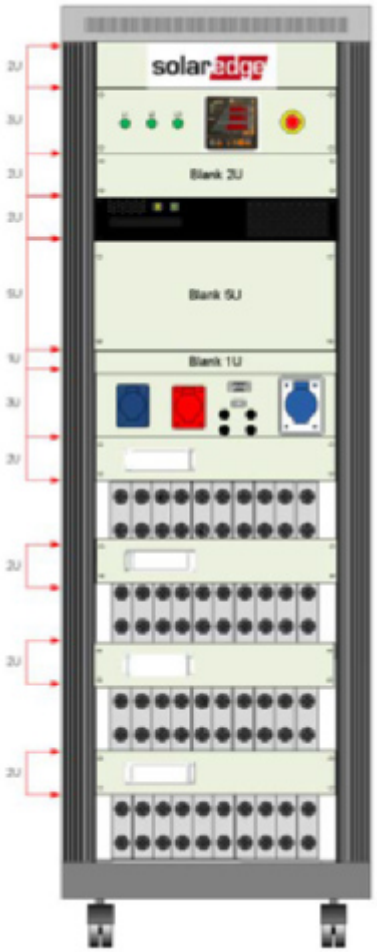
Quality Assurance & Control Tools

Advanced tracking & policing system

- All SolarEdge production lines employ a QMS/EMS control system to perform the following functions:
  - Full component traceability - every component reel and batch is logged and registered **per unit S/N for full traceability**
  - Process policing – each unit is scanned at every station to verify unit does not skip stations or change routing
- Incoming goods and material QC tests at WH while extra tests are preformed for specific parts
- Advanced (non-human) QC tools (dispensers, optical assembly control etc.)
- Batch sampling
  - Full 'Out of Box' inspection and disassembly
  - HALT or ALT statistical testing

Product Testing

- Statistical long term Burn-In screening
  - 2% of every batch is tested in a system-level integrative test at high temp (60°C) for 6h
  - 1% of every batch is tested in a system-level integrative test at high temp (60°C) for 48h
  - 0.1% of every batch is tested in a system-level integrative test at high temp (60°C) for 30 days
- 100% of PCBAs (printed circuit board assemblies) undergo:
  - Automatic Optical Inspection (AOI)
  - In-Circuit Testing (ICT)
  - Functional Testing (FT)



Non-Electric Test Program

These are additional tests performed every production run to verify various steps and protect specs that cannot be tested as part of electrical testing:

- Potting process:
  - Machine calibration every shift
  - Potting weight – 100% of units
  - Hardness and curing time (every two hours)
  - Potting Material Viscosity test (every two hours)
- Inverter sealing:
  - Sealing test– 100% of units
- PCBs:
  - HATS coupons test – statistical per batch
  - Microscopic Stuck-up measurements of Cross Sections
- O-rings testing jigs:
  - Jigs for testing O-ring dimensions
  - Rubber Hardness test in IQC
  - Compression set test in IQC
- Magnetics:
  - Tester for inverter's and optimizers chokes – 100% of units
  - High Power Optimizers Heat Spreaders insulation test and coating thickness

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Thank You!

Cautionary Note Regarding Market Data & Industry Forecasts

This power point presentation contains market data and industry forecasts from certain third-party sources. This information is based on industry surveys and the preparer's expertise in the industry and there can be no assurance that any such market data is accurate or that any such industry forecasts will be achieved. Although we have not independently verified the accuracy of such market data and industry forecasts, we believe that the market data is reliable and that the industry forecasts are reasonable.

Version #: V.1.0

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NREL
Transforming ENERGY

Evaluating the Durability of Transparent Backsheets for Bifacial Modules

Michael Kempe

National Renewable Energy Laboratory (NREL)

PV Reliability Workshop, Lakewood, Colorado (2019)

Introduction

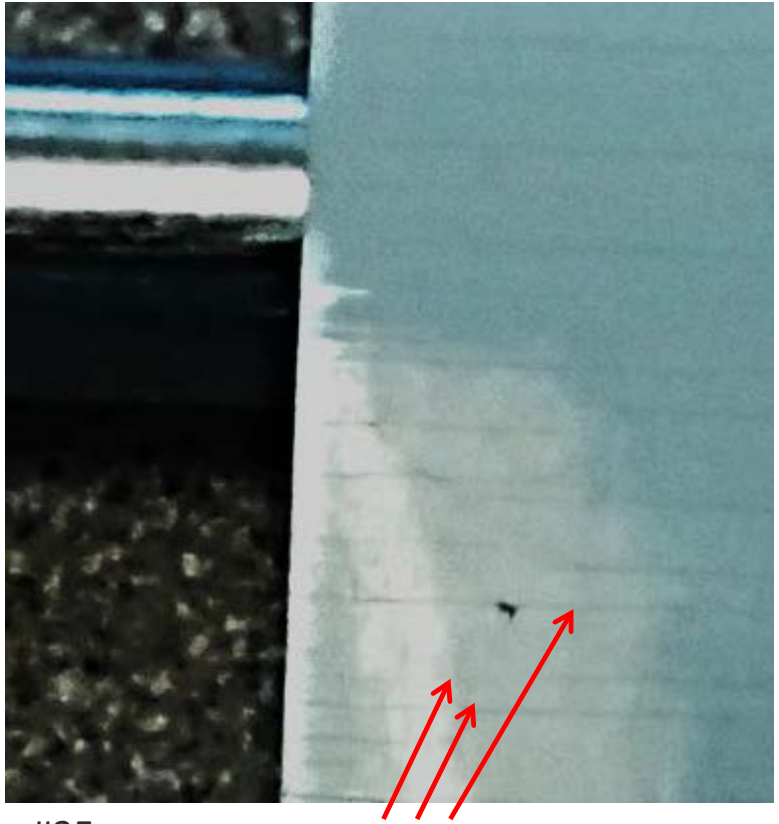
- Glass is most frequently used as a backsheet in a bifacial module because of it's good transmittance, high durability and low cost.
- However, glass is heavy, more susceptible to PID, and more difficult to laminate to another piece of glass as compared to a polymeric backsheet. (i.e. because of edge pinch, tempered glass flatness, and surface topology).
- Will the balance of costs, weight, and manufacturability favor glass or polymers?
- Typical polymeric backsheets utilize polyethylene terephthalate (PET) in a core layer to provide electrical insulation.
- However PET is not inherently UV stable and is frequently protected by placing it between two highly pigmented layers to block UV light.
- For bifacial PV modules robust designs and stabilization techniques are needed to create a polymeric backsheet that is durable and transmits light.

Outline

1. Bend test
2. Frontsheet barrier stabilization
3. Design of backsheet UV exposure testing
4. Current efforts for backsheet testing standards
5. Conclusions

Mandrel Bend Test Experiments

56 backsheets surveyed of which 7 were transparent.*



- Samples are bent around a 6.35 mm diameter mandrel in both directions.
- Testing is conducted every 250 h till failure occurs.
- A3 Exposure (0.8 W/m^2/nm @340 nm, 65°C CAT, 90°C BPT, 20% RH.)

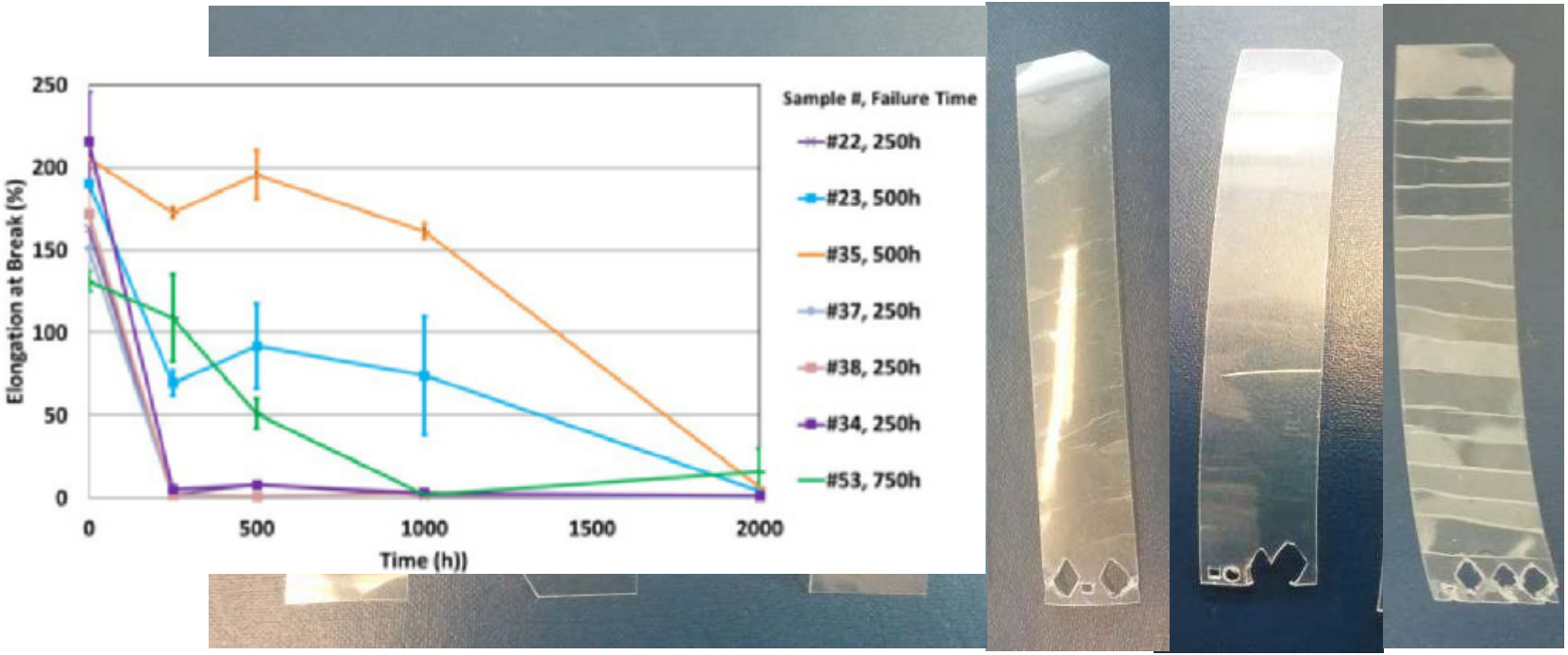
Machine direction sample #35.

Cracks in transverse direction on cell side.

*M. D. Kempe, D. C. Miller, A. Zielnik, D. Montiel-Chicharro, J. Zhu, and R. Gottschalg, "Survey of Mechanical Durability of PV Backsheets," *IEEE PVSC, Washington, DC,* 2017.

All 7 of the clear backsheet samples failed in the PET layer

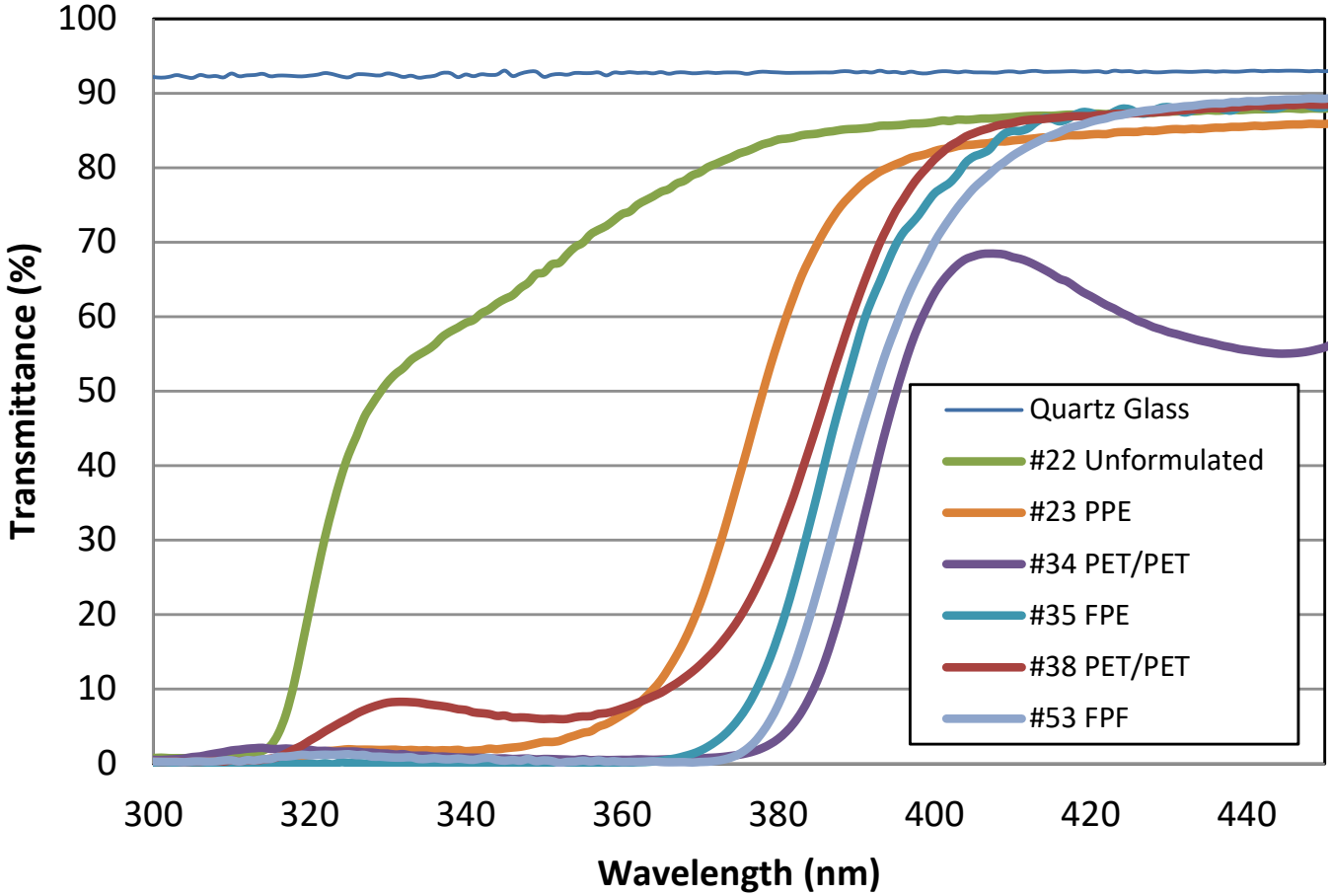
#38 RR-UVPET	#37 RR-PET	#22 Unstabilized PET	#23 PET/PET/Primer	#35 FPE	#53 FPF
250 h	250 h	250 h	500 h	750 h	750 h



- None of the unpigmented PETs were able to withstand exposure for more than 750 h of A3 (0.8 W/m^2/nm @340 nm, 65°C chamber temperature, 90°C Black Panel, 20% RH).
- Red colored samples were likely intended for a PV application.
- Blue samples were expected to fail.

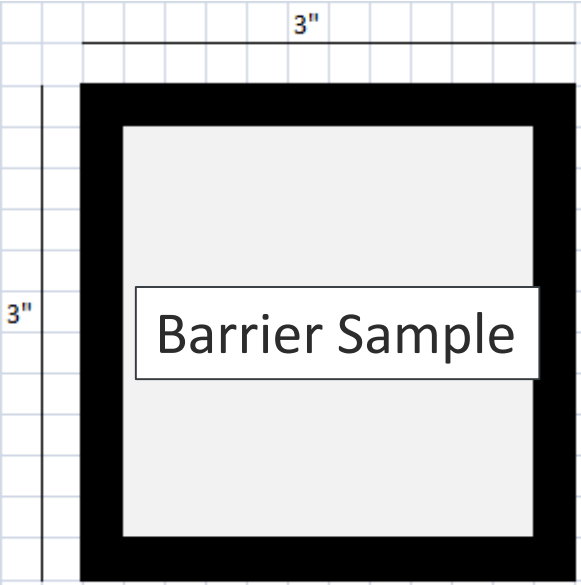
M. D. Kempe, D. C. Miller, A. Zielnik, D. Montiel-Chicharro, J. Zhu, and R. Gottschalg, "Survey of Mechanical Durability of PV Backsheets," *IEEE PVSC, Washington, DC,* 2017.

UV Absorber not Necessarily Sufficient to Protect the PET Layer



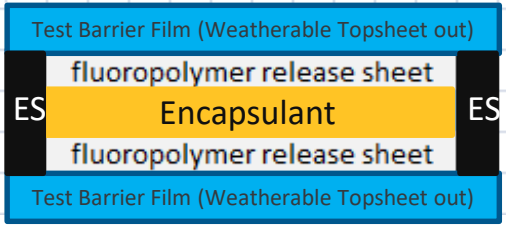
- **It is not known which layer(s) had the UV absorber in it.**
- **This bend test is not documented to predict 25 y, and failed to identify a known bad material. The testing of free standing films is only giving a partial answer.**
- **However, failure in such short times is a significant indication of some problems.**

Frontsheet Moisture Barrier Using PET can be Stabilized

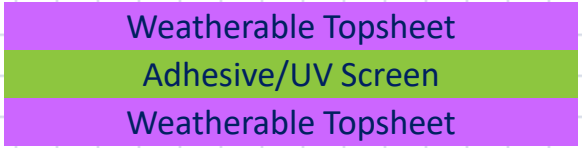


1/4" edge seal
Fluoropolymer relase sheets to isolate encapsulant
Experimental Barrier film used on front AND back
-for LIGHT+HEAT and HEAT ONLY (dark) samples

M. D. Kempe *et al.*, "Evaluation of the durability of flexible barrier materials," in *2015 IEEE 42nd Photovoltaic Specialist Conference (PVSC)*, 2015, pp. 1-6.

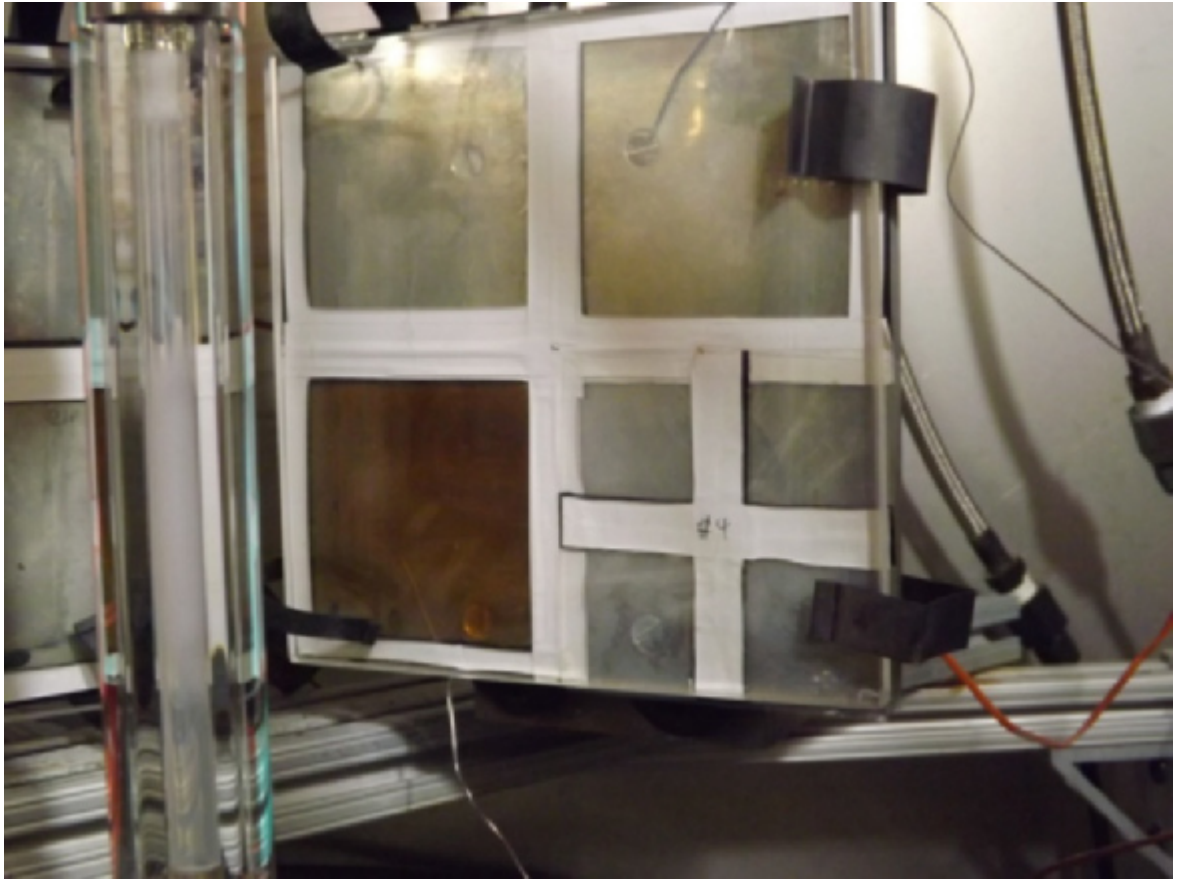


Adhesive Only Sample

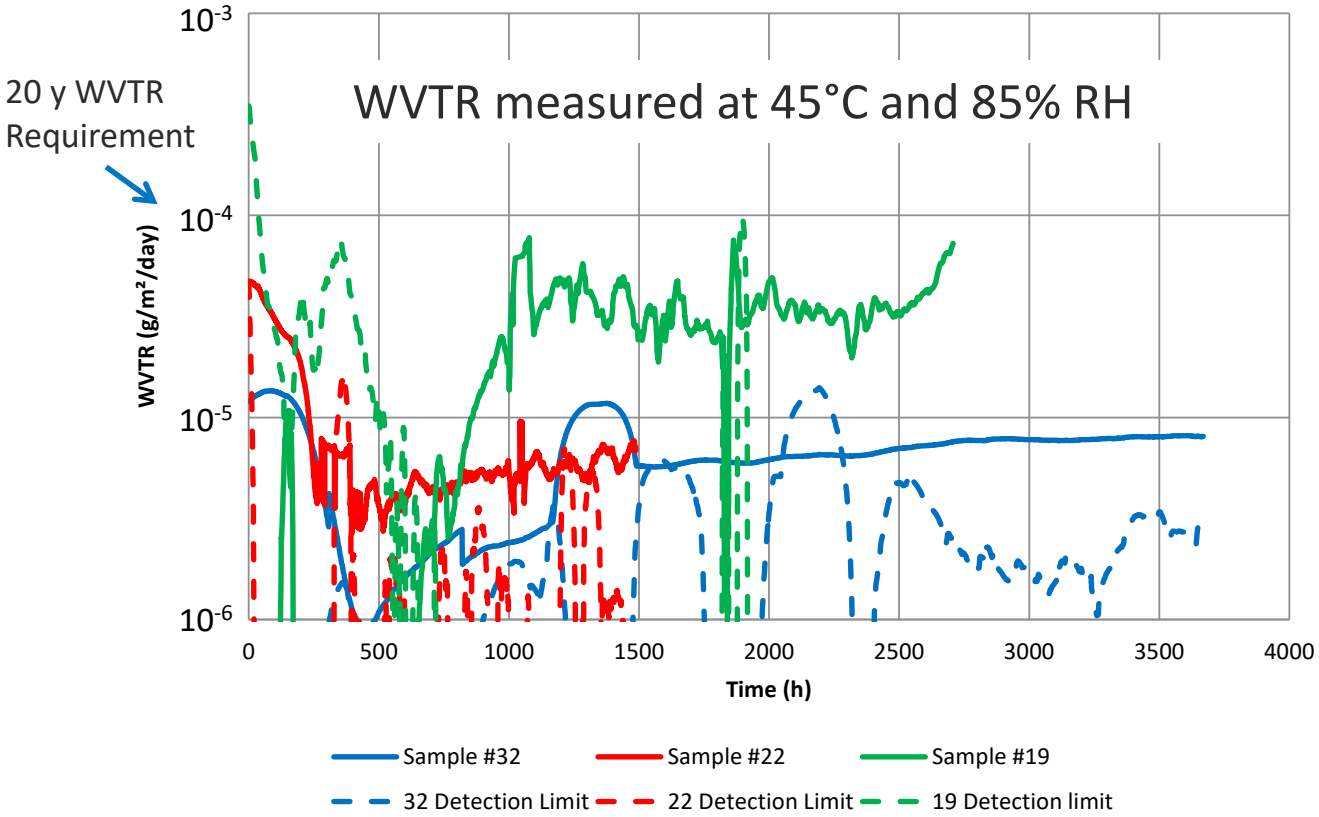


Accelerated Stress Test Exposure

- Samples exposed to:
  - 10 UV suns, 105°C
  - 10 UV suns, 85°C
  - 4 UV suns, 105°C
  - 4 UV suns, 85°C
- Chamber set to 85°C and 20% RH resulting in a sample RH of 9.6% RH at 105°C
- Samples exposed for up to 2000 h



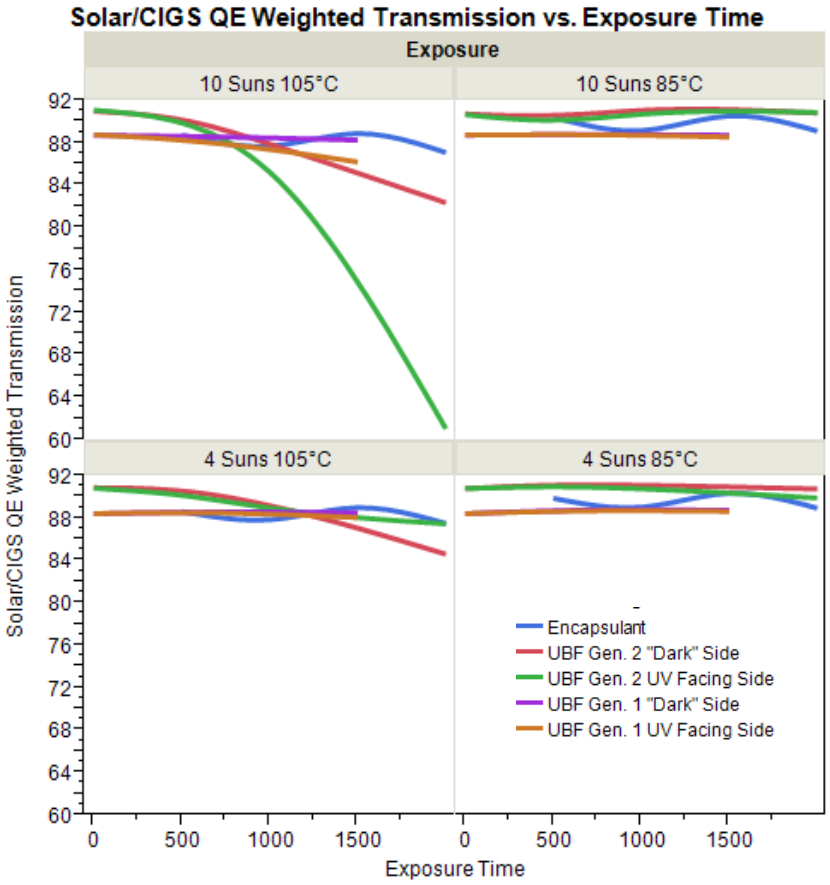
The Barriers Survied Exposure to Extreme Light and Temperature



- Of the dozens of barriers exposed to heat at humidity, up to 10 suns and 105°C, these were the worst performers.
- These barriers are organic/inorganic stacks on a PET substrate.
- It is possible to stabilize PET.

The Detection limit is defined as the apparent WVTR of the Witness line.

PET-Based Frontsheet Barrier Maintained Transmittance



CIGS-QE solar photon weighted transmittance of exposed barrier films. Here "dark" refers to the backside, and "light" refers to the side facing the light source.

For the one 10 sun, 105°C sample that experienced significant losses, it is possible that there was some thermal runaway or that another highly activated process has become important.

This data for frontsheets is a proof of concept that PET films can be adequately UV stabilized.

In other experiments, NREL is working with SunPower to evaluate low cost alternatives for polymeric frontsheets.

Kinetics of Paints and Coatings Degradation

$$R_D \sim I^x \cdot (b + m \cdot TOW) \cdot T_f^{\frac{T-T_o}{10}}$$

*Fischer *et. al*

T_f=1.41±0.23	Acceleration per 10°C increase.
X=0.64±0.2	Irradiance acceleration exponent.
m=-0.0015±0.12	Time of Wetness (TOW) factor.
b=1.071±0.0026	

- 50 coatings with respect to color shift, cracking, gloss loss, fluorescence loss, retroreflectance loss, adhesive transfer, and shrinkage.
- In the absence of good kinetic data for PV specific materials, we looked at values for these polymeric materials.

R. M. Fischer and W. D. Ketola, "Error Analyses and Associated Risk for Accelerated Weathering Results," *Third International Service Life Symposium, Sedona, AZ February 2004,* 2004.
M. D. Kempe, "Evaluation of the uncertainty in accelerated stress testing," in *Photovoltaic Specialist Conference (PVSC), 2014 IEEE 40th*, 2014, pp. 2170-2175

Modeling Assumptions for a PV Backsheet

- Assume UV on back of rack mounted system is 0.5% of global horizontal irradiance (GHI).
- This is assuming the back gets about 10% of the UV dose as does the front side.
- Ignore TOW
  - Very high uncertainty with a lower mean value indicating typically no predictable effect.
  - Condensation is predominantly on the front making application of this effect dubious on the back.

$$R_D \sim I^x \cdot T_f^{\frac{T-T_O}{10}}$$

M. D. Kempe, "Evaluation of the uncertainty in accelerated stress testing," in *Photovoltaic Specialist Conference (PVSC), 2014 IEEE 40th*, 2014, pp. 2170-2175

Optimal Exposure Conditions were Developed by Minimizing Uncertainty

Optimized test conditions for an equivalence to 25 years exposure

Temperature and Irradiance optimized Data	Accelerated Stress Test Duration					
	1000 h		6 month		2.5 y	
	T_o (°C)	(W/m²/nm @340 nm)	T_o (°C)	(W/m²/nm @340 nm)	T_o (°C)	(W/m²/nm @340 nm)
Munich, Germany	67	2.5	54	0.50	40	0.086
Denver, Colorado	74	3.6	61	0.71	46	0.12
Albuquerque, New Mexico	78	4.4	65	0.89	51	0.15
Miami, Florida	80	4.1	67	0.81	53	0.14
Bangkok, Thailand	85	4.2	72	0.83	58	0.14
Phoenix, Arizona	89	4.7	76	0.94	62	0.16
Riyadh, Saudi Arabia	90	5.0	77	1.00	63	0.17

- ASTM G173 using 0.5018 W/m²/nm @340 nm
  - 1000 h test - 5 to 10 UV suns
  - 6 month test - 1 to 2 UV suns
  - 2.5 y test - 0.17 to 0.33 UV suns

$$R_D \sim I^x \cdot T_f^{\frac{T-T_o}{10}}$$

T_f=1.41±0.23

X=0.64±0.2

The optimal test conditions for a 6 month test to be equivalent to 25 y exposure are well represented by the A3 condition.

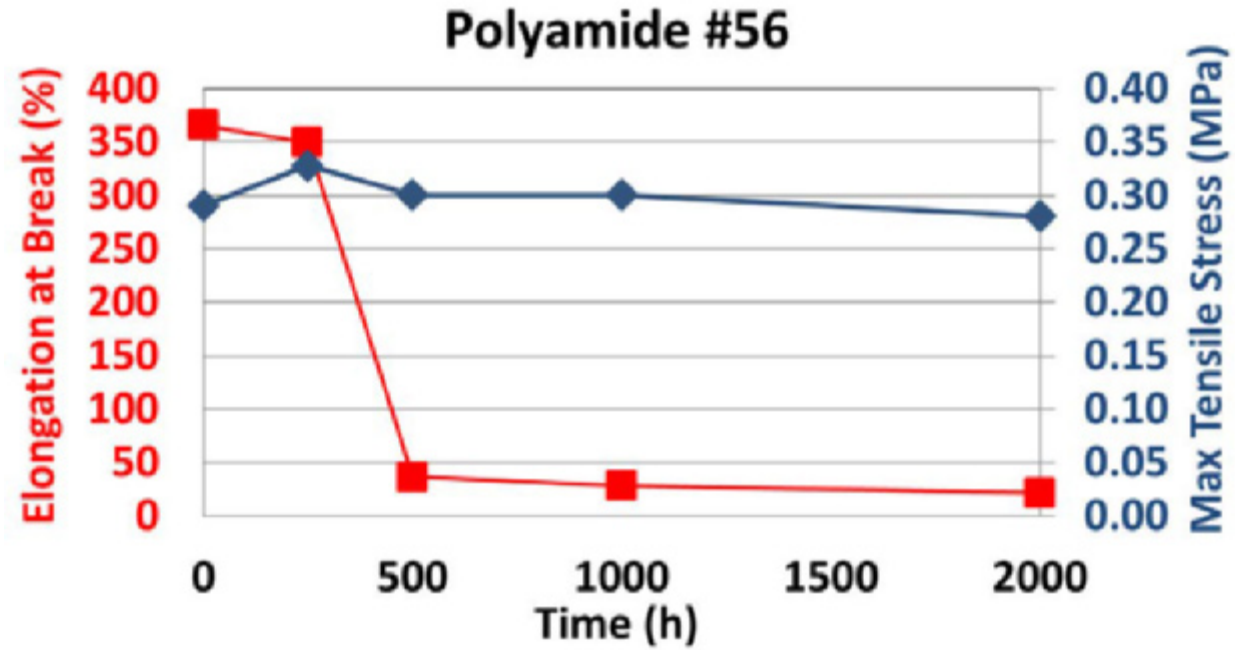
(0.8 W/m²/nm @340 nm, 65°C chamber temperature, 90°C Black Panel, 20% RH).

M. D. Kempe, "Evaluation of the uncertainty in accelerated stress testing," in *Photovoltaic Specialist Conference (PVSC), 2014 IEEE 40th*, 2014, pp. 2170-2175

The Future of Testing Standards for Backsheets

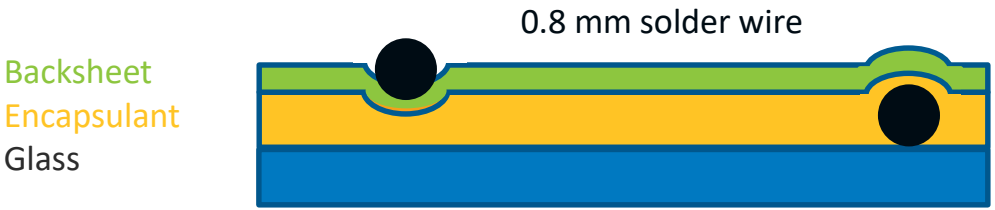
- IEC 62788-2-1
  - Currently out for vote as a New Work Item
  - Will be referenced by IEC 61215 and IEC 61730 to be used as a prequalification for backsheets.
  - Contents under consideration (may go into IEC 62788-2 first):
    - UV transmittance retention for bifacial applications.
    - Tensile test for retention of mechanical properties.
    - Solder bump test for cracking.

Tensile Testing



- A rapid loss of elongation is correlated with field failure of a polyamide after as little as 4 years.
- Similar losses were seen in the transparent PET-based backsheets tested in the bend test.

Laminated test samples to duplicate module contours

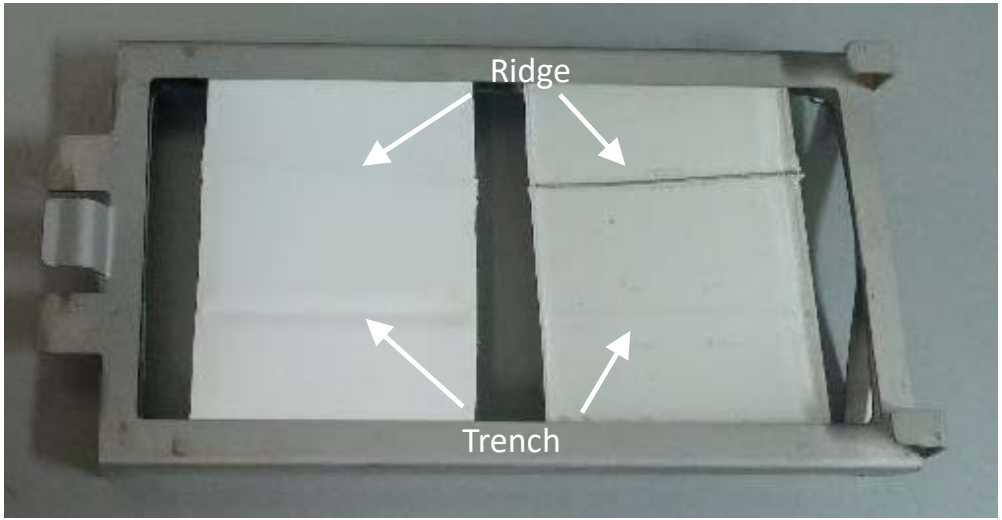


Because cracks often appear along surface contours of a module, samples were laminated with a solder wire to produce “ridges” and “trenches.

Test samples were made with the polyamide, a PPE, and a PVDF/P/E backsheet.

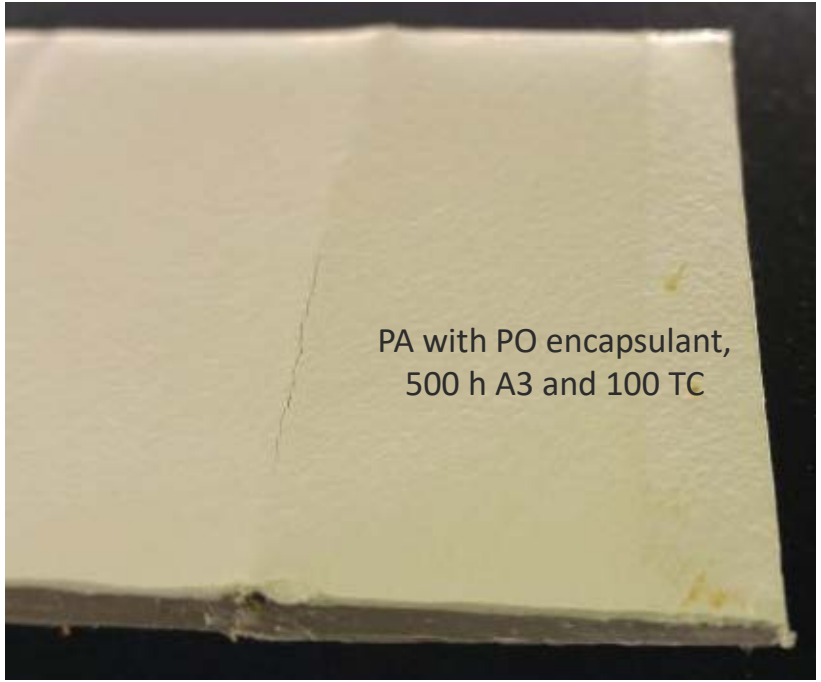
Samples were exposed to condition A3 of 62788-7-2.

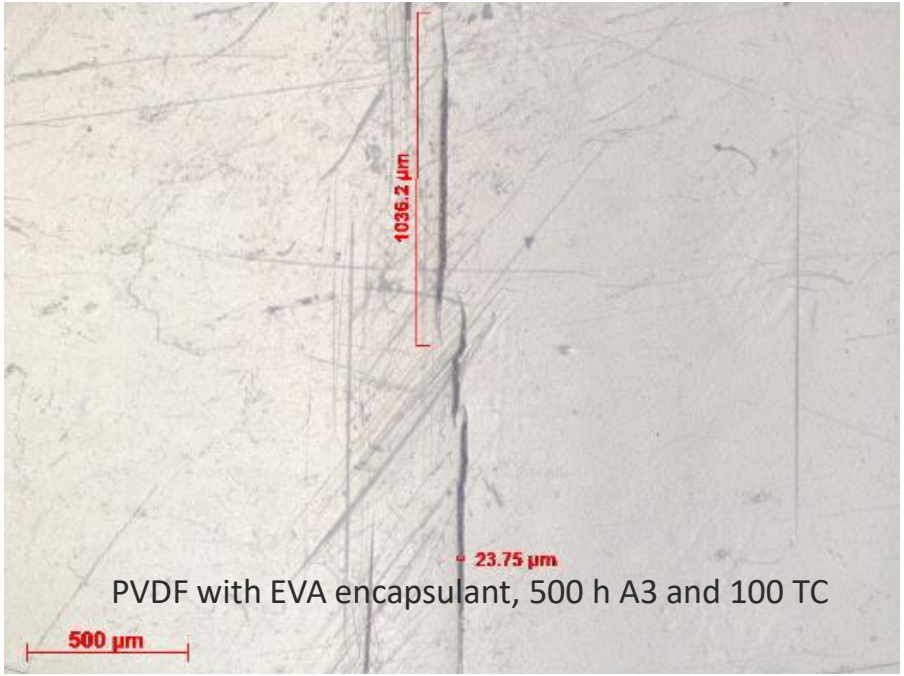
Air side Encapsulant Side



500 h A3 and 100 TC Causes Cracking

- After 500 h A3 and 100 TC.
  - PPE – No cracks
  - PVDF – Cracks on cell-side exposed samples only.
  - PA – Cracks on air-side exposed samples for both PO and EVA encapsulant.
- The use of TC after UV/thermal stressors is a key missing component of testing that allowed some bad backsheets to pass qualification tests.





Conclusion

- The economics for glass vs polymers for use in bifacial modules remains a topic of much debate.
- Designing a PET-based transparent backsheet to be durable is a difficult but achievable goal.
- Careful consideration of the use environment and degradation kinetics is essential for designing appropriate testing standards.
- Within the IEC community we are closing in on tests suitable for evaluating the use of polymeric materials for backsheets in bifacial modules.

Comparison of glass/glass and glass/backsheet mini-modules by accelerated test

Yuji Ino, Shuichi Asao, Katsuhiko Shirasawa, Hidetaka Takato

Fukushima Renewable Energy Institute, AIST (FREA)

NREL PV Reliability Workshop, Feb. 28 2019

Outline

- Introduction

  FREA & Works for PV modules in FREA

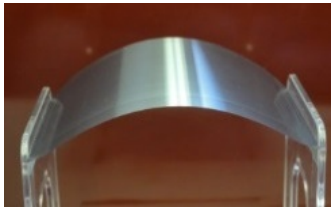
- The result of reliability tests for Glass/Glass mini-modules (Comparison with Glass/Backsheet modules)
  - DML（Dynamic mechanical loading）test
  - PCT (Pressure cocker test)

Introduction: FREA

FREA was established in Fukushima in 2014 as a part of the National Institute of Advanced Industrial Science and Technology (AIST)
to research on renewable energy .

Consistent fabrication from Si ingot to module testing for c-Si PV module in FREA

Wafer → **Cell** → **Module** → **Reliability testing**



- High quality ingot
- Thin wafer

- BC cell
- Bifacial cell
- Ion implantation for PERC

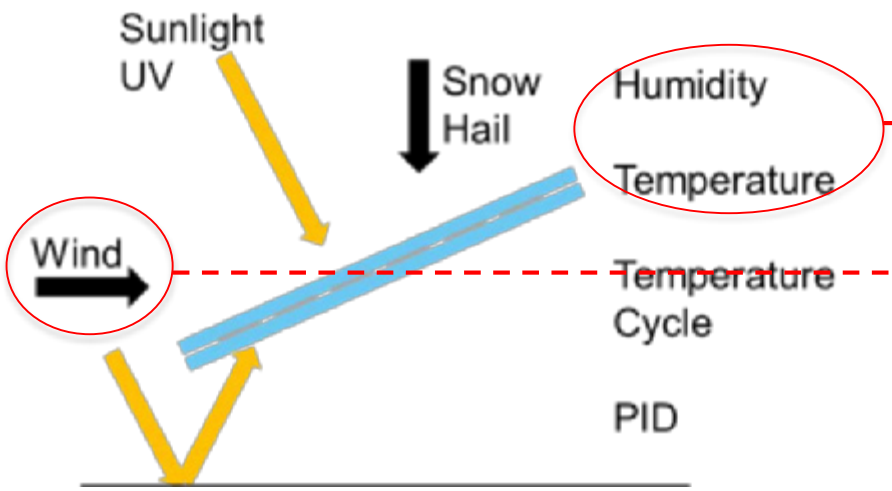
- Test/full size module
- Glass/Glass module
- Roof integrated module

- DH, PCT, TCT, DML, UV, PID, LID

Objective: Observation of the failure modes of Glass/Glass modules by accelerated test

Glass/Glass PV modules are attracting attention for

- use of bifacial cells
- BIPV
- high reliability of modules



PCT (Pressure cocker test)
110°C/85%RH

DML（Dynamic mechanical loading）
Max. 4 kPa loading

We investigated the failure modes of Glass/Glass (G/G) mini-module using accelerated test (here DML and PCT), and compared them with Glass/Backsheet (G/BS) mini-module.

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DML test：Module structure

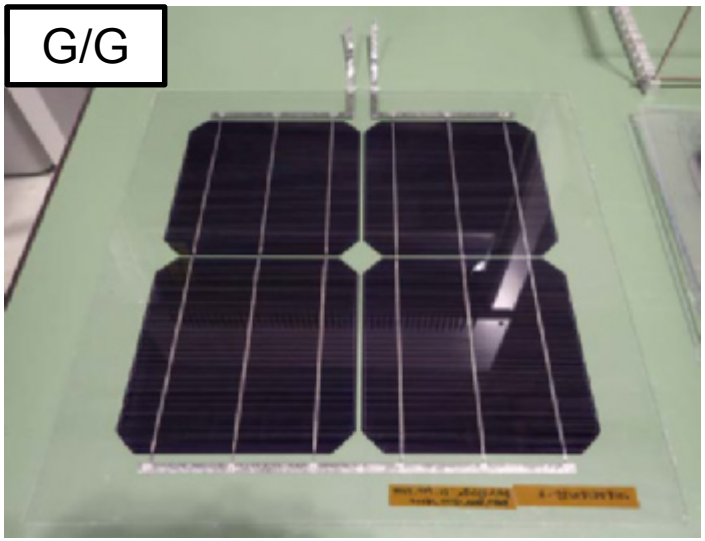
	Glass/Backsheet	Glass/Glass
Front cover	Tempered glass, 0.85 mm	Tempered glass, 0.55 mm
Encapsulant (front)	EVA, 0.45 mm	
Interconnector	Cu rectangular wire coated with lead solder, 1.2 mm x 0.2 mm	Cu rectangular wire coated with lead-free solder, 1.2 mm x 0.2 mm
Cell	c-Si Al-BSF, 175 um	
Encapsulant (back)	EVA, 0.45 mm	
Back cover	PET, 25 um	Tempered glass, 0.55 mm

- 400 mm ×400 mm
- Frameless
- Without edge sealing
- Without Junction-box

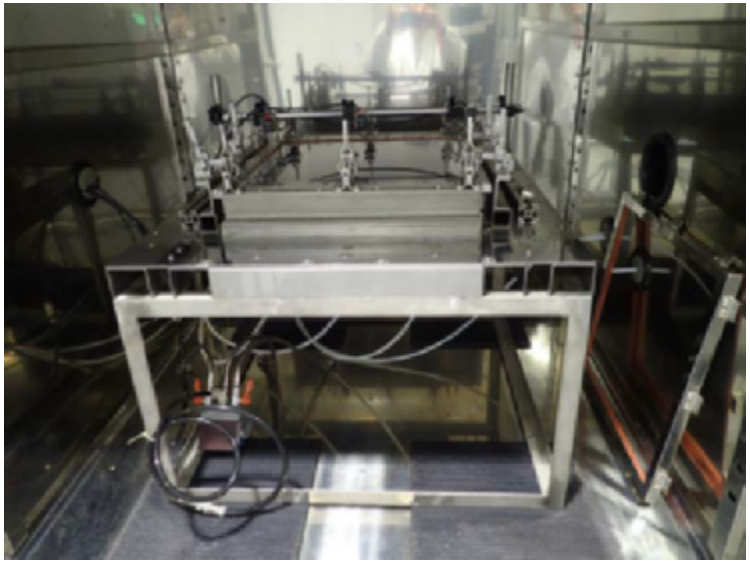
Thin glass and backsheet were used to check the failure mode quickly.

G/BS

G/G

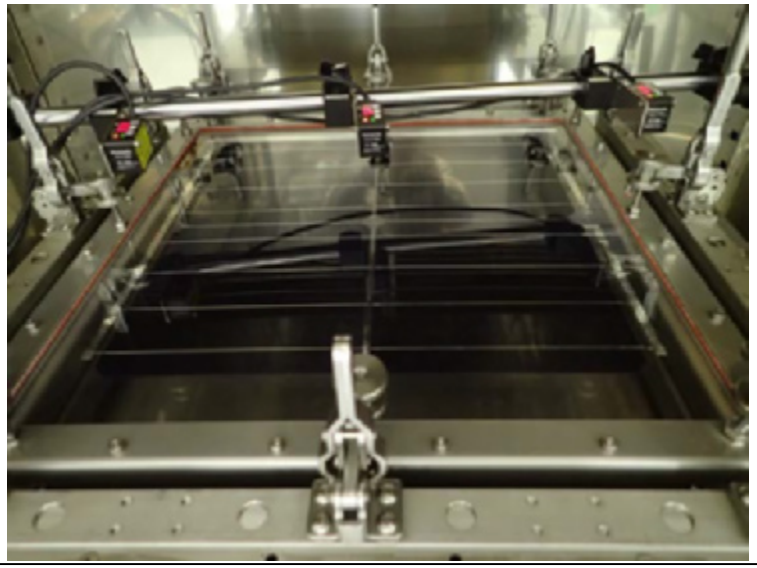


DML test: Test apparatus



DML-4000M (ESPEC CORP., Osaka)

The sample size is up to 400 mm x 400 mm.
Loading up to ±4 kPa by air compression and pumping.
The temperature range is between −40 and +60 ℃.

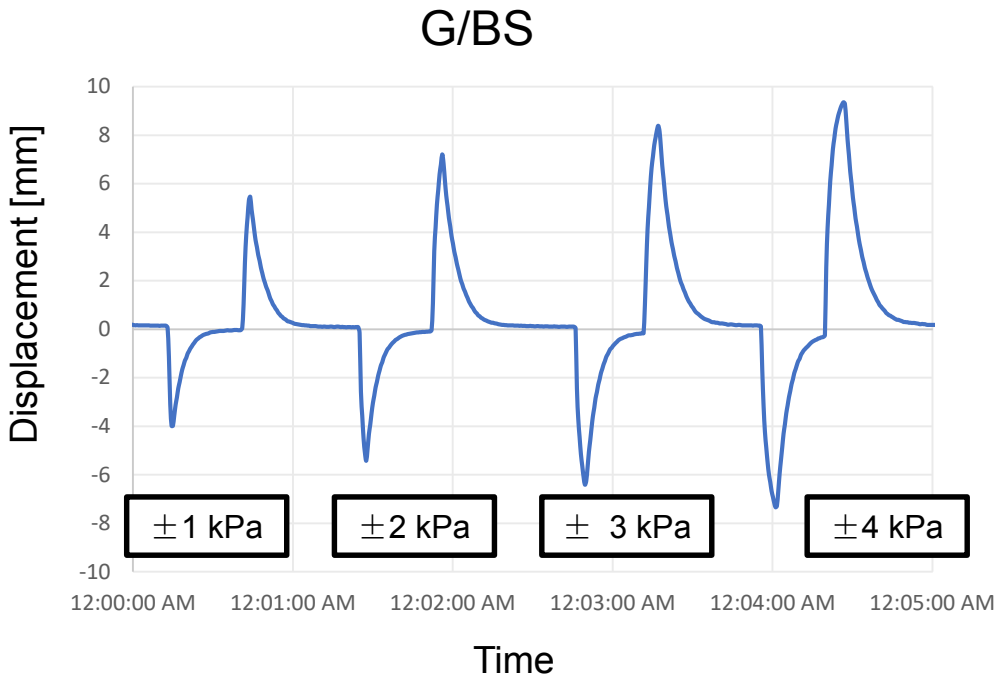


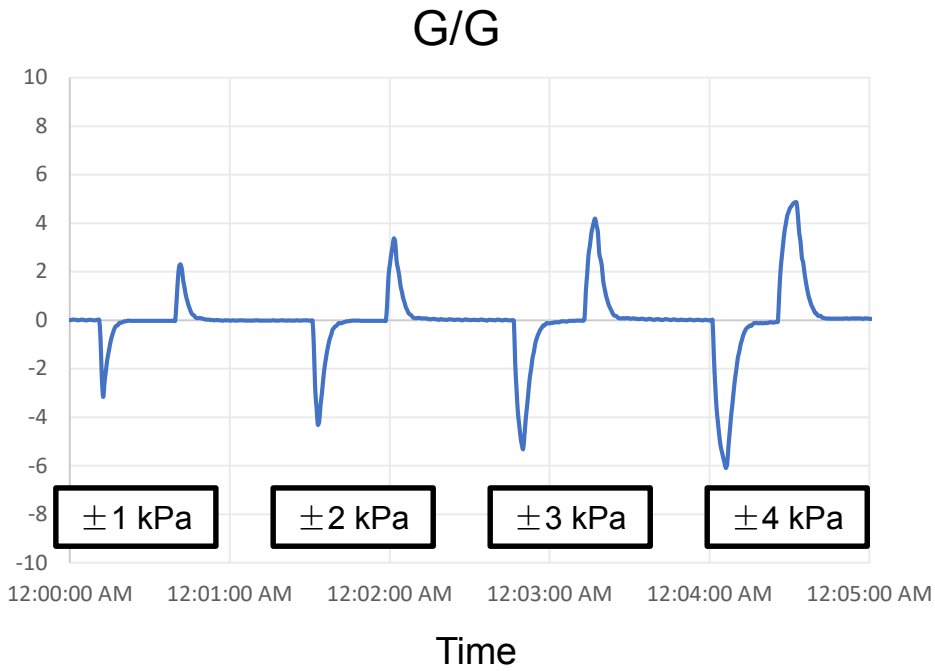
The four sides of the mini-module are fixed to the frame with rubber packing and clamp.

The displacement of module under test is measured by laser sensors.

In this test, a sinusoidal load was applied with 1 cycle/min at 25 ℃.

Deflection at the center of module

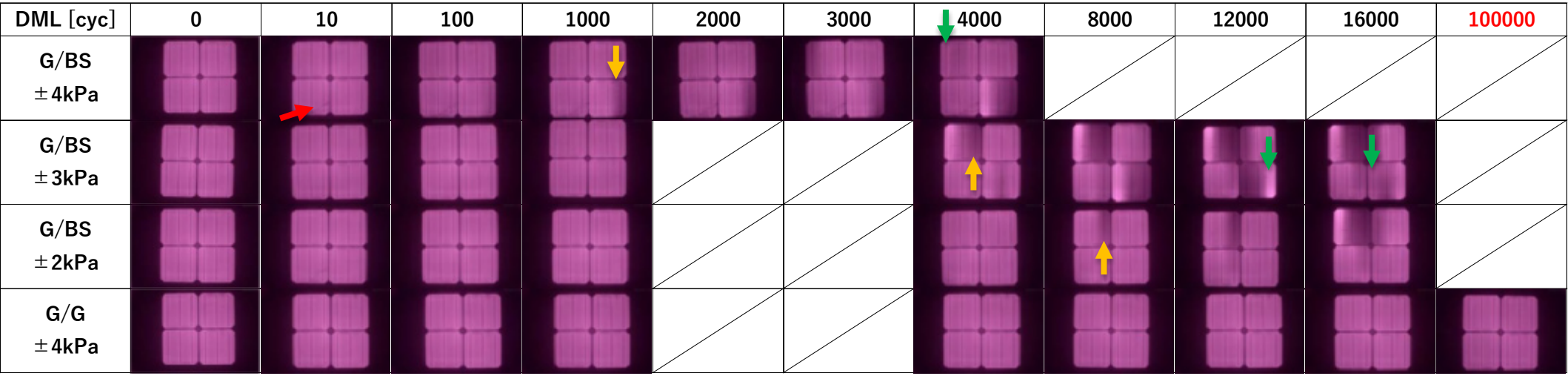




load [kPa]	Deflection [mm] $(D_{max}-D_{min})/2$	
	G/BS	G/G
±1	4.7	2.7
±2	6.3	3.8
±3	7.4	4.7
±4	8.4	5.5

As the G/G module in this work is more rigid than the G/BS module,
we applied load of **±4kPa for the G/G module** and loads of **±2, 3, and 4 kPa for the G/BS modules** to compare.

EL imaging



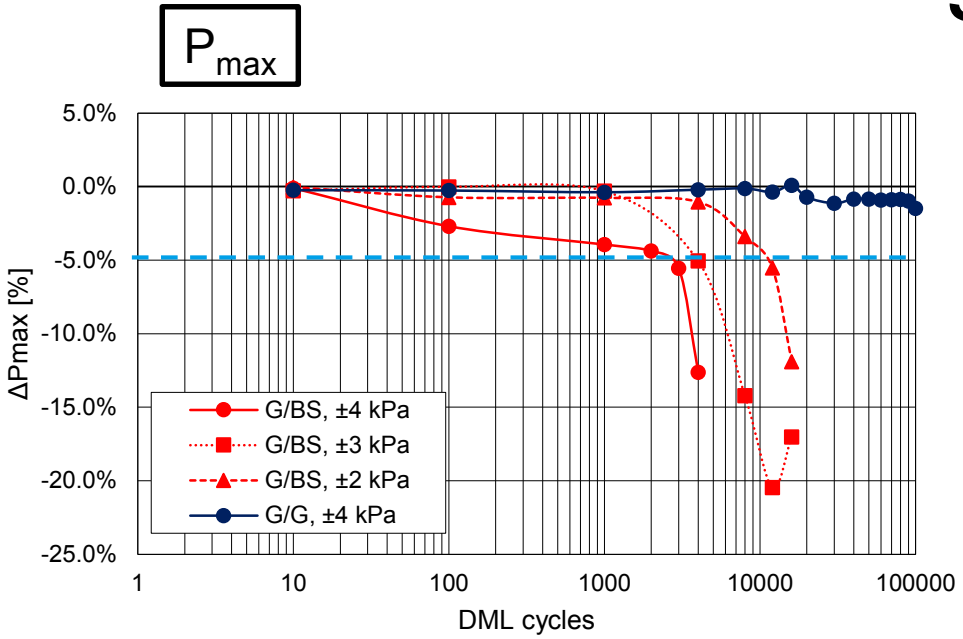
For G/BS modules,

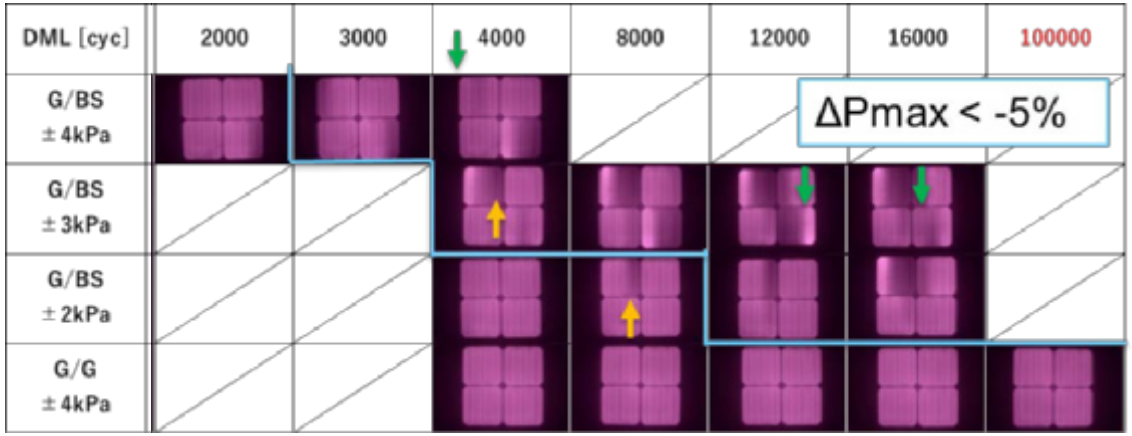
- Cell crack (after 10 cycles with loading of ±4kPa)
- Failure of Interconnector
  - after 1,000 cycles with loading of ±4kPa
  - after 4,000 cycles with loading of ±3kPa
  - after 8,000 cycles with loading of ±2kPa
  - The number of failed Interconnector increased as the number of test cycles increased, but there was also a place where the appearance recovered.

For the G/G module,

- Any failures such as cell crack and interconnector failure **were not observed even after 100,000 cycles.**

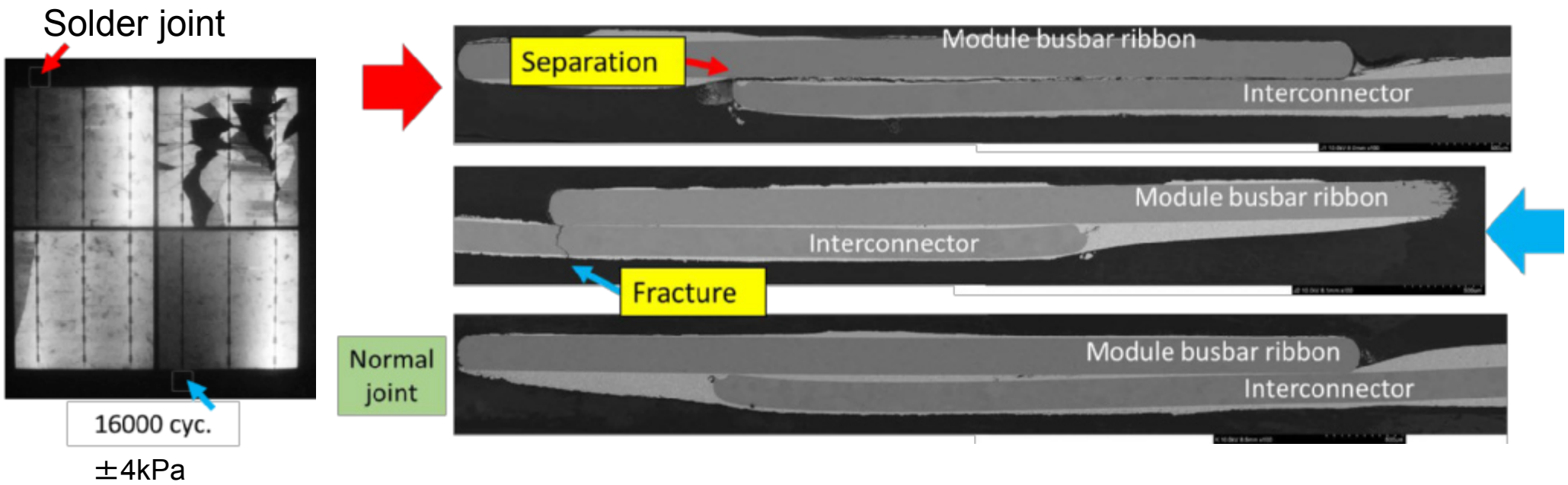
Change in P_{max}





- The cell crack in this work did not significantly affect the I-V parameter.
- The failure of interconnector occurred in one position decreased the P_{max} by about 5%.
- The decrease in P_{max} was caused by a decrease in FF.
- The G/G module showed excellent durability with the slight decrease in P_{max} of -1.5% even after 100,000 cycles (I_{sc} = −0.5%, V_{oc} = −0.6%, FF = −0.4%).

Cross-sectional SEM at the joint between interconnector and module busbar ribbon

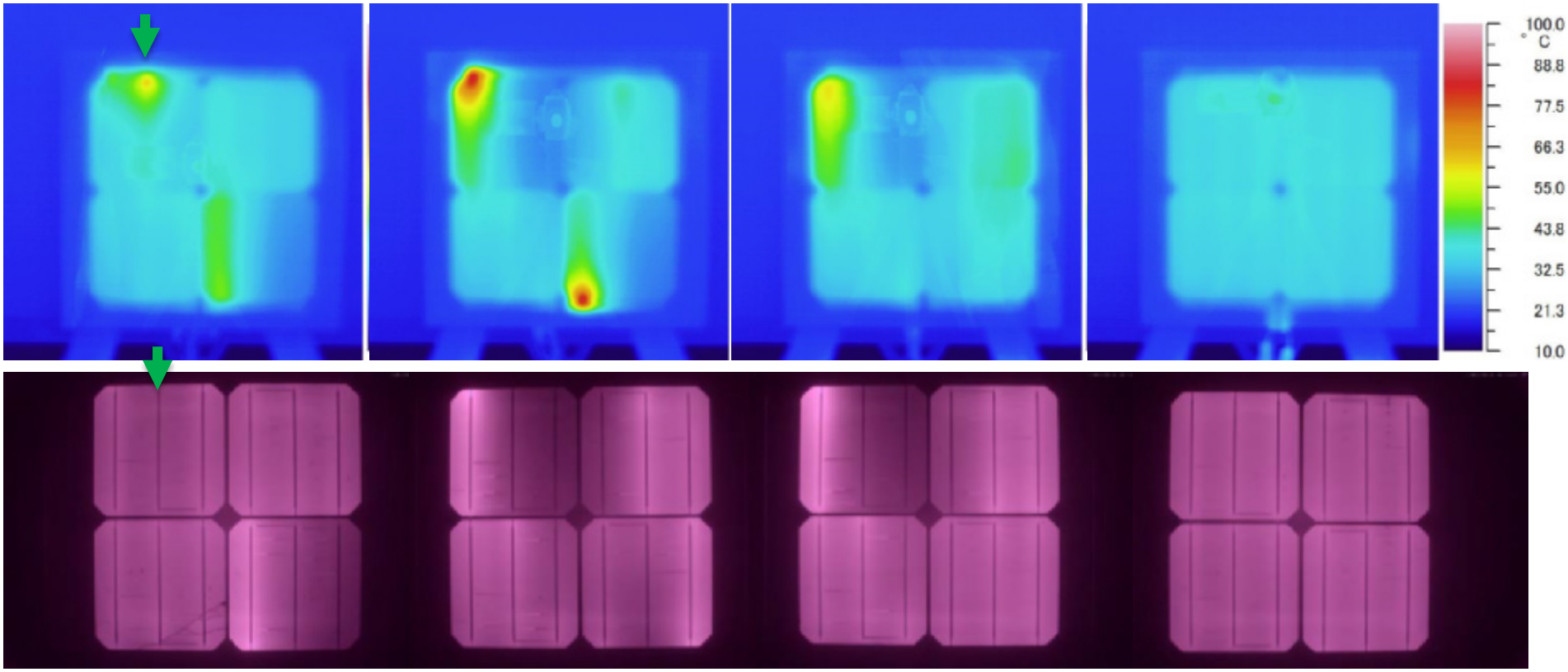


- It has been found that the failure of interconnector is caused by two phenomena:
  - **Separation of the solder joint** between the interconnector and the busbar ribbon.
  - **Fracture of the interconnector** at the edge of busbar ribbon.

- These failures must be caused by **fatigue failure** of solder joints or interconnectors as the cycles number of the failure decreases with increasing load.

Thermography (after 3 min. with ~90%I_{sc})

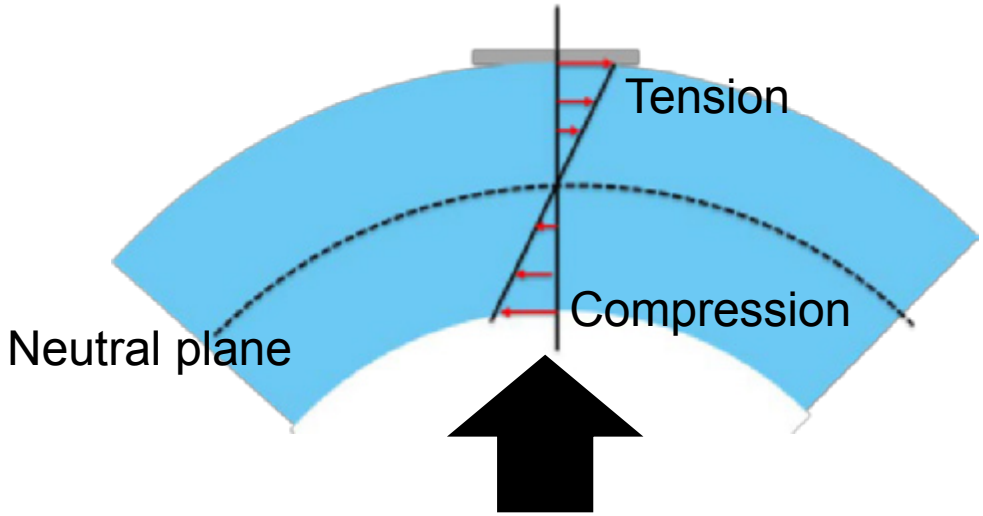
G/BS ±4 kPa 4,000 cyc.	G/BS ±3 kPa 16,000 cyc.	G/BS ±2 kPa 16,000 cyc.	G/G ±4 kPa 100,000 cyc.



- The failure of interconnector causes hot-spots due to current concentration or discharge.
- The G/G module does not show a local increase of temperature.

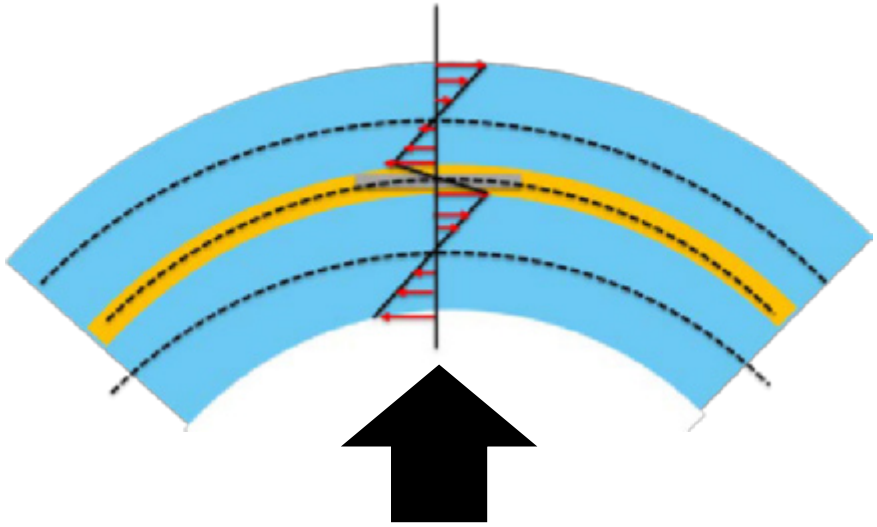
Qualitative explanation for the good durability of a G/G module

Monolithic glass + cell
(G/BS module)



As the G/BS module has an asymmetric structure, the loading form the glass side causes **a tensile stress to the cell**, and if the stress exceeds the breaking strength of the cell, a crack occurs.

Laminated glass + cell
(G/G module)



Since the structure of the G/G module is symmetric, the cell and interconnectors is **near the neutral plane**, and the stress to the cell and interconnectors is small even at the same load.

(The evaluation such as FEM is necessary for quantitative discussion.)

Application of test results to full size modules?

To apply the test results to the full size module,
it is necessary to calculate the stress distribution in the modules.

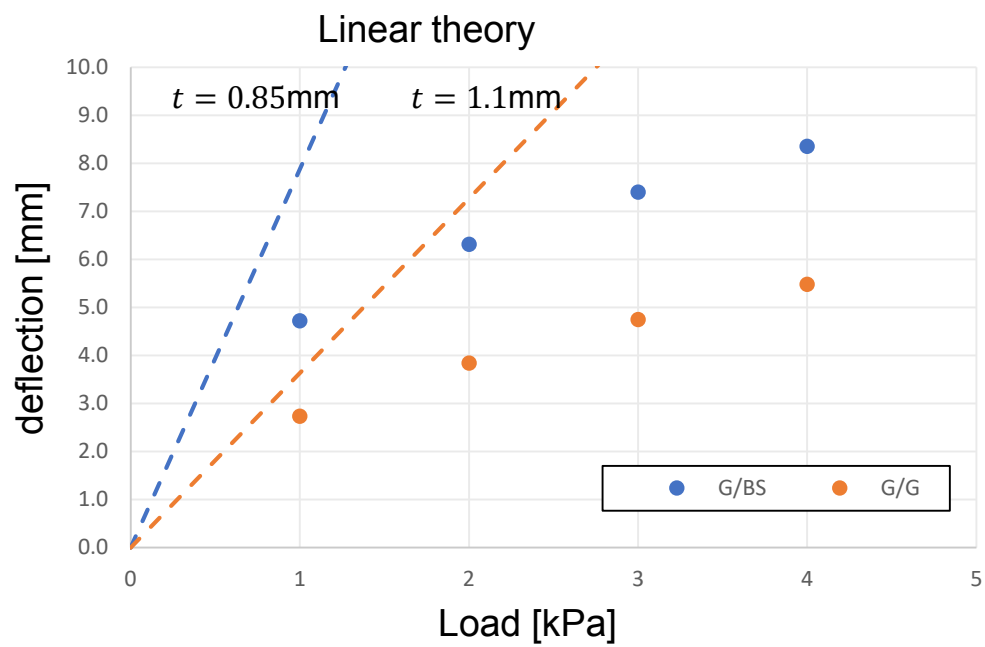
As a first step, it is considered that the linear deflection ω and the maximum bending stress σ under the uniformly distributed load p of the (glass) plate.
They have analytical series solutions, and approximately

$$\omega = 12(1-\nu^2)\alpha p a^4/Et^3$$

$$\sigma = 6\beta p a^2/t^2$$

If the plate is square and the four sides are fixed,

$$\alpha = 0.00126,\ \beta = 0.0513$$



- **The calculated deflections are greater than the actual deflections.**
- **The actual deflections are not linear with respect to the load.**

➡ As the deflection is larger than the module thickness, the analysis of linear deflection can not be applied.
Nonlinear analysis using large deformation theory is necessary.

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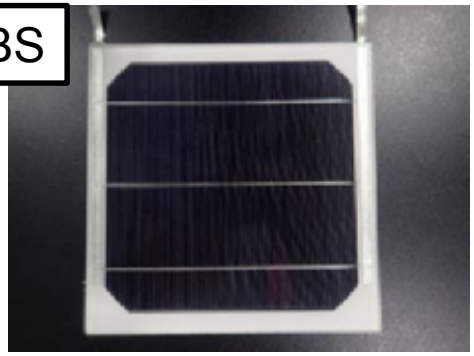
  - PCT (Pressure cocker test)

PCT: Module structure & condition

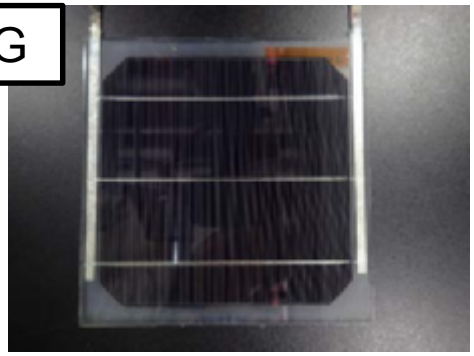
	Glass/Backsheet	Glass/Glass
Front cover	Tempered glass, 3.2 mm	Tempered glass, 0.85 mm
Encapsulant (front)	EVA, 0.45 mm	
Interconnector	Cu rectangular wire coated with lead solder, 1.2 mm x 0.2 mm	
Cell	c-Si Al-BSF, 175 um	
Encapsulant (back)	EVA, 0.45 mm	
Back cover	PVF/PET/PVF	Tempered glass, 0.85 mm

- 200 mm ×200 mm
- Frameless
- Without edge sealing

G/BS



G/G

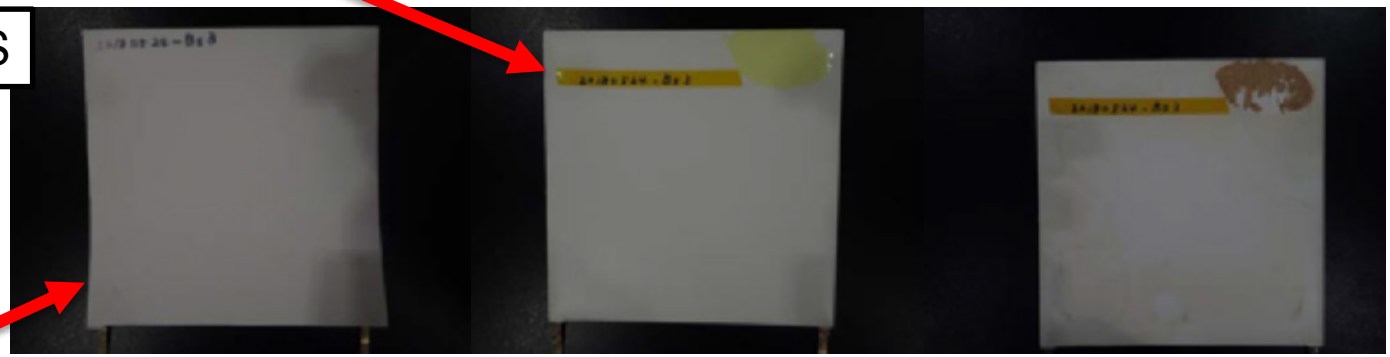


PCT: at 110 ºC and 85 %RH up to 1000 hours.

Appearance of the modules

- Peeling off of the backsheet (degradation of an intermediate PET layer)

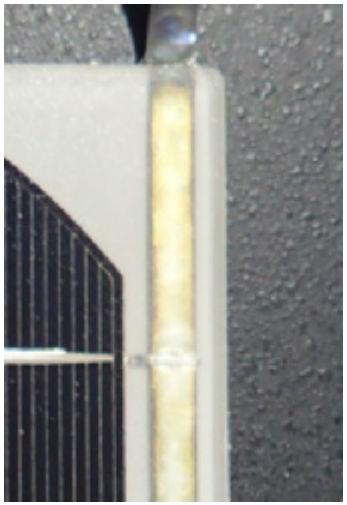
G/BS



Partially PCT 300 h 400 h 1000 h

- Corrosion of module busbar ribbon (PCT ~ 600 h)

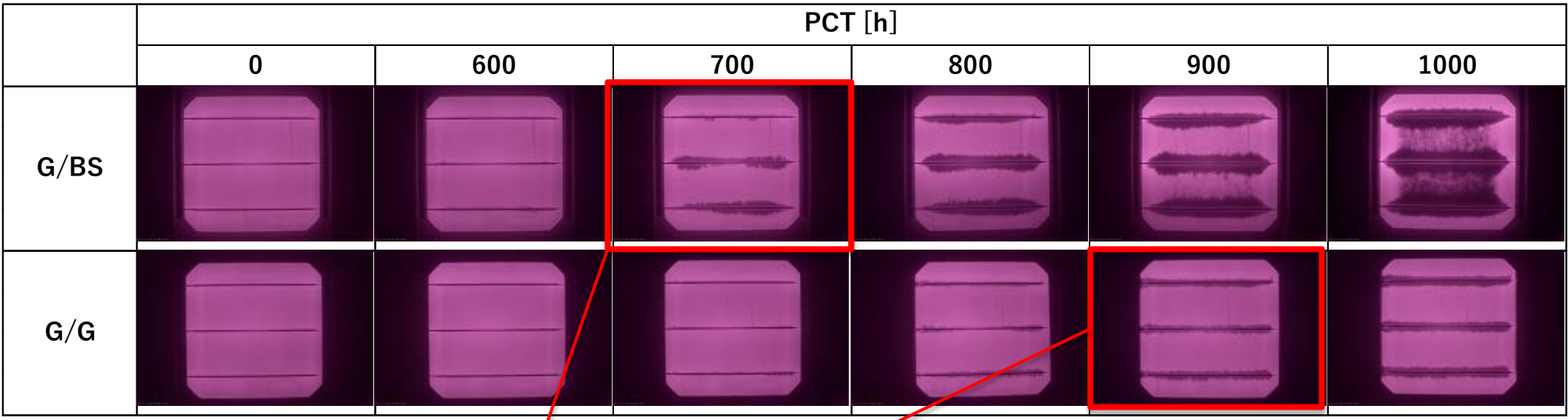
G/BS

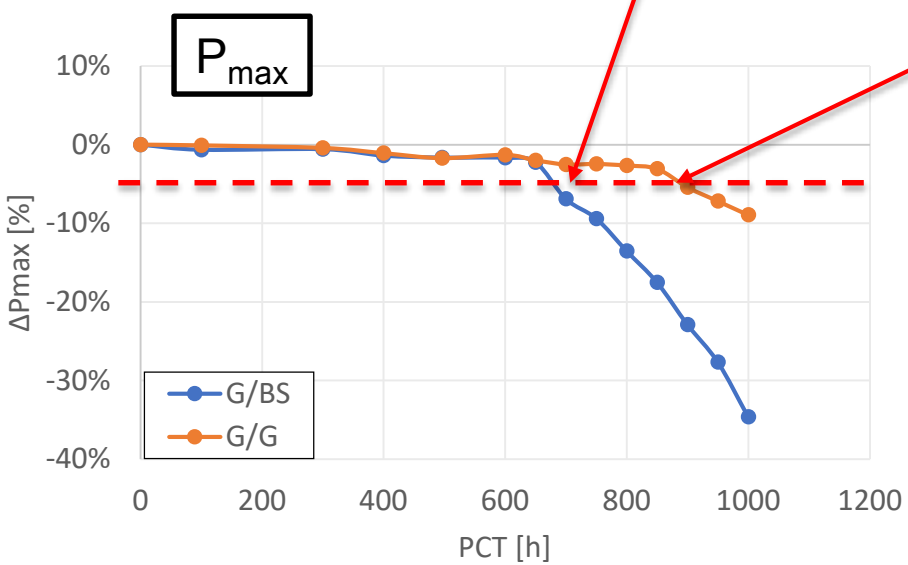


G/G

- No delamination

EL imaging & P_{max}



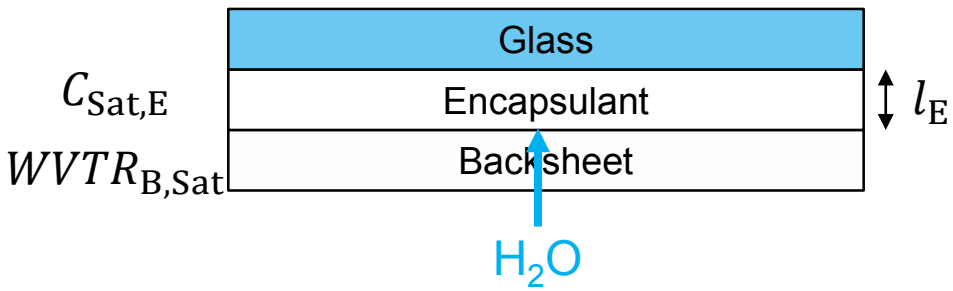


- Degradation along the interconnector occurred for both modules after 600 -700 h.
- The decrease in P_{max} of ~5% occurred after 650-700 h for the G/BS module and 900 h for the G/G module.
  The degradation for G/G module is ~30% slower than the G/BS module.
- The decrease in P_{max} is mainly due to the decrease in FF. (Decrease in I_{sc} is also seen when degradation progresses)

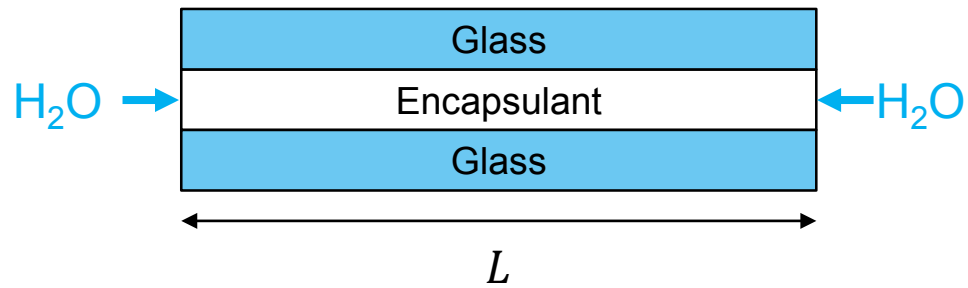
Moisture ingress for G/BS and G/G modules

Based on M. D. Kempe, "Modeling of rates of moisture ingress into photovoltaic modules", Solar Energy Materials & Solar Cells 90 (2006) 2720–2738.

Through BS



From 4 sides



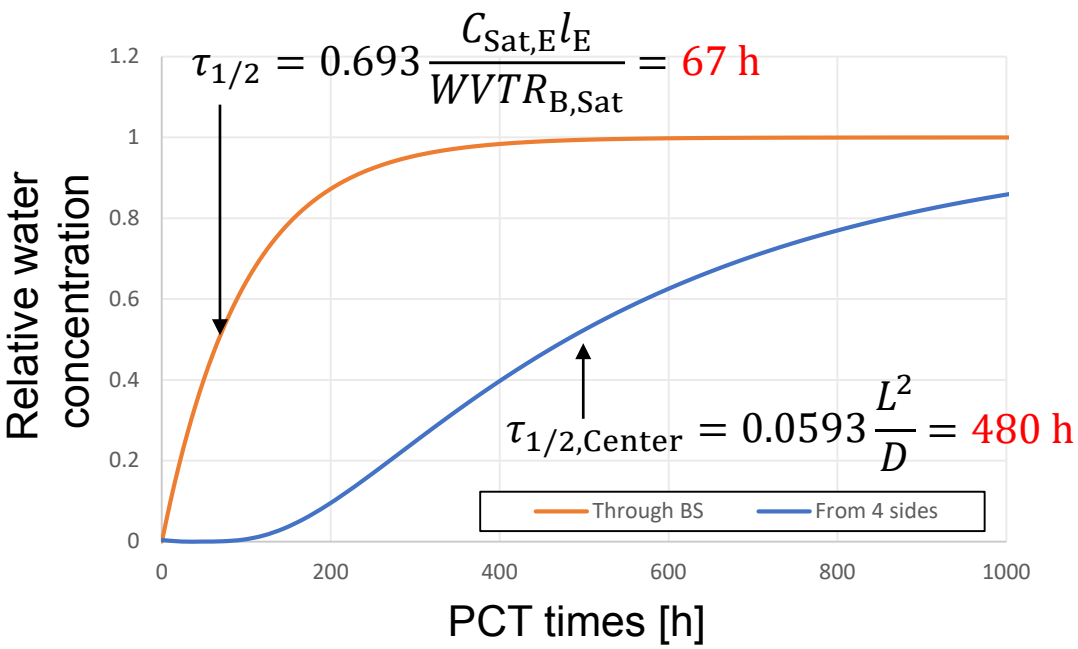
$C_{\mathrm{Sat,E}} = 0.009$ g/cm³ (EVA, 110°C)

$l_{\mathrm{E}} = 0.9$ mm

$WVTR_{\mathrm{B,Sat}} = 2.0$ g/m²/day

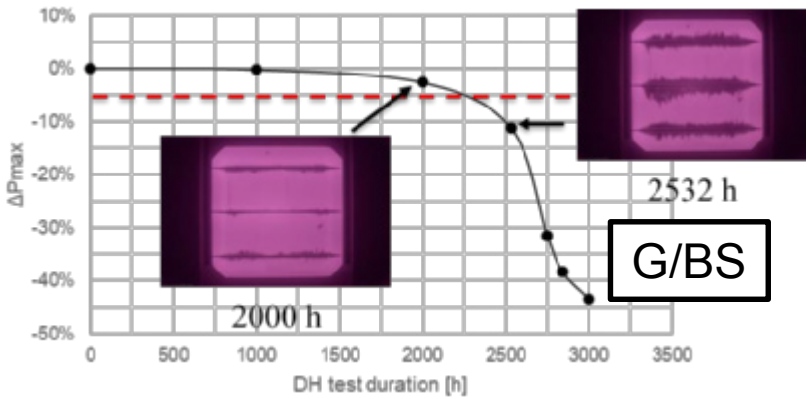
$L = 20$ cm

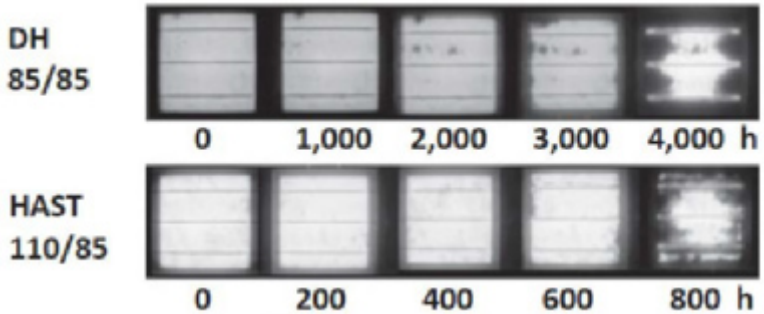
$D = 1.37 \times 10^{-5}$ cm²/s (EVA, 110°C)



- Moisture ingress into the G/G module is slower than the G/BS module and <u>is not saturated even after 1000 h.</u>
- The lower moisture ingress can suppress the degradation in G/G module in PCT.
- (But there is a mismatch between the times of moisture ingress and the start of degradation.)

Estimated times of decrease in P_{max} of ~5% due to damp-heat stress in field

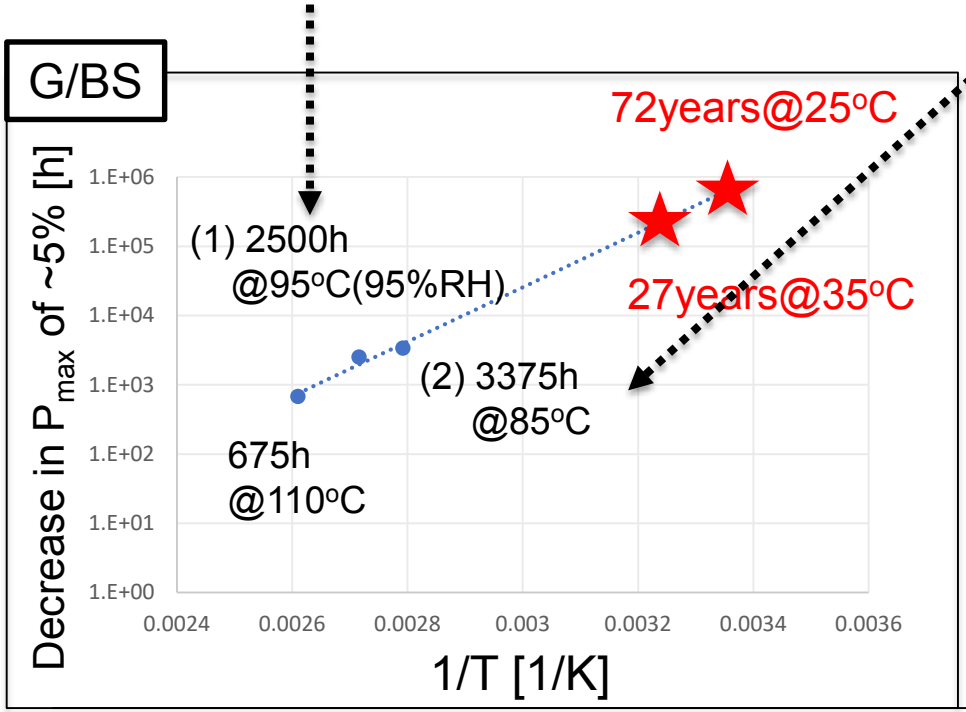




S. Suzuki et al., "Acceleration of degradation by highly accelerated stress test and air-included highly accelerated stress test in crystalline silicon photovoltaic modules", J. Jpn. Appl. Phys. 55 (2016) 022302.

(1) DH (95°C/95%RH) for G/BS showed that the decrease in P_{max} of ~5% occurred after 2000-2500 h for the G/BS module .

(2) PCT (HAST) at 110°C/85%RH has a nearly 5-fold acceleration to DH at 85°C/85%RH.



- If we estimate the times of decrease in P_{max} of ~5% due to damp-heat stress from limited data, **the G/BS module** is expected to have the times of 72 years at 25 °C and 27 years at 35 °C.
- Assuming that the times of **the G/G module** is 1.3 times that of the G/BS module, it is predicted to have the times of 93 years at 25 °C and 35 years at 35°C.

Conclusions

- We investigated the failure modes of G/G and G/BS mini-module using DML test and PCT.
- The G/G modules showed **excellent durability for mechanical and moisture stress** compered with the G/BS modules.

(Especially, despite using a thin glass with a thickness of 0.55 mm in the DML test)

	DML			PCT	
	Cycles when Pmax decreased by 5%		Failure modes	Times when Pmax decreased by 5%	Failure modes
G/BS	±4 kPa	3,000 cyc	**Separation of the solder joint** or **Fracture of the interconnector** + Cell crack	650-700 h ↓ ×1.3	**Degradation along the interconnector** + Corrosion of ribbon (+ Peeling off of BS)
	±3 kPa	4,000 cyc	**Separation of the solder joint** or **Fracture of the interconnector**		
	±2 kPa	12,000 cyc			
G/G	±4 kPa	None (up to 100,000 cyc)		900 h	**Degradation along the interconnector** + Corrosion of ribbon

Future Works

- To predict the failure of a full size module, based on this DML results, it is necessary to calculate by nonlinear analysis for the stress distribution in the modules.
- Also the result can be affected by the module temperature (the elasticity of the encapsulant) and the fixing method of the modules.

- To predict the lifetime due to damp-heat stress in PCT test, the additional tests with different test levels are required.

- And the effects of other stress such as temperature cycle, …

Acknowledgements

This work has been supported New Energy and Industrial Technology Development Organization (NEDO).

The Risk/Reward of BiFacial PV System Design

Utility-scale solar development in the modern age

NREL PV Reliability Workshop, 02/28/2019

AGENDA: OVERVIEW

A A rapidly evolving bifacial PV market

B Bifacial performance models and parametric sensitivities

C Project economics and optimization of system design

D IEC efforts in standardization of bifacial performance monitoring & performance testing

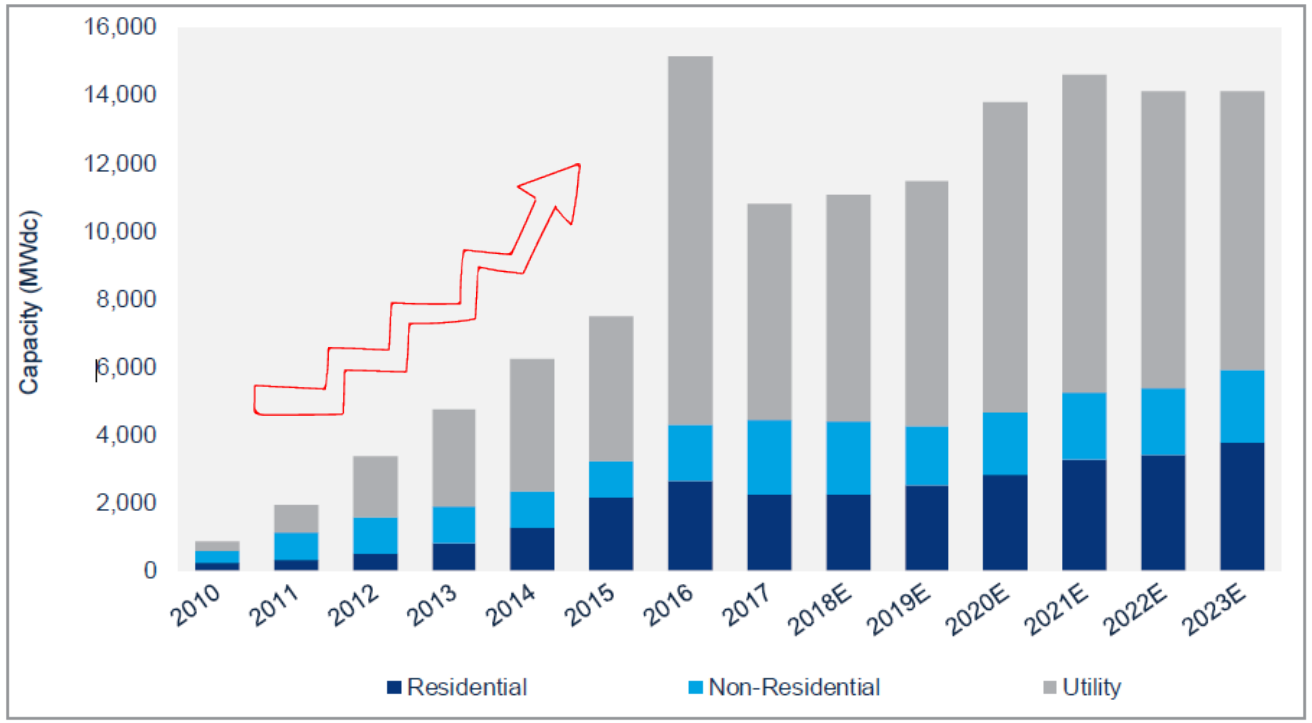
A RAPIDLY EVOLVING BIFACIAL PV MARKET

Near-term market conditions in the USA

The PV Market in the United States

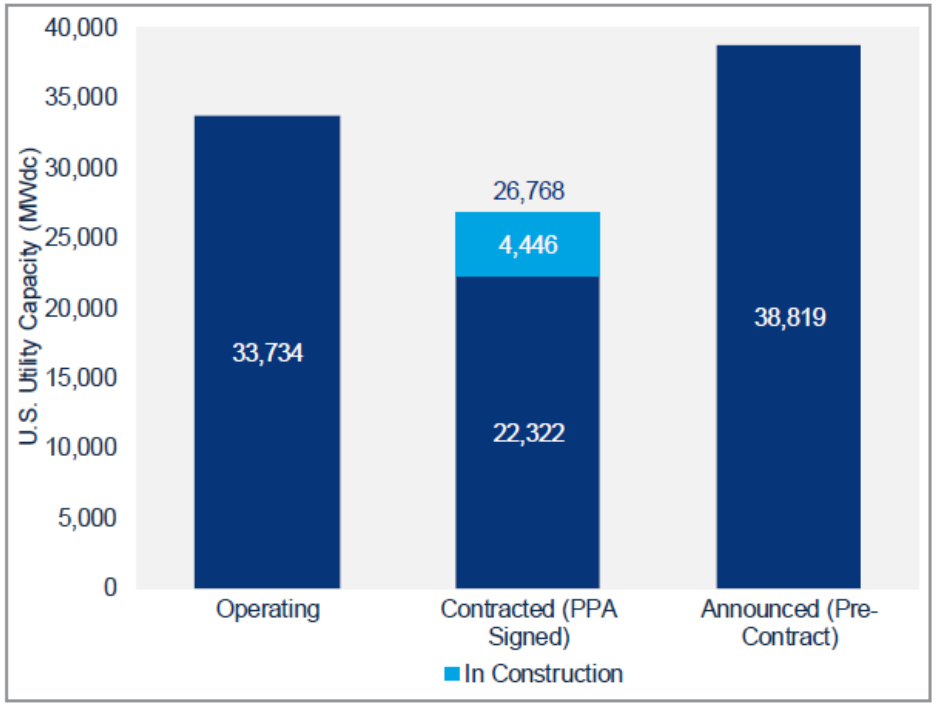
Utility vs. residential

Figure 8.4 U.S. PV installation forecast, 2010-2023E



Source: Wood Mackenzie Power & Renewables

Figure 5.1 U.S. utility PV pipeline



Source: Wood Mackenzie Power & Renewables

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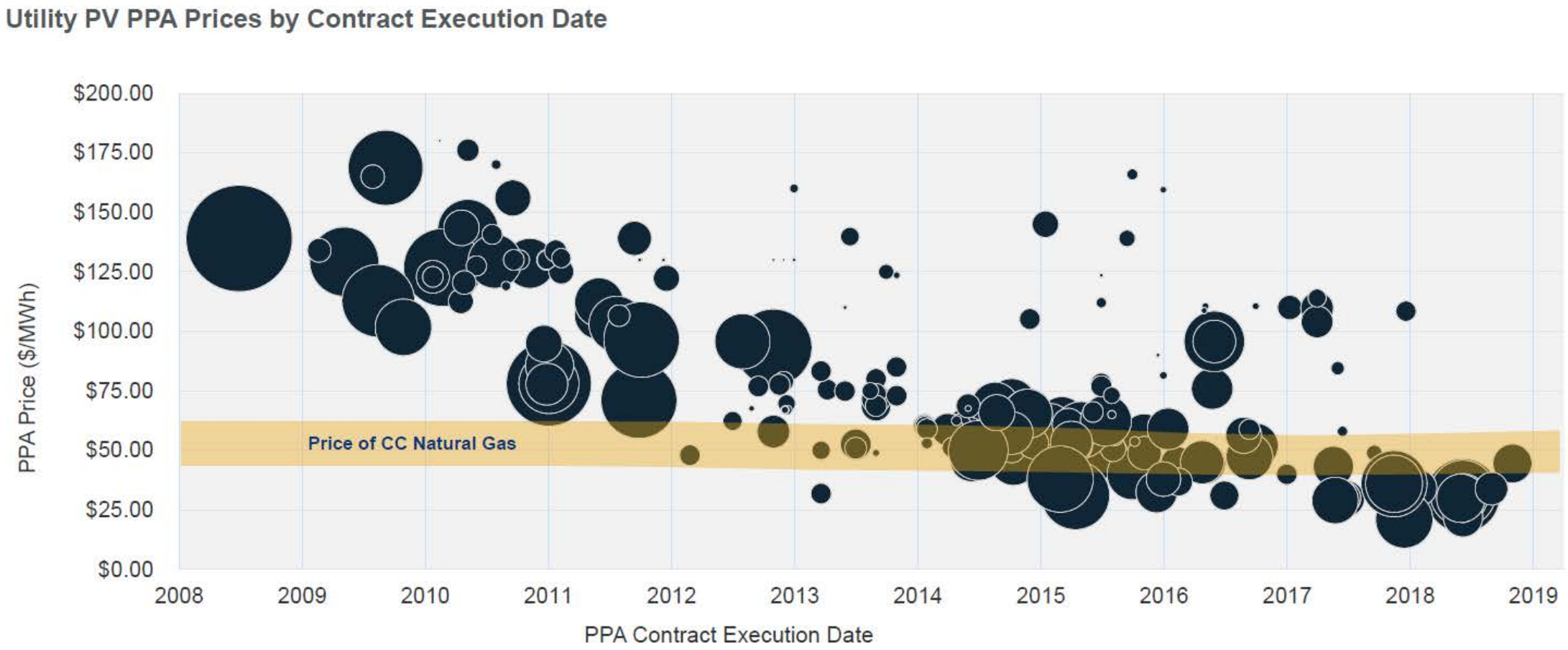
Contracted PV Energy price trends

The evolution of US-based PPA prices



Source: Wood Mackenzie Power and Renewables

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From Zero to GigaWatt

The BiFacial PV market in the not so distant future

Solar Edition @solar_edition · Jan 18
Nextracker rolls bifacial solar dice for 750 megawatts.

According to Clean Technica news, NEXTracker is currently involved in close to 750 megawatts of new bifacial solar tracker projects, following recent bank approval of the first utility-scale projec... bit.ly/2RwUGHY

Nextracker Rolls Bifacial
For 750 Megawat
Fewer Ground Cover & Much More En

Solar Edition @solar_edition · Jan 21
Grid connection of N-bifacial solar power plant done.

According to Saudi Gazette news, Cooperation Unisun Energy announced that the 11.75MW Zonnepark Rilland project, which uses N-type bifacial modules from Jolywood (Taizhou) Solar Technology Co. Ltd. h... bit.ly/2Hnxvet

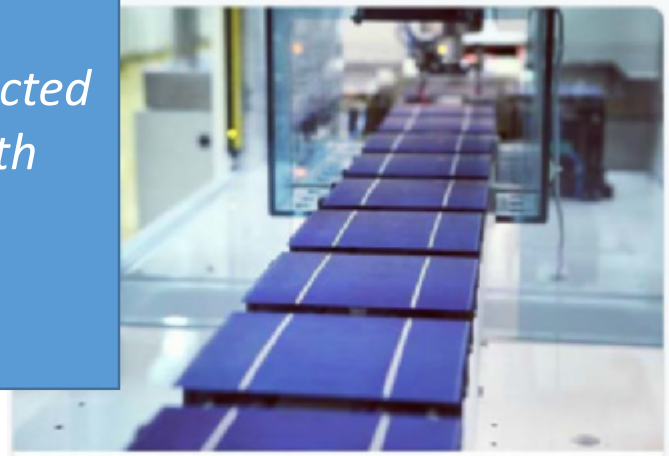
Jolywood to supply N-type bifacial cells to 100 MW of Aussie projects

March 22 (Renewables Now) - Jolywood Taizhou Solar Technology Co Ltd has teamed up with Australian company Golden Invest Pty Ltd to jointly build 100 MW of solar parks in Australia using N-type bifacial photovoltaic (PV) cells.

Solar park. Author: Chris Baird. License: Creative Commons, Attribution 2.0 Generic.

The companies have signed a partnership agreement that calls for Golden Invest to develop the projects, while the equipment will be supplied by Jolywood Taizhou Solar, the latter said on Wednesday. The Chinese company pointed out that N-type bifacial solar cells have higher efficiency when working under weak light conditions and are cheaper as compared to other PV options.

#JASolar announced that it will supply all bifacial mono PERC double glass modules for SolarGrid's 3MW PV project in #Brazil. This stands as Brazil's first bifacial double glass solar project. In addition, JA Solar's supply represents the entry of its bi... bit.ly/2EQuG3H



JA Solar provides modules for Brazil's first bifacial mono PERC double-glass project

"NREL estimates that the market share for bifacial tracker systems will expand from a near-zero base today to a projected 10% market share in 2019, and 30% by 2025, compared with monofacial panels."

Michael Woodhouse, economic analyst at NREL

In May of 2018, Invenergy and Georgia Power announced a power purchase agreement for Georgia Power to buy all the energy, environmental attributes and electrical products from Southern Oak Solar through 2049. This agreement is part of the utility's Renewable Energy Development Initiative (REDI), which is designed to advance the growth of renewable energy goals across the state of Georgia.

"The completion of construction financing for Southern Oak Solar represents far more than a financial milestone," said Invenergy's President and Chief Operating Officer Jim Murphy. "Southern Oak Solar is a significant transaction with leading utility Georgia Power, and it is also our largest solar project to date, firmly establishing Invenergy as a leading developer of utility scale solar projects."

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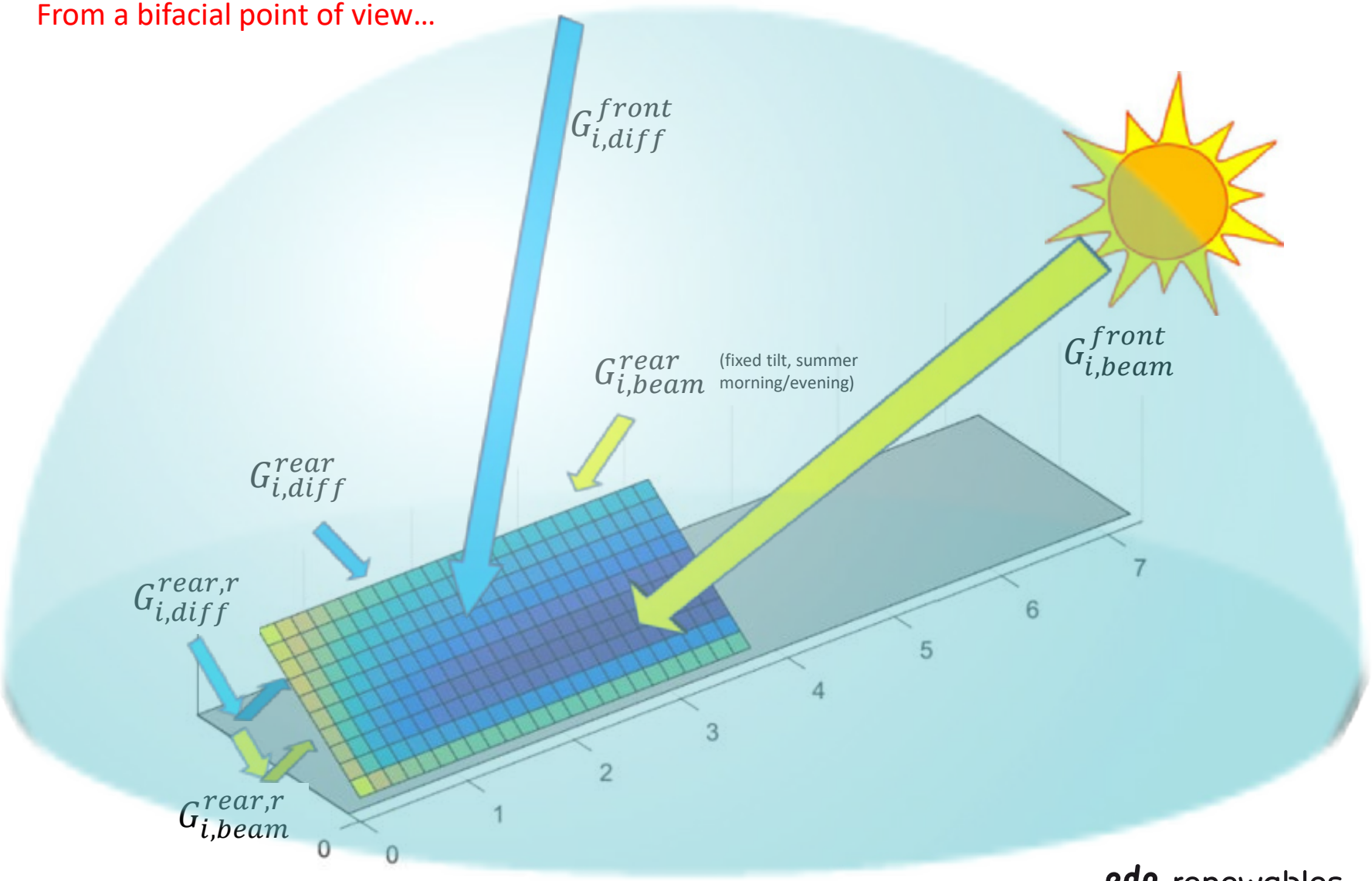
BIFACIAL PERFORMANCE MODELS AND PARAMETRIC SENSITIVITIES

AN OVERVIEW OF THE SOLAR RESOURCE

From a bifacial point of view…



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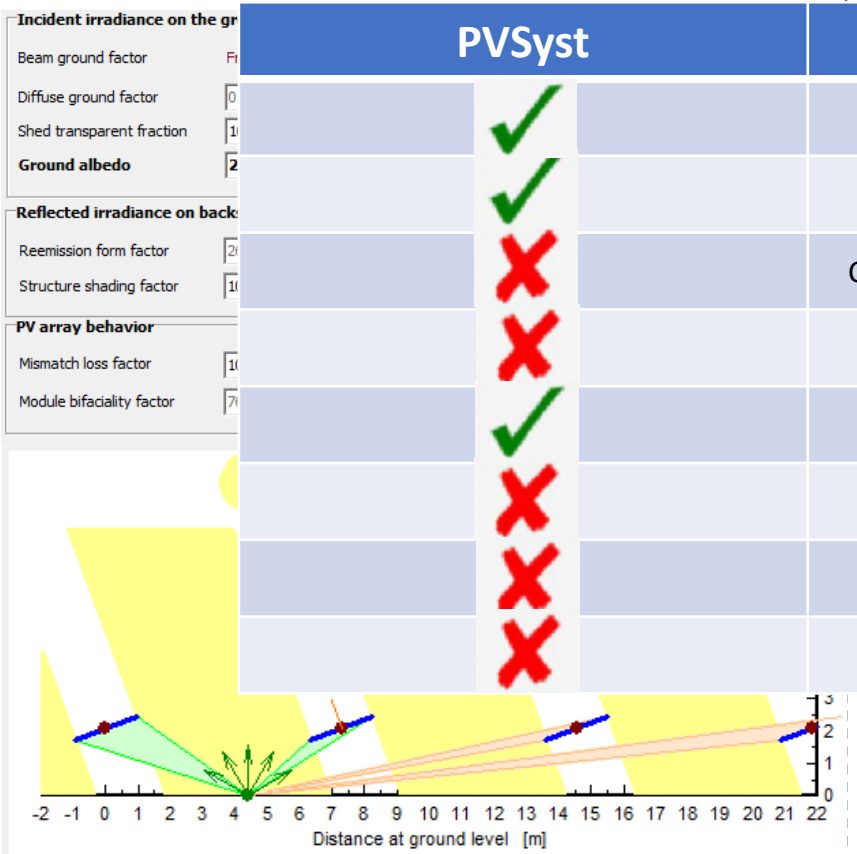
Commercially available Bifacial PV simulation software

Modeling assumptions in currently released versions

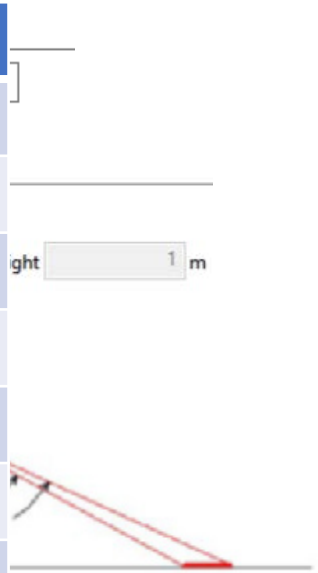
PVSYST PHOTOVOLTAIC SOFTWARE

NREL NATIONAL RENEWABLE ENERGY LABORATORY

System Advisor Model 2018



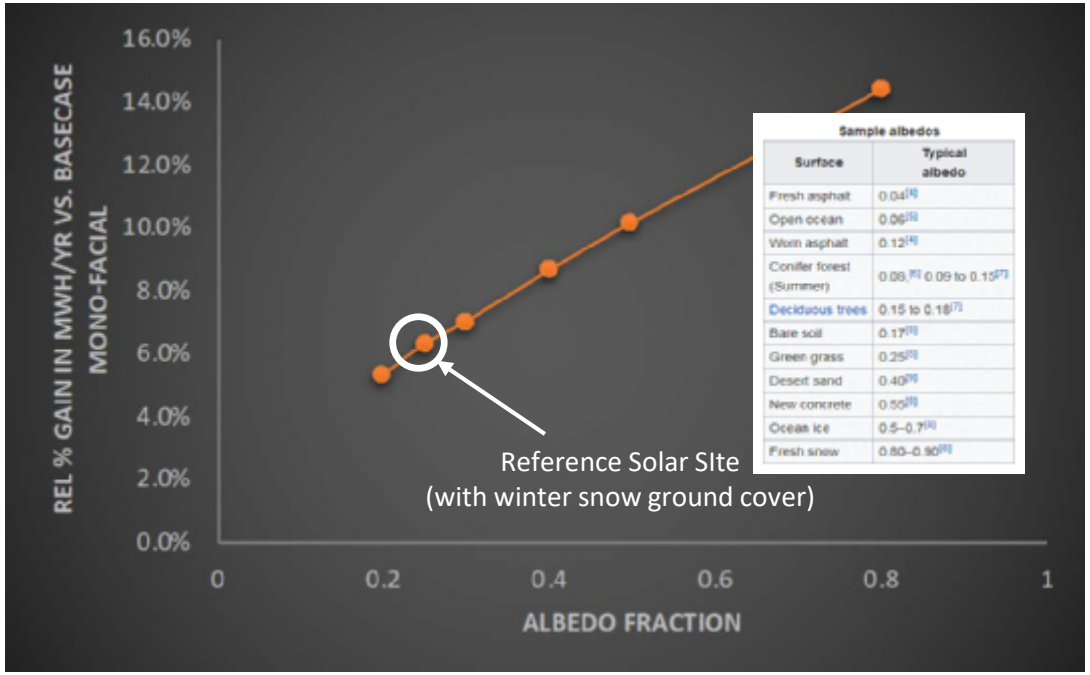
PVSyst	Features	NREL VF
✓	2D simulation of sheds	✓
✓	Monthly albedo values	✓
✗	Circumsolar anisotropy for back side diffuse	✗
✗	IAM for backside reflections	✗
✓	Diffuse shading w/trackers	✗
✗	Irradiance non-uniformity	✗
✗	Spectral-corrected backside irradiance	✗
✗	Specular reflections	✗



- Project shadows into row-to-row dimension
- Divide row-to-row into n (100) segments
- Identify whether each segment is shaded or not

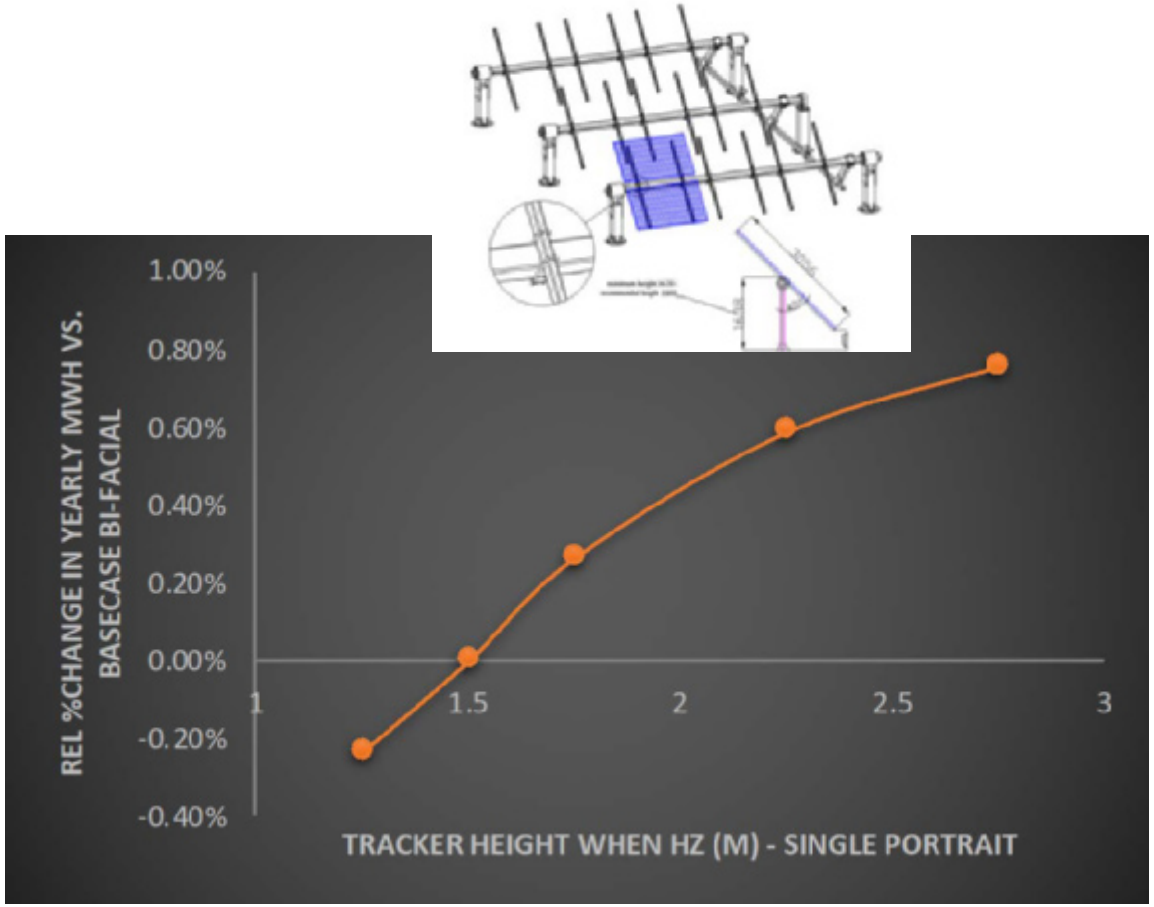
Parametric sensitivities

Albedo, racking height (tracker)



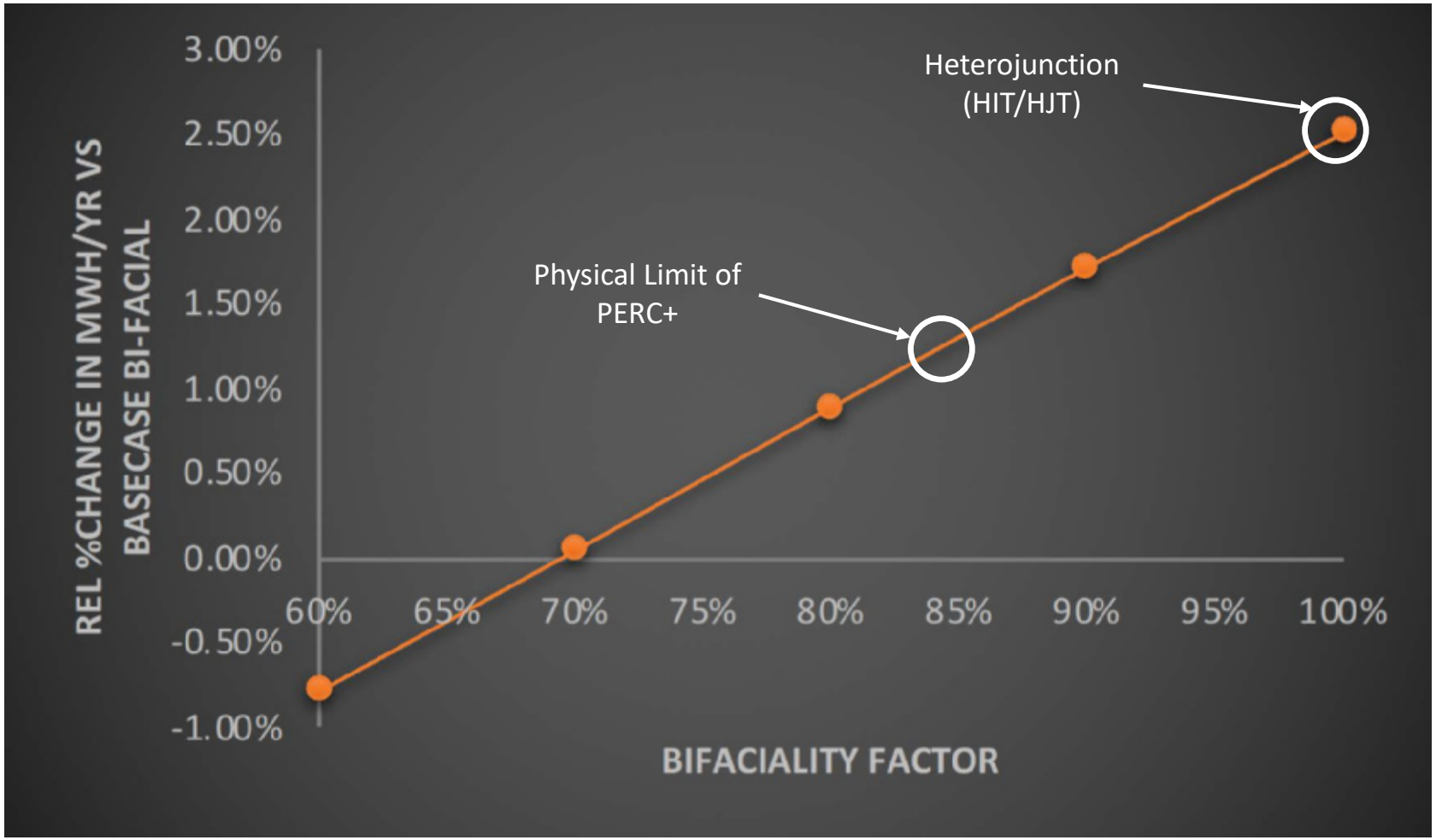
Sample albedos

Surface	Typical albedo
Fresh asphalt	0.04[4]
Open ocean	0.06[5]
Worn asphalt	0.12[4]
Conifer forest (Summer)	0.08,[6] 0.09 to 0.15[7]
Deciduous trees	0.15 to 0.18[7]
Bare soil	0.17[8]
Green grass	0.25[8]
Desert sand	0.40[9]
New concrete	0.55[8]
Ocean ice	0.5–0.7[10]
Fresh snow	0.80–0.90[8]



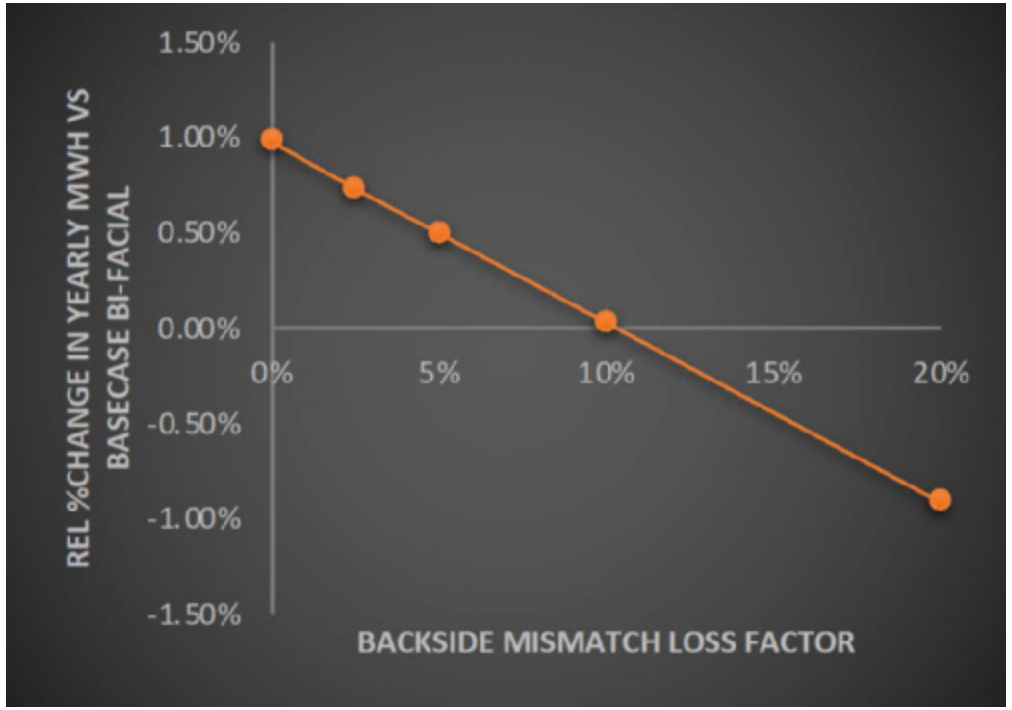
Parametric sensitivities

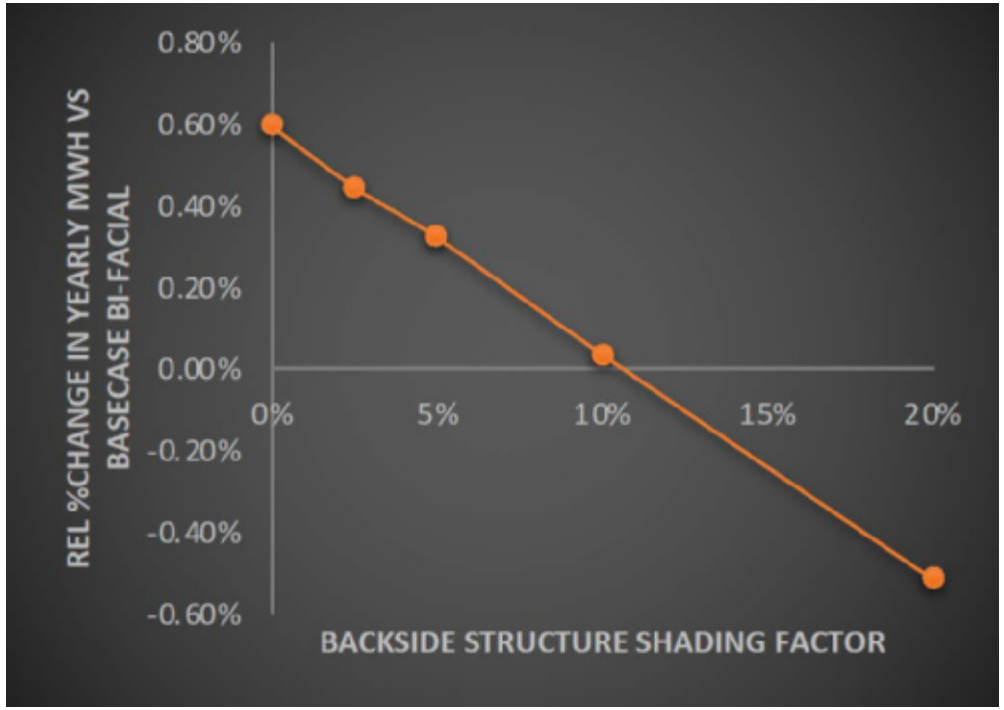
Bifaciality Factor



Parametric sensitivities

Structure shading, backside mismatch loss



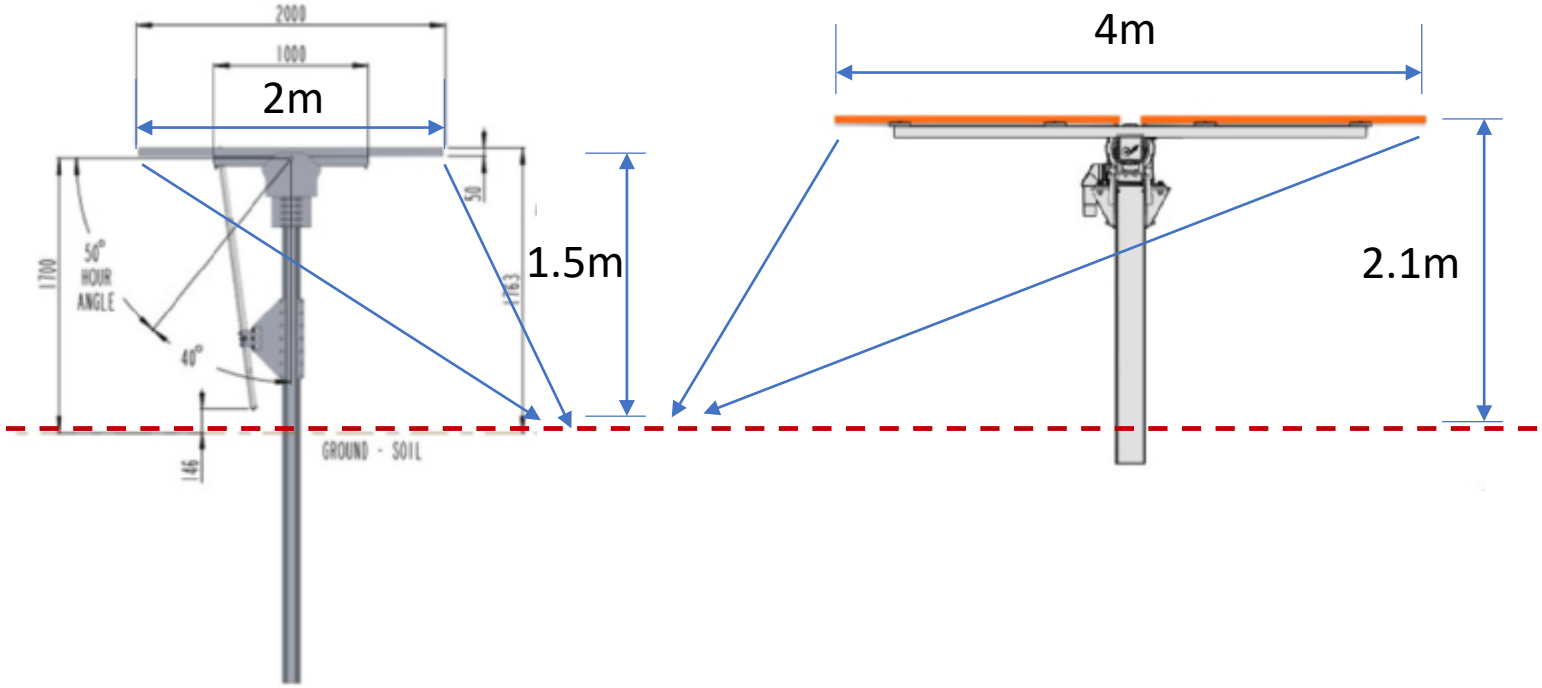


- Initial Estimates (not based on field data):
  1. 2P Tracker = 5% Mismatch/2.5% Structure Shading
  2. 1P Tracker = 10% Mismatch/10% Structure Shading

- TOTAL IMPACT OF SHADING/MISMATCH ~1.5% on MWh/yr per 10% increase

Racking type (Tracker)

1P vs. 2P (single portrait/dual portrait)



Single-Portrait

Dual Portrait

- Lower Aspect Ratio of Module Width to Tracker height produces better “ViewFactor”
- Single Portrait vs. Dual Portrait = 2% Gain in performance (fixing all other variables)

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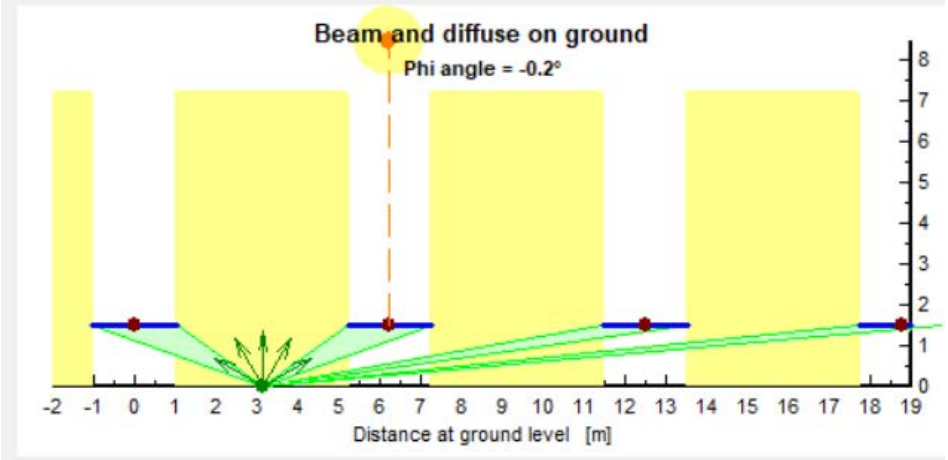
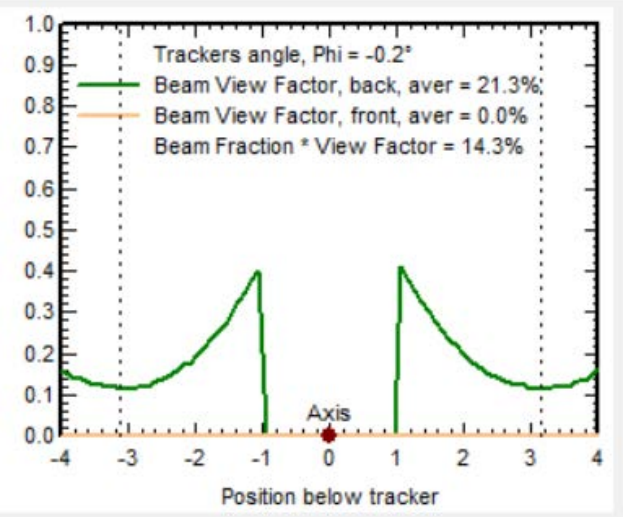
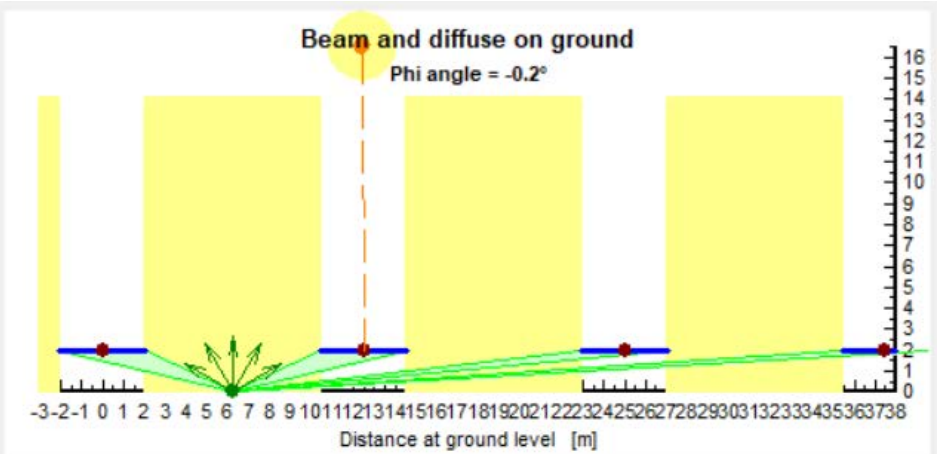
Racking type (Tracker) – Horizontal (noon)

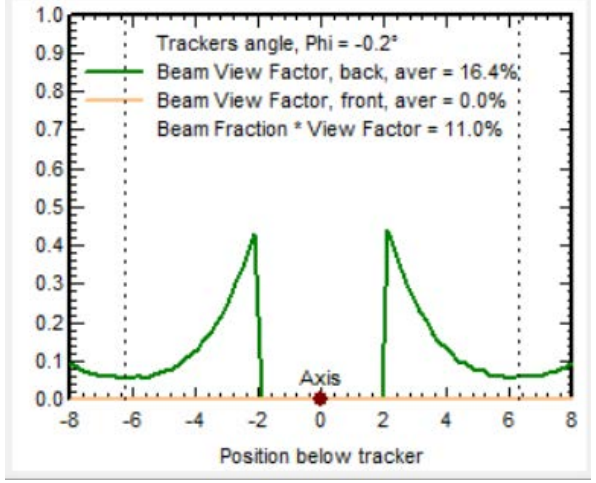
1P vs. 2P (single portrait/dual portrait)





Single-Portrait

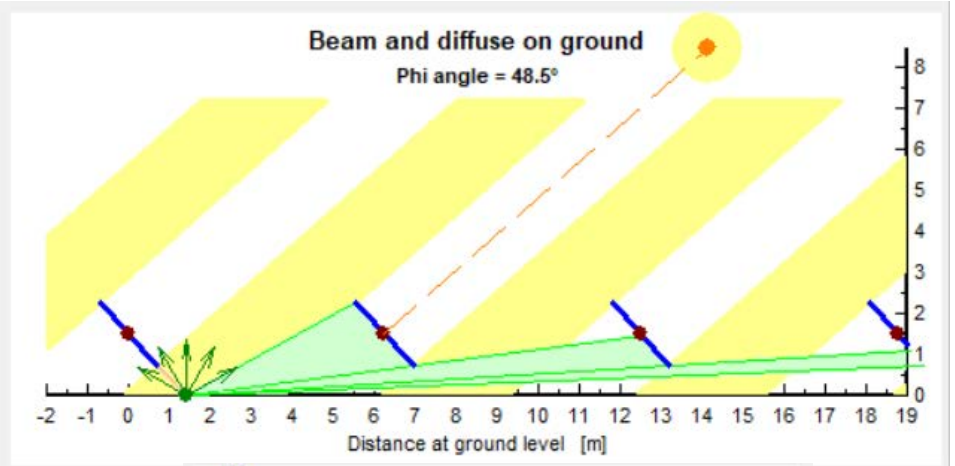


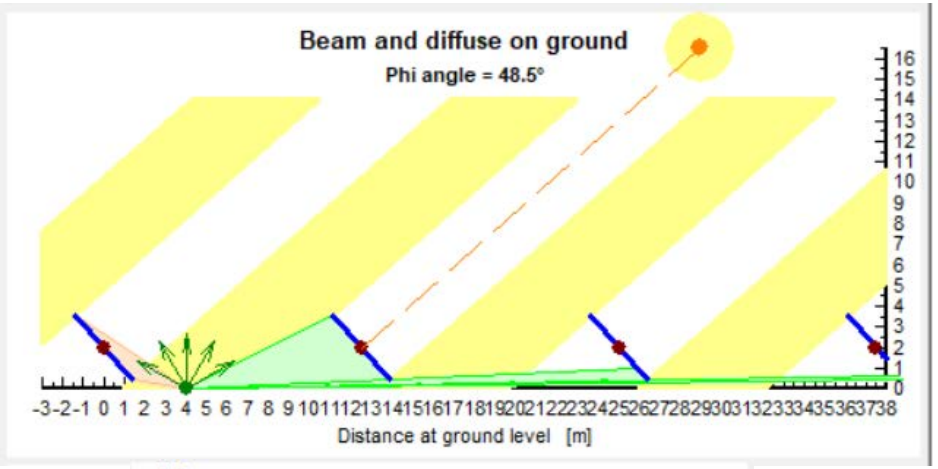


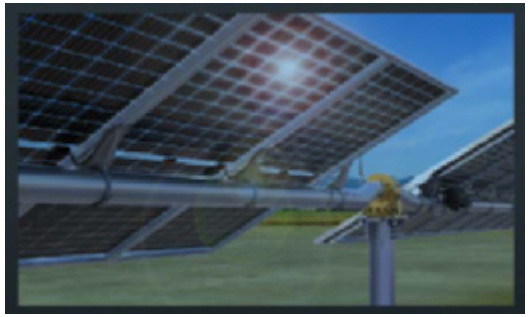
Dual Portrait

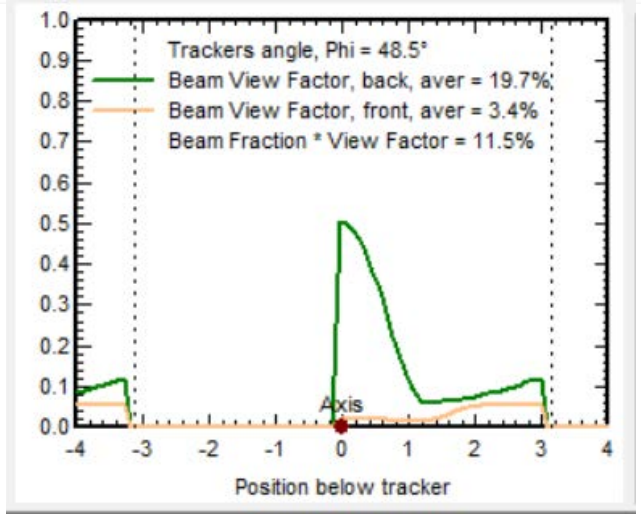
Racking type (Tracker) – Angled, morning/evening

1P vs. 2P (single portrait/dual portrait)

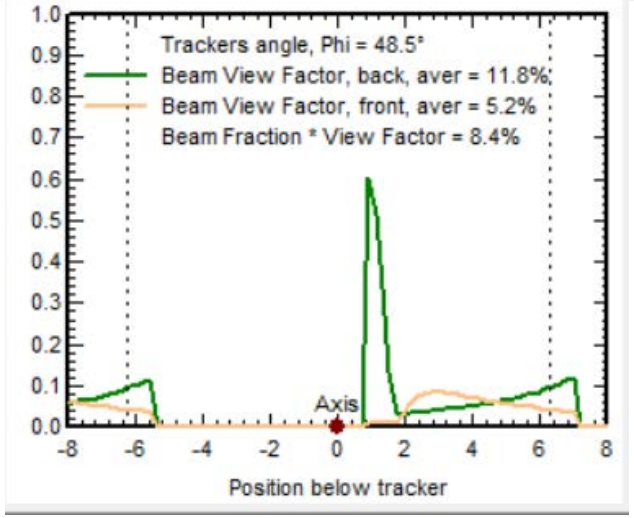








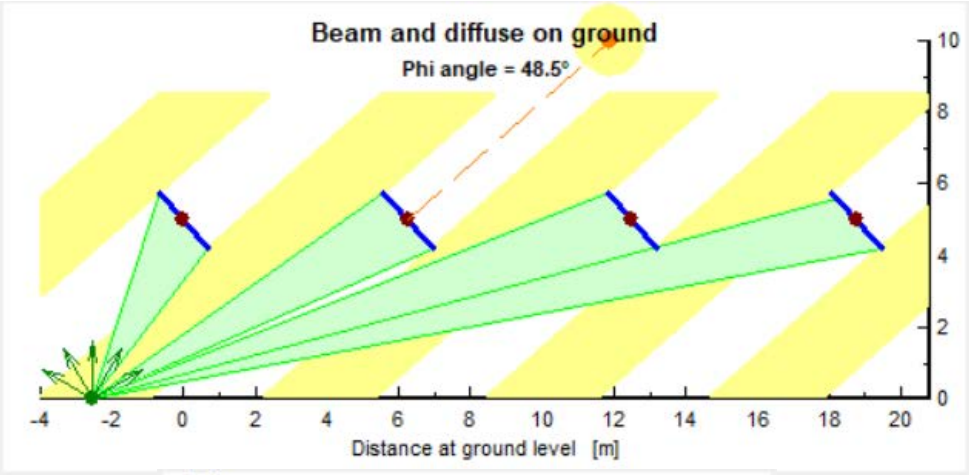
Single-Portrait

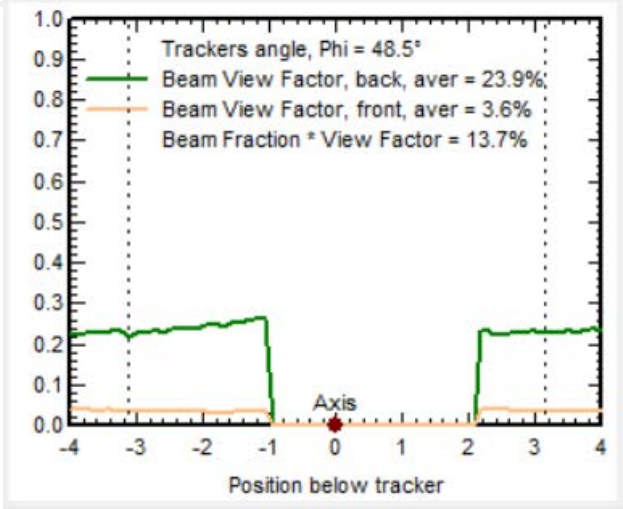


Dual Portrait

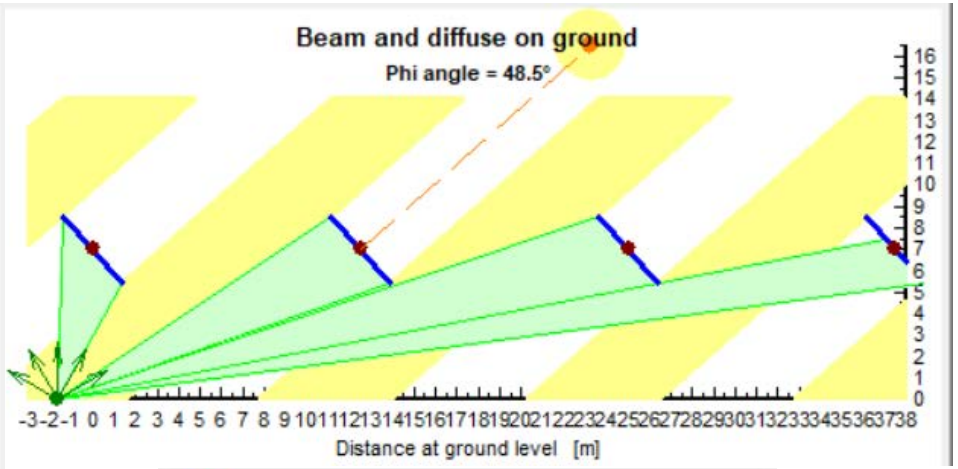
Racking type (Tracker) – Unconstrained Height

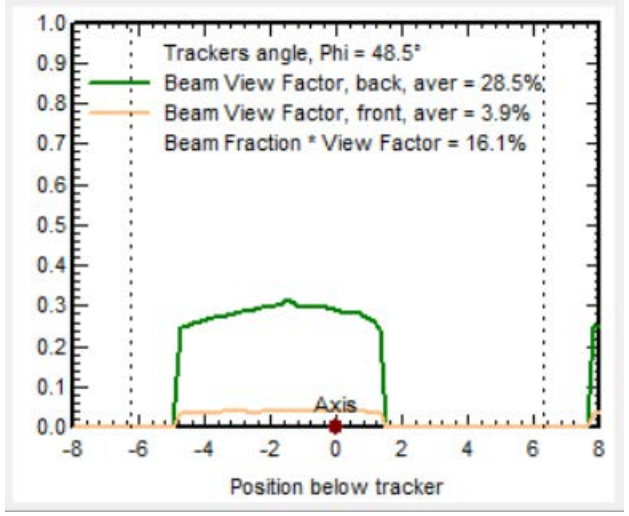
1P vs. 2P (single portrait/dual portrait)





Single-Portrait





Dual Portrait

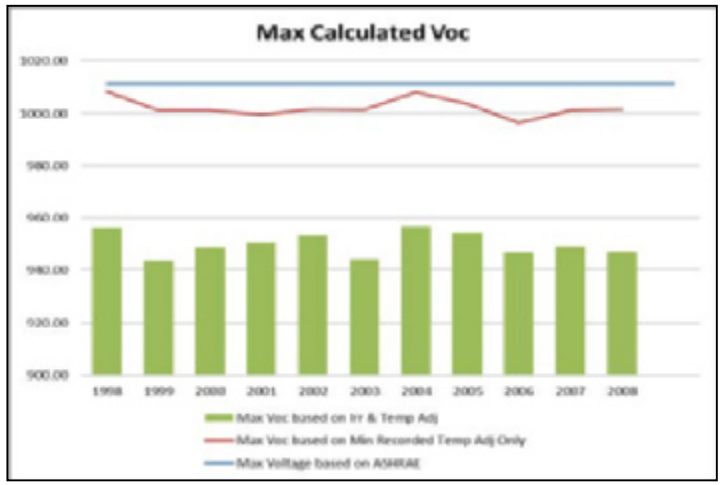
PROJECT ECONOMICS AND OPTIMIZATION OF SYSTEM DESIGN

Bifacial – The disruptive technology of our time

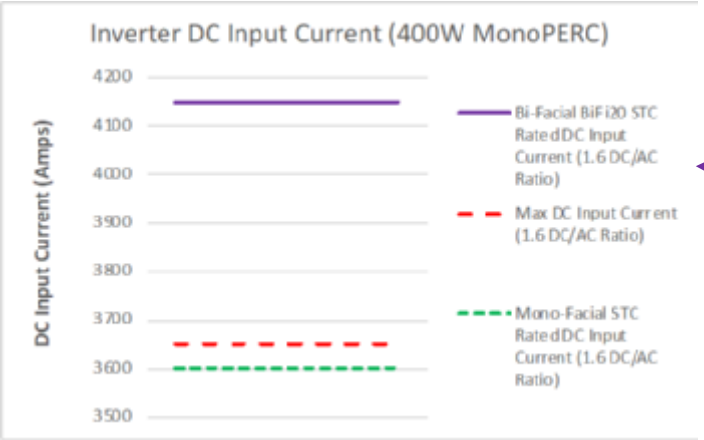
Bi-Facial System Design Considerations

String Sizing Impacts

- Max system voltage = 1500V (UL North American market)
- Modules are connected in series:
  - Max system voltage = Voc*#modules in series
- Voc is a function of temperature and irradiance
- Max Voc occurs in the mornings when temperature is lowest
- **BIFACIAL modules = HIGHER EFFICIENCY = HIGHER VOC = LESS MODULES PER STRING**



Inverter Impacts



Currently, no standards exist to define how to rate DC current nameplate for BiFacial PV modules under standard test conditions (STC). Today's inverters cannot yet handle these types of DC currents at BiFi20 (or even BiFi10)

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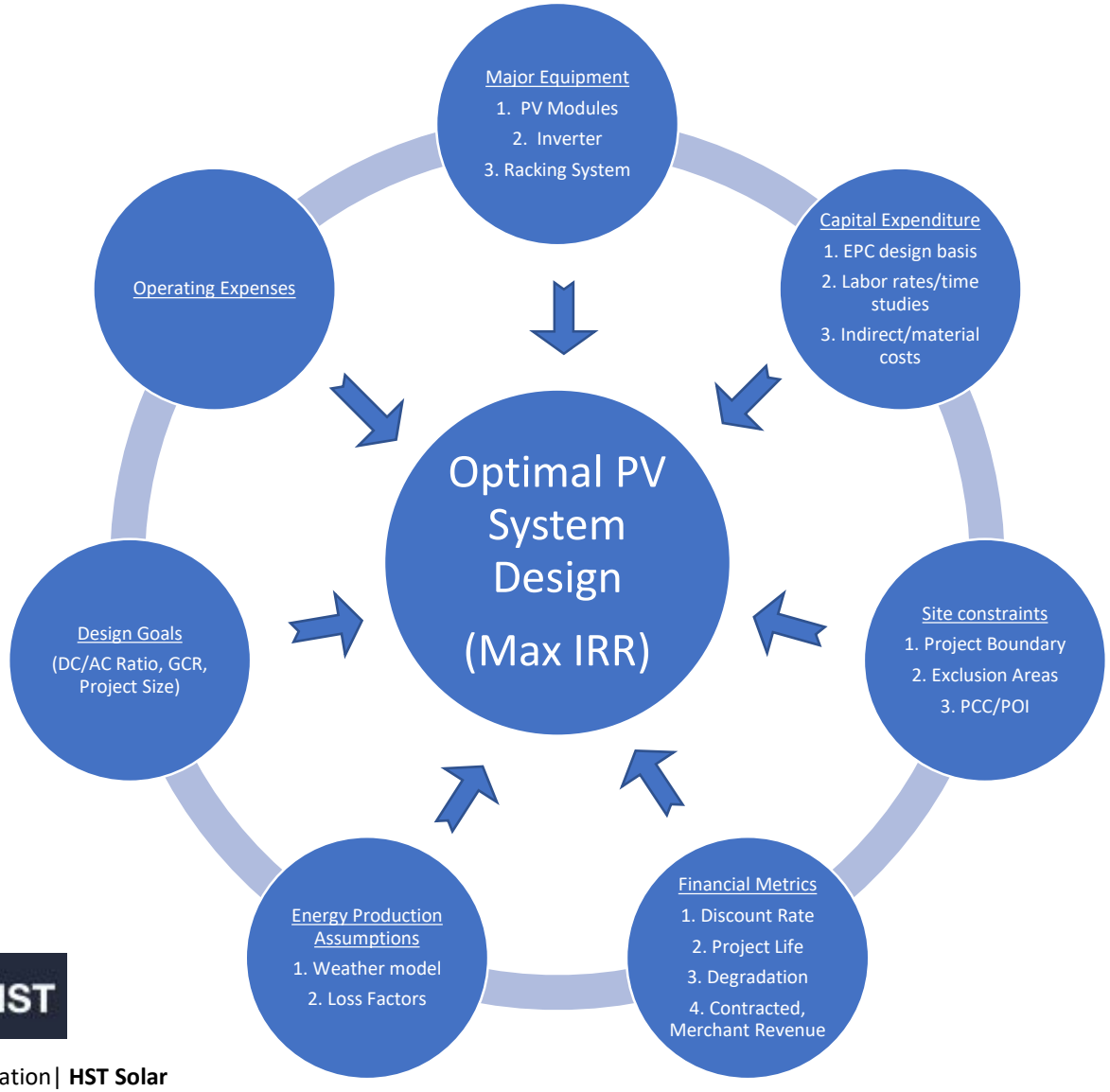
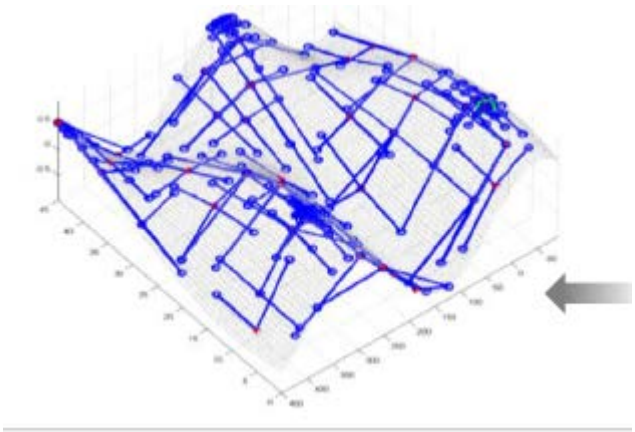
PV Plant Optimization Software

Multivariable optimization of design based on financial output



NREL System Advisor Model (SAM) inside

- ❑ Potential for 1000's of combinations
- ❑ All possible designs must be constrained by project boundaries & various exclusion areas
- ❑ Manual approach to design optimization is inherently limited…



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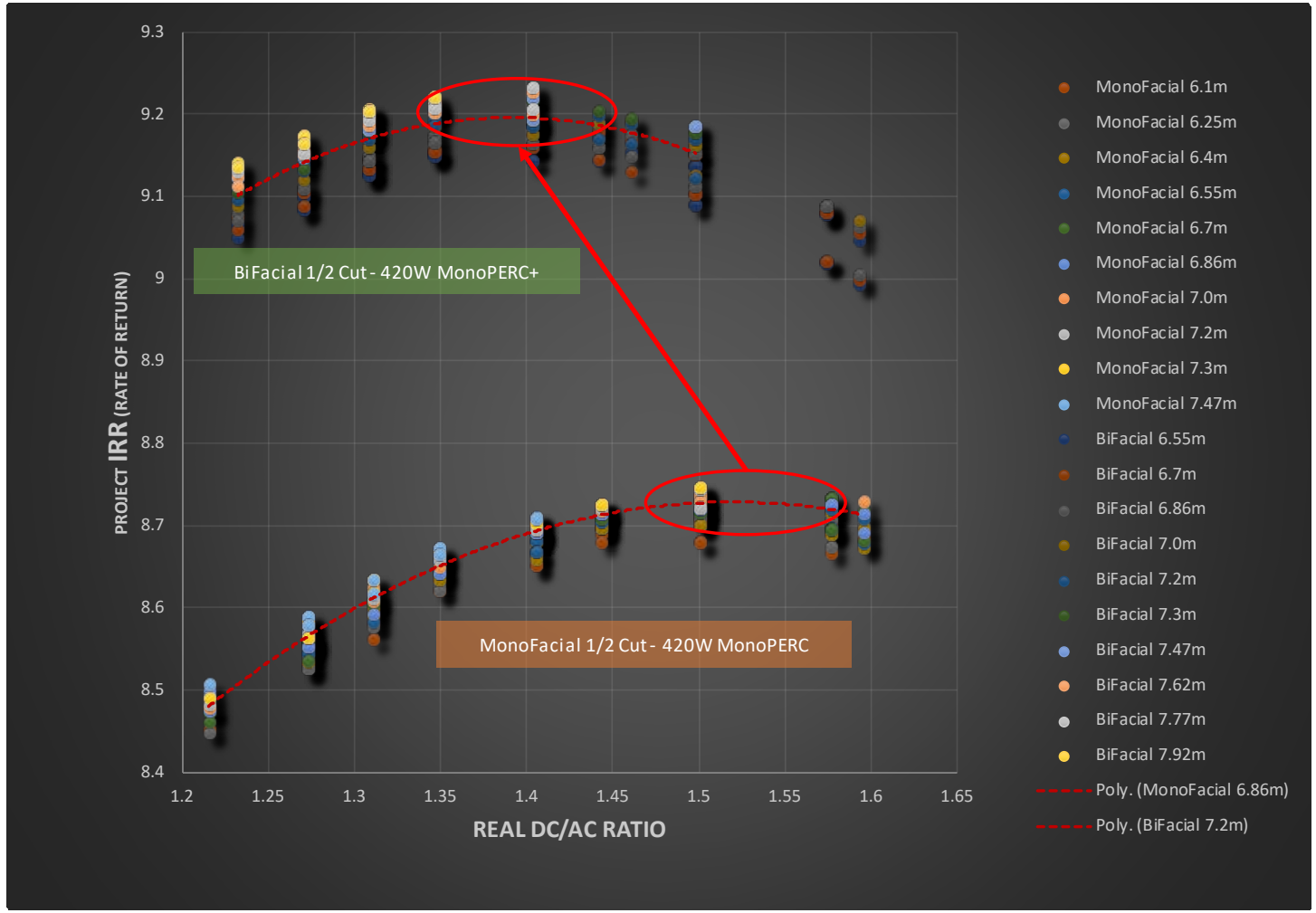
BIFACIAL VS. MONOFACIAL SYSTEM DESIGN OPTIMIZATIONS

Project site in Georgia (higher DHI/GHI)



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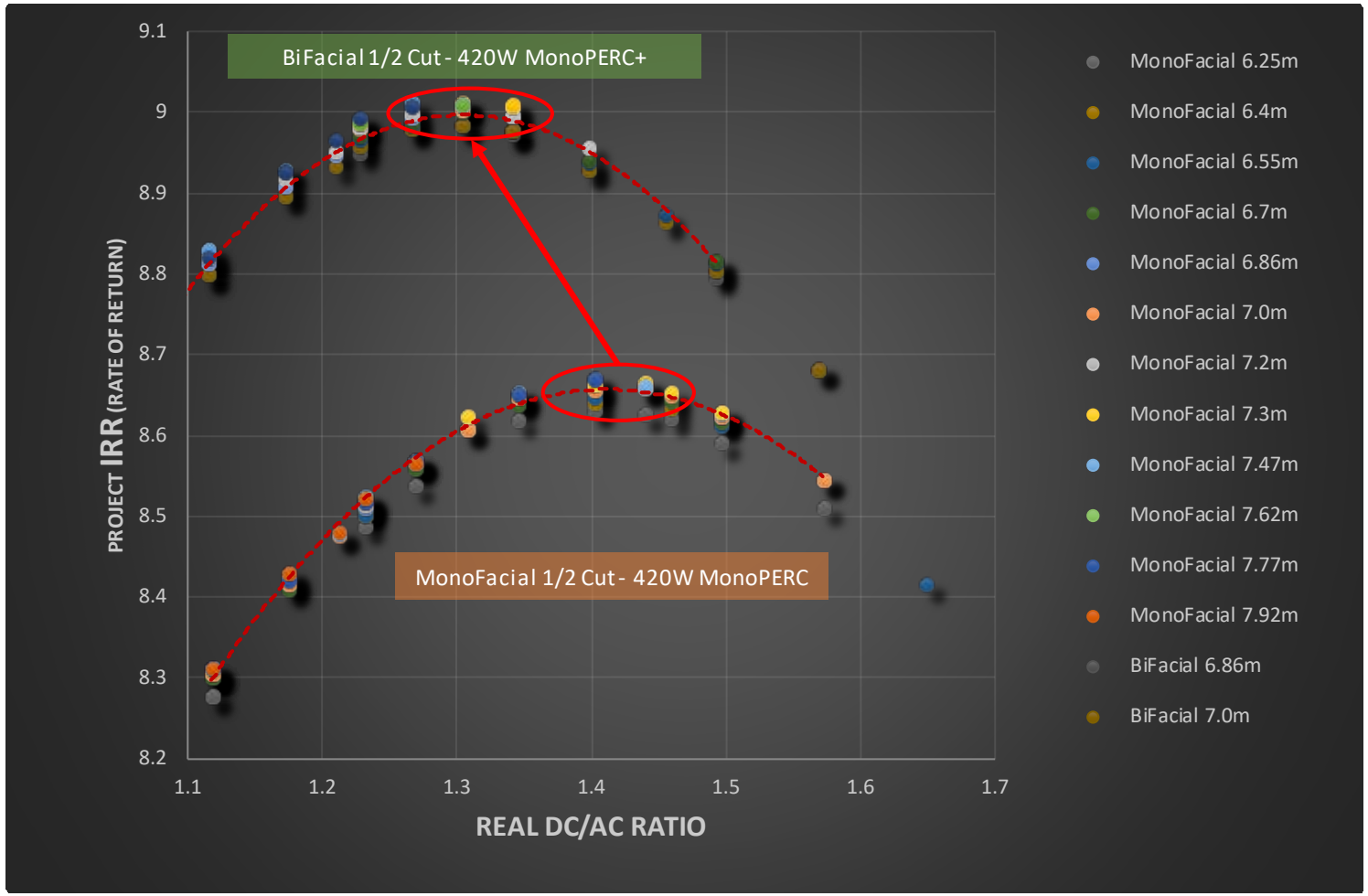
BIFACIAL VS. MONOFACIAL SYSTEM DESIGN OPTIMIZATIONS

Project site in California (lower DHI/GHI)



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Modeled Bifacial gains in various parts of the United States

All horizontal single-axis tracking systems (relative gains, same GCR+DC/AC ratio)

Indiana

BiFacial Gain = **6.3%**

Bifacial yield
(1,529 kWh/kWp)

S. California

BiFacial Gain = **3.2%**

Bifacial yield
(2,078 kWh/kWp)

Georgia

BiFacial Gain = **5.2%**

Bifacial yield
(1,808 kWh/kWp)

Alabama

BiFacial Gain = **2.6%**

Bifacial yield
(1,712 kWh/kWp)

Colorado

BiFacial Gain = **4.8%**

Bifacial yield
(1,968 kWh/kWp)

Wisconsin

BiFacial Gain = **6.0%**

Bifacial yield
(1,448 kWh/kWp)

Washington

BiFacial Gain = **6.3%**

Bifacial yield
(1,647 kWh/kWp)

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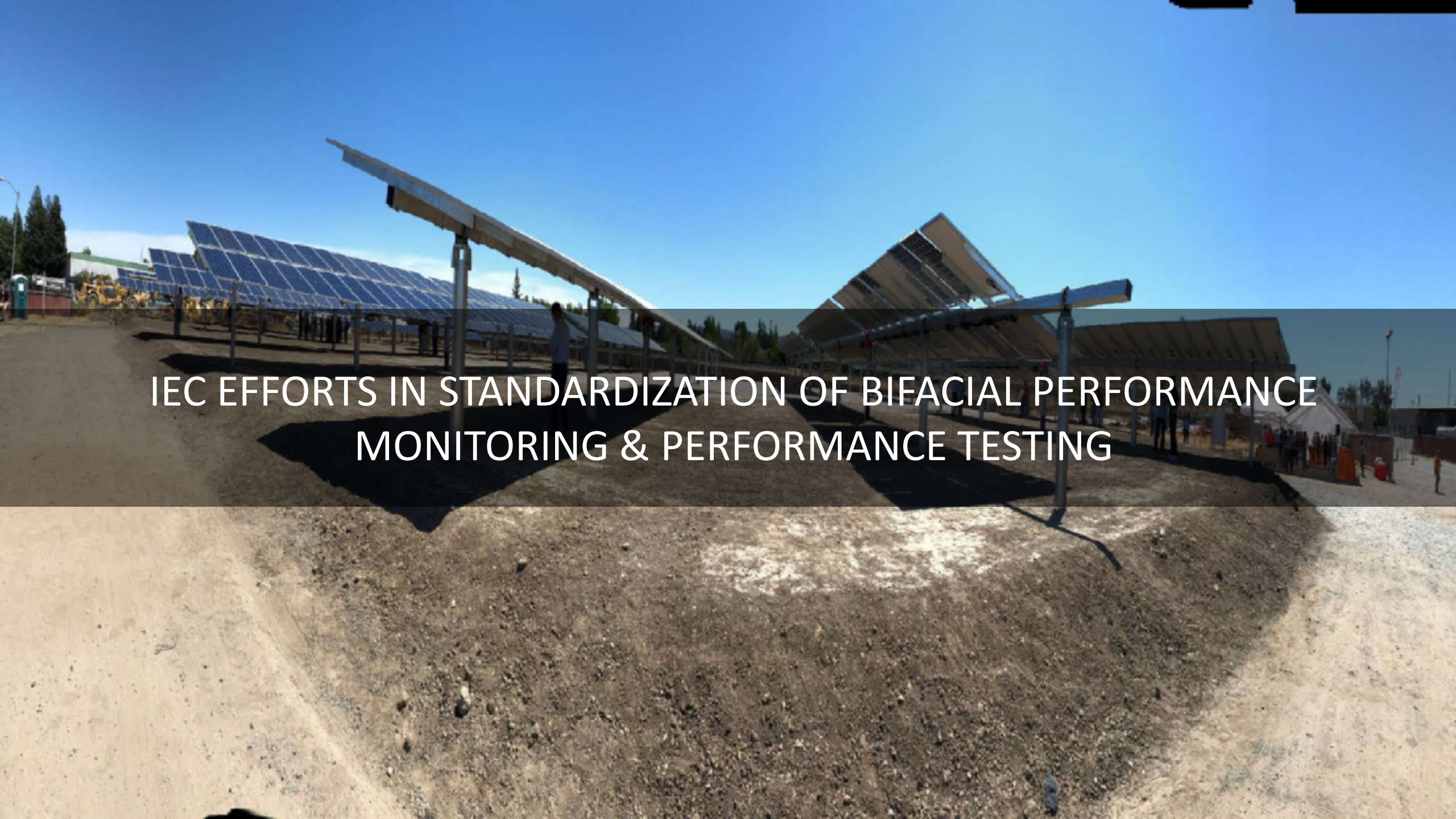
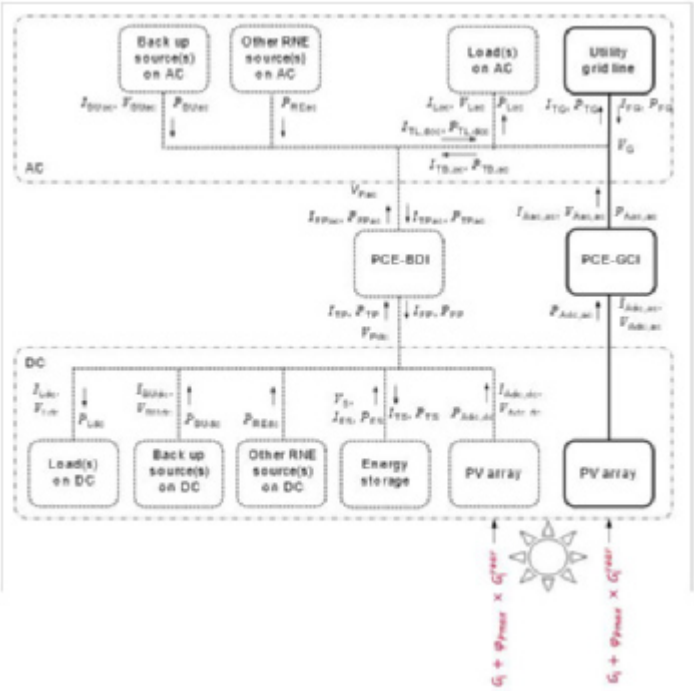


IEC EFFORTS IN STANDARDIZATION OF BIFACIAL PERFORMANCE MONITORING & PERFORMANCE TESTING

Status of efforts to standardize bifacial performance

Working Groups 3/6: IEC Technical Committee 82



A BiFacial performance and component ratings team formed following TC82 Plenary Meeting in Busan, S. Korea (Oct. 2019)

B Initial draft edits to IEC 61724-1, -2, and -3 sent to project team and IEC 61724 revision team (led by Michael Gostein)

C Major overhaul to defined terms will be necessary (back side plane-of-array irradiance, spectrally-corrected albedo, etc)

D Expect to have drafts of IEC 61724 revisions with bifacial system consideration completed within the 2019 calendar year

$$PR_{bi} = \left(\sum_k P_{out,k} \times \tau_k\right) \Big/ \left(\sum_k \frac{P_0 \times \left(G_{i,k} + \varphi_{Pmax} \times G_{i,k}^{rear}\right) \times \tau_k}{G_{i,ref}}\right)$$

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Summary and Conclusions

A Bifacial adoption is happening much faster than anticipated

B Modeling energy production of bifacial systems is in very early stages, but likely on the conservative side

C Project economics are overwhelmingly favorable, but design and optimization require new ways of thinking

D Performance guarantees will be challenging, but international standards will be necessary to pave the way

THANK YOU
FOR
YOUR ATTENTION

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Solar Energy Research Institute of Singapore

Reliability considerations of floating PV systems: experiences from the world's largest floating PV testbed

Haohui LIU, Abhishek KUMAR, Thomas REINDL

Solar Energy Research Institute of Singapore (SERIS)
National University of Singapore (NUS)

NREL PV Reliability Workshop
February 28, 2019

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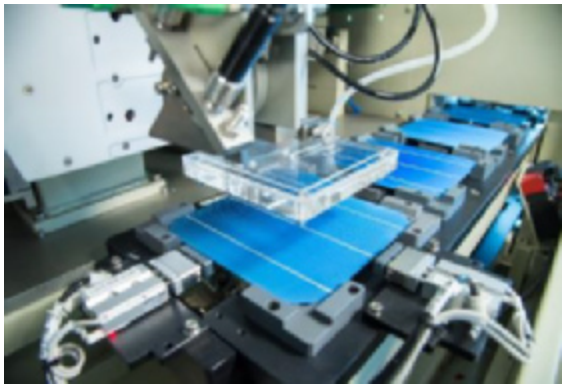
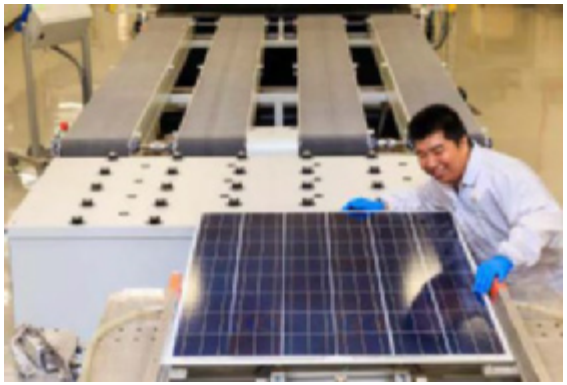
SERIS

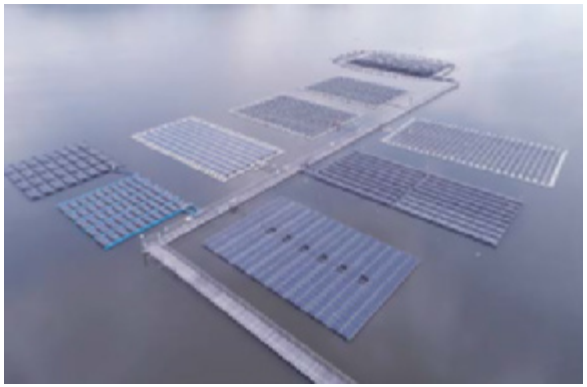
Solar Energy Research Institute of Singapore

- Founded in 2008; focuses on applied solar energy research
- Part of the National University of Singapore (NUS)
- Rapid growth (now > 200 people and > 6000 m^2 of space)
- State-of-the-art laboratories
- R&D focus is on solar cells, PV modules and PV systems
- Specialised in professional services for the PV industry
- ISO 9001 & ISO 17025* certified
  (* PV Module Testing Lab)

Main R&D areas of SERIS







Solar cells:

- Silicon wafer solar cells (various cell architec-tures)
- Tandem solar cells on silicon (e.g. GaAs, perovskites)
- Characterisation & simulation

PV modules:

- Module development
- Module testing (indoor & outdoor)
- Module certification
- Characterisation & simulation

Solar systems:

- System technologies, incl. Floating PV
- PV grid integration
- Solar potential & energy meteorology
- Urban Solar, incl. BIPV
- Quality assurance of PV systems
- Solar thermal systems

Outline

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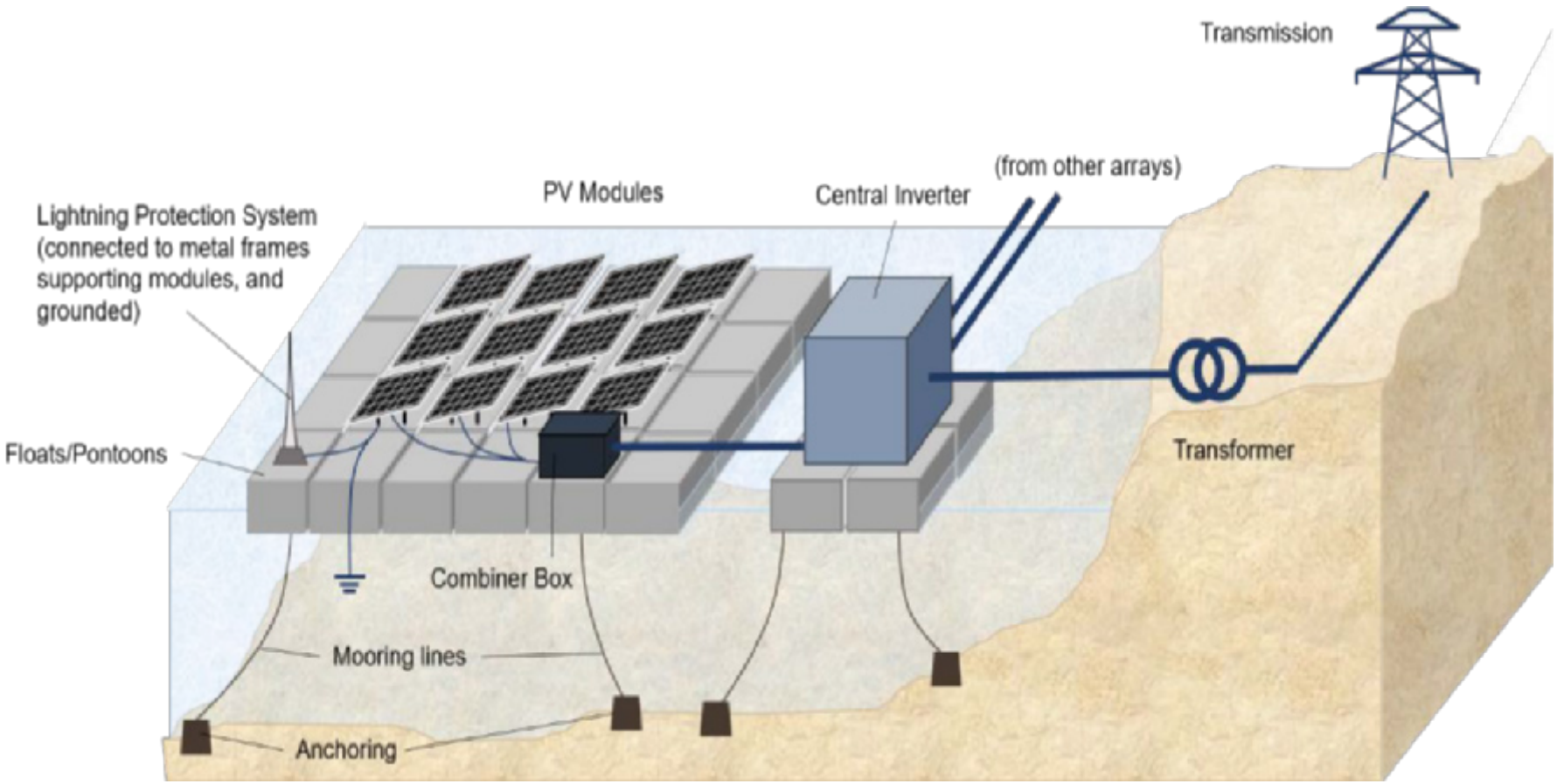
What is Floating PV or “FPV” ?

- PV systems floating on water bodies such as lakes, drinking water reservoirs, hydroelectric dams, mining ponds, industrial ponds, water treatment ponds, etc.
- Third pillar for PV deployment after ground-mounted and rooftop
- First system built in 2007 in Japan
- Relevant where land is scarce and expensive, or needed for other purposes (agriculture, urban habitat, etc.)
- Typical benefits: (1) increased energy yield, (2) water evaporation reduction, (3) maximization of existing infrastructure usage

Typical large-scale FPV system

Using central inverter on a separate island (can also be placed on land)
Various anchoring and mooring systems are possible



The largest floating PV plants

40MW, Huainan, Anhui, China

150MW, Huainan, Anhui

13.7MW, Yamakura Dam reservoir Japan

8.5MW, Sanshan, Wuhu, Anhui

Coal mining subsidence area, Huainan, Anhui

Image sources: Google Map and Sungrow press release.

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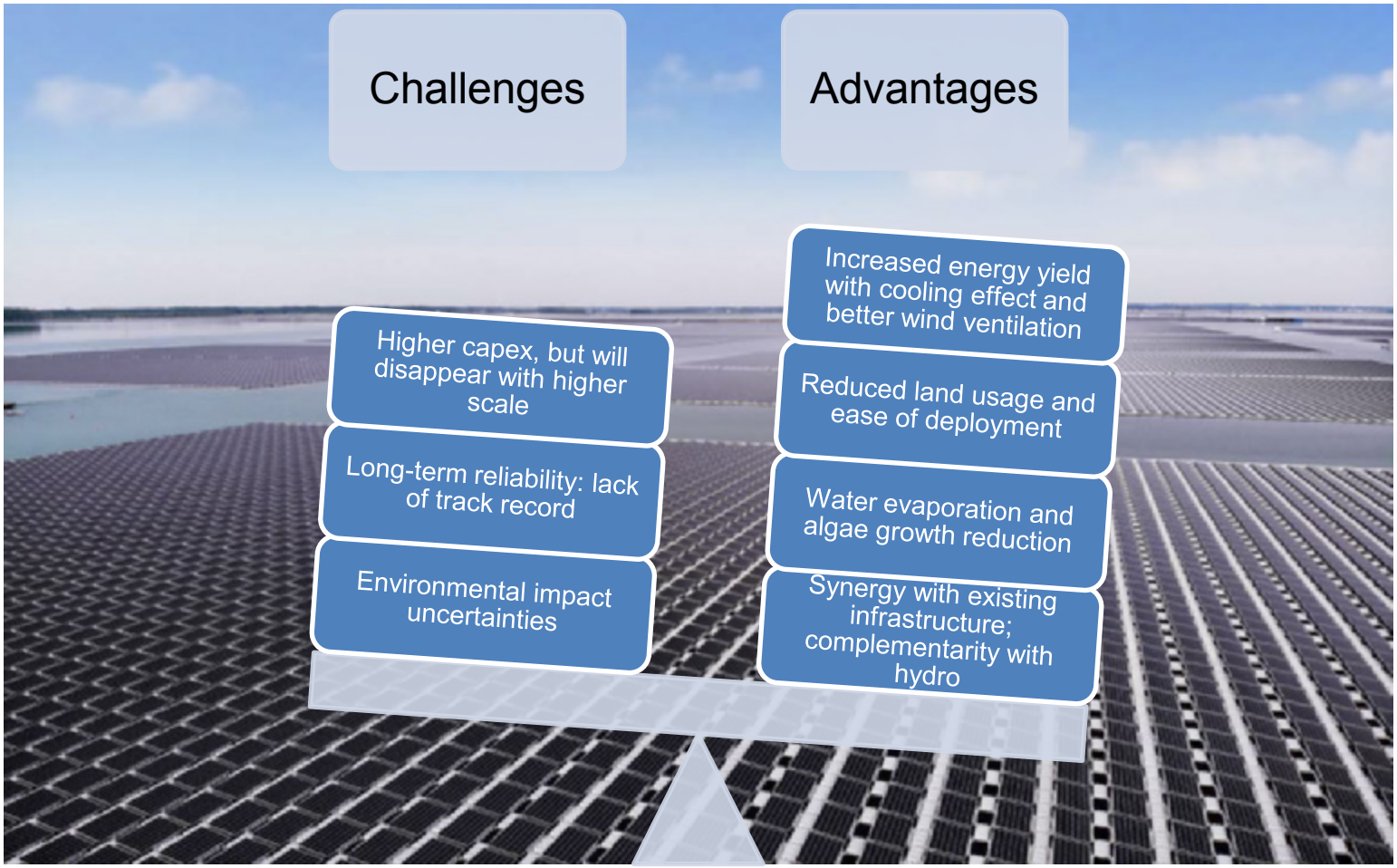
Perceived challenges & advantages

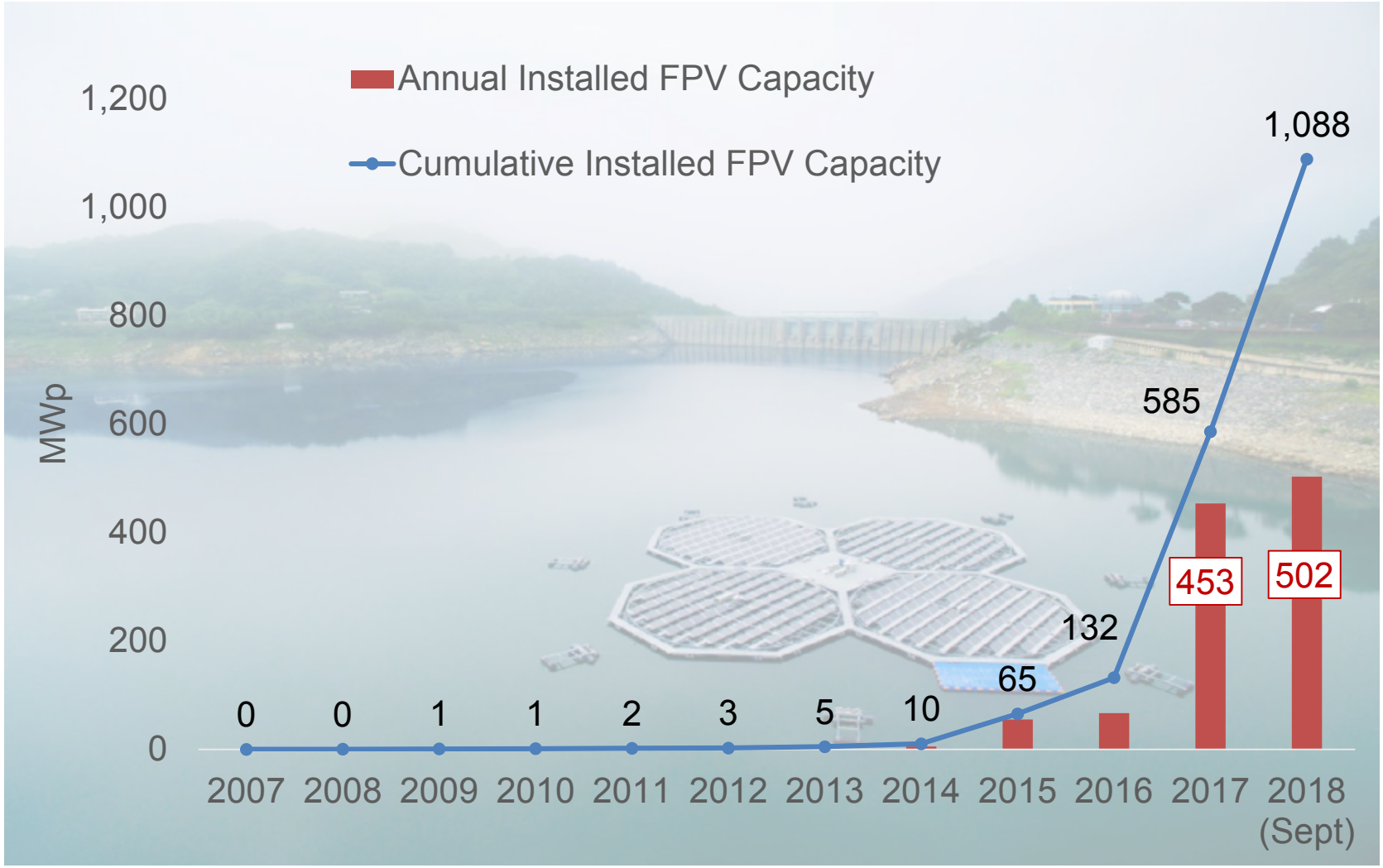
Site-specific EIA* and experienced quality suppliers are paramount



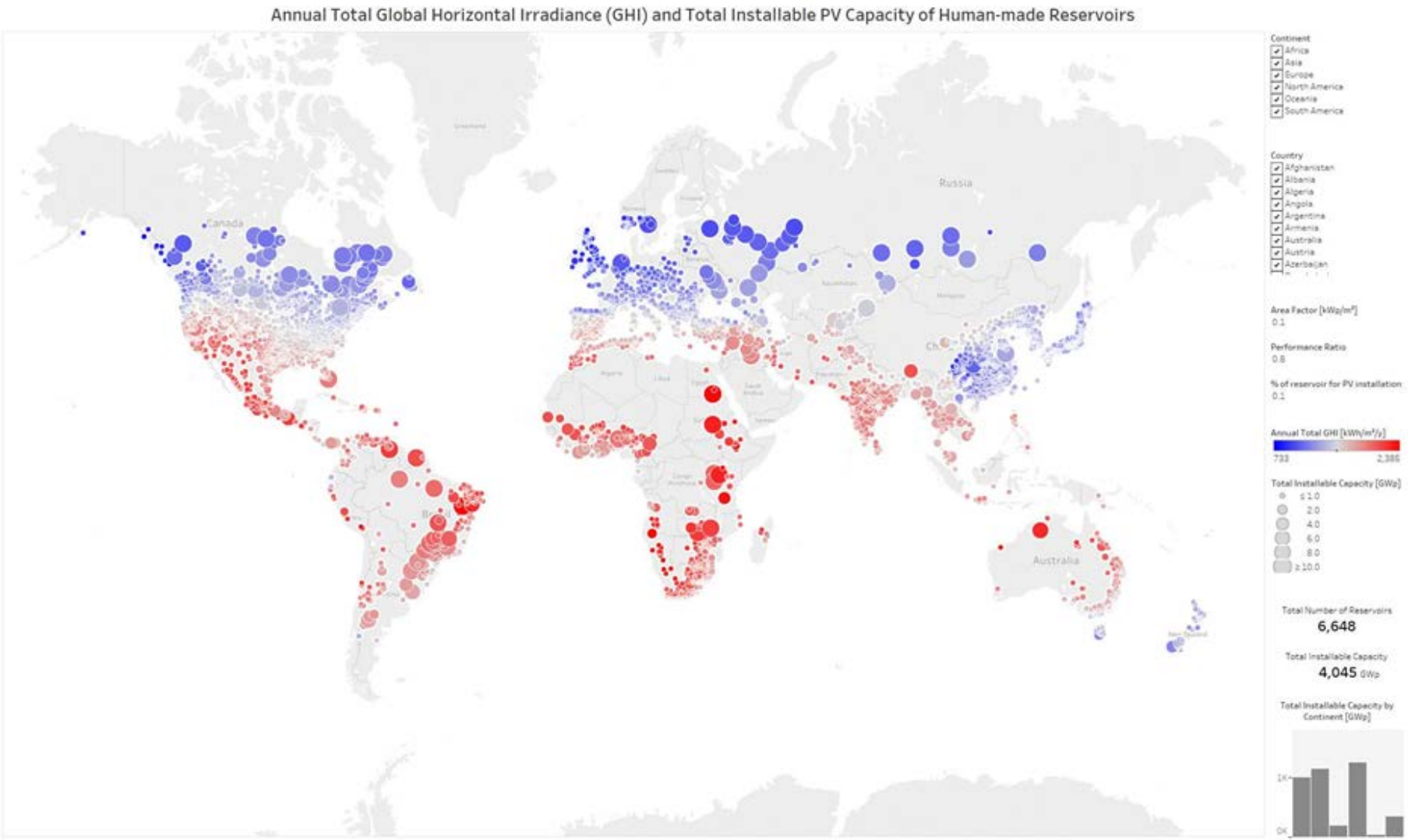
* EIA = environmental impact assessment.

More than 1.1 GW FPV installed

Below figures represent installed FPV projects of 2 MW+



World: ~4 TWp with 10% coverage



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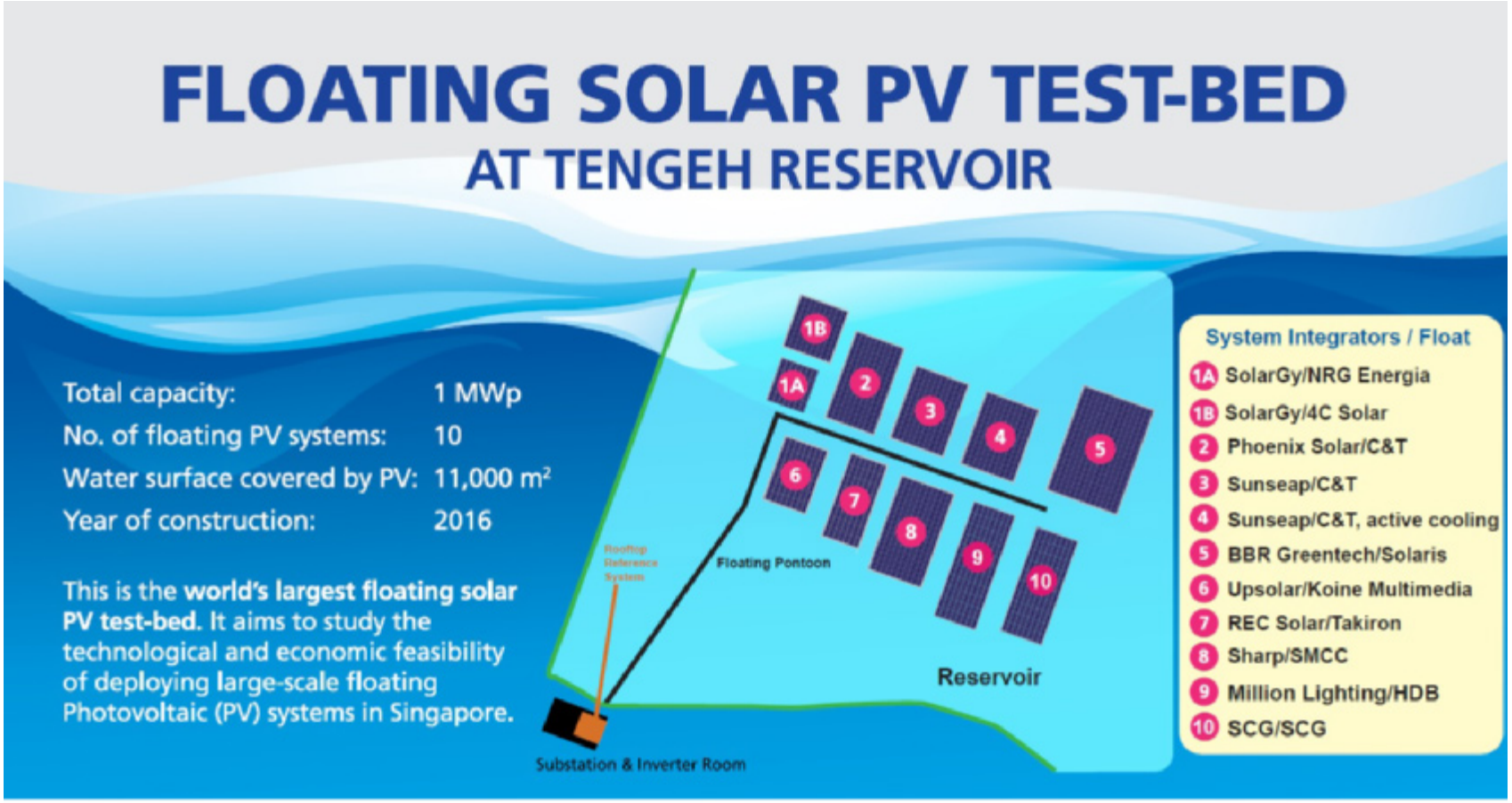
The Singapore floating PV Testbed

- Total capacity ~ 1 MWp



Project collaborators: PUB Singapore's National Water Agency, EDB Singapore, NUS, SERIS

Testbed design and objectives

- Large scale FPV testbed
- Side-by-side comparison of major commercial FPV technologies
- Detailed monitoring
  - Environment
  - Energy yield
  - Module temperature
  - Bi-facial module
  - Active cooling
- Economics, LCOE

Research facilities

- Comprehensive monitoring infrastructure, with >500 parameters
  - Meteorological station (reservoir & rooftop)

  - PV System performance monitoring

DC (PV String) AC (PV array) Motion sensor Module Temp.

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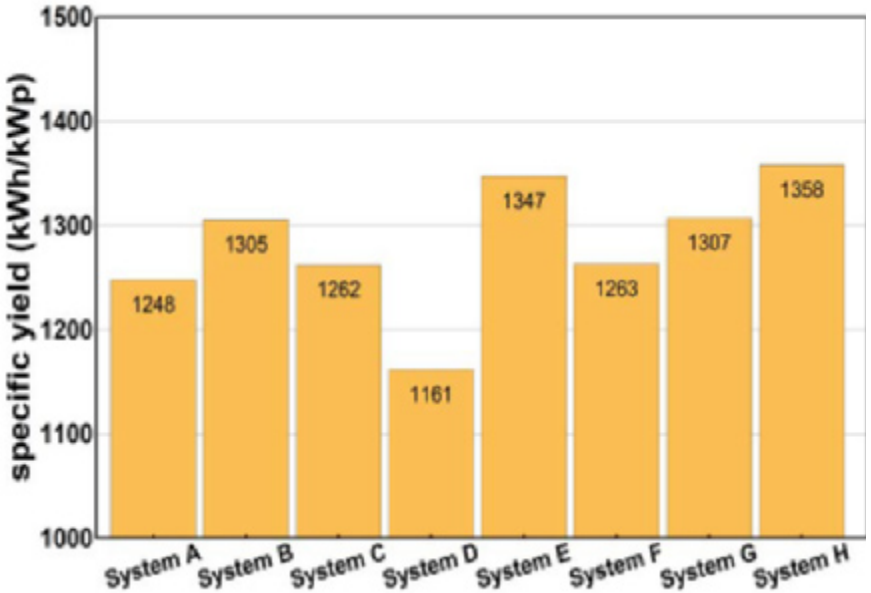
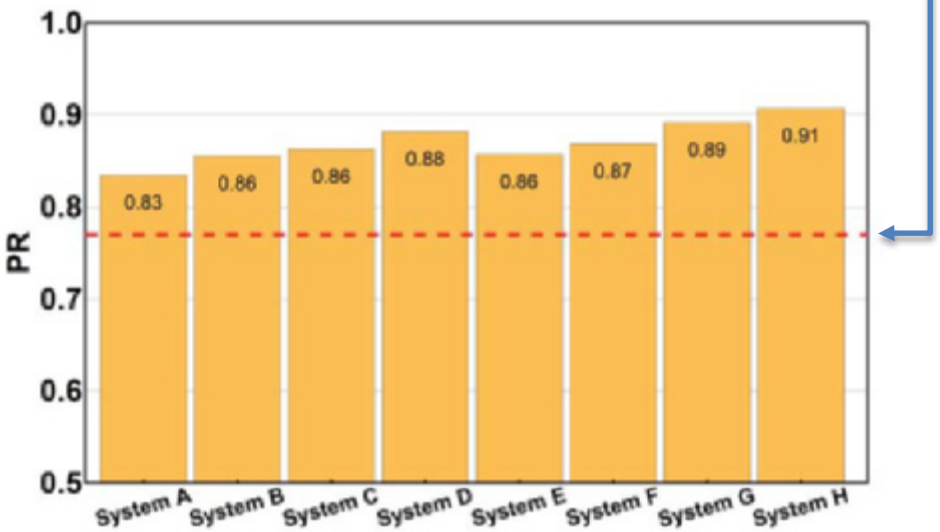
Specific yield and PR

For the first year

Yearly insolation=1601 kWh/m^2



Average rooftop system in Singapore



Excluding major downtime

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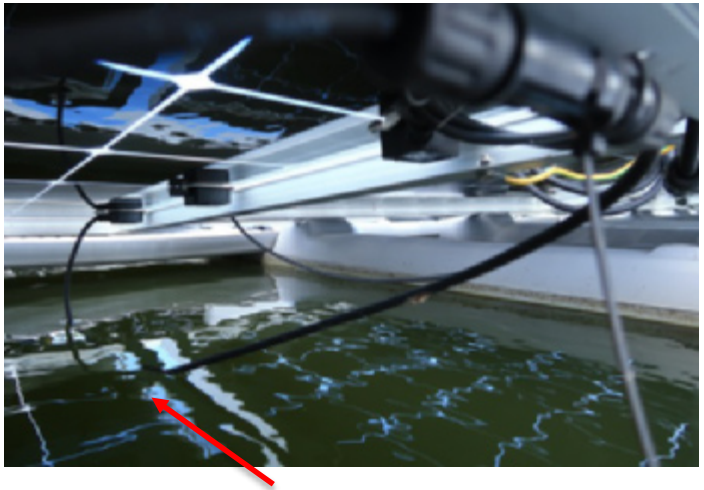
Cables or connectors touching water

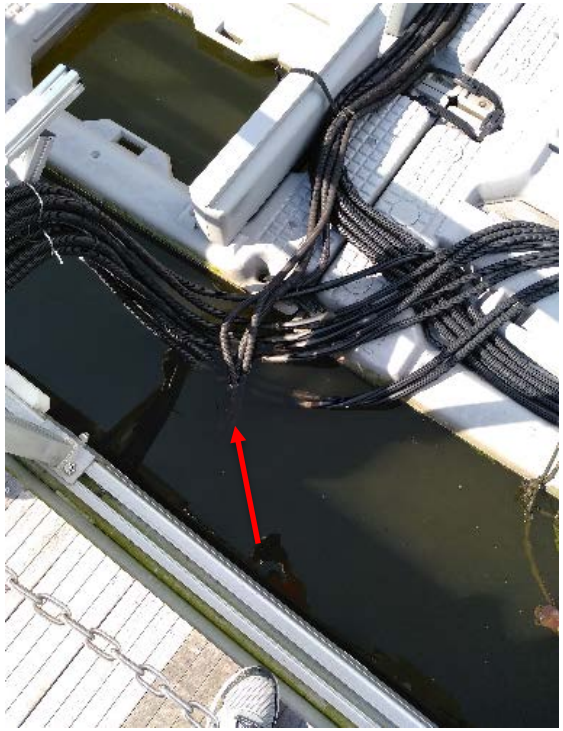
- Causes
  - Low clearance from water surface as well as mismatch in module cable length and floats dimension.
  - Waves due to wind or boat
- Consequences
  - Leakage and low insulation resistance
  - Degradation (corrosion) of cables



- Recommendation: better cable routing, matching module & float dimensions

Submerged cables

- Returning cables submerged in water
  - Due to slackness needed to accommodate platform movement
  - Risk of electrical safety and leakage



Cables snapped or sheath damaged

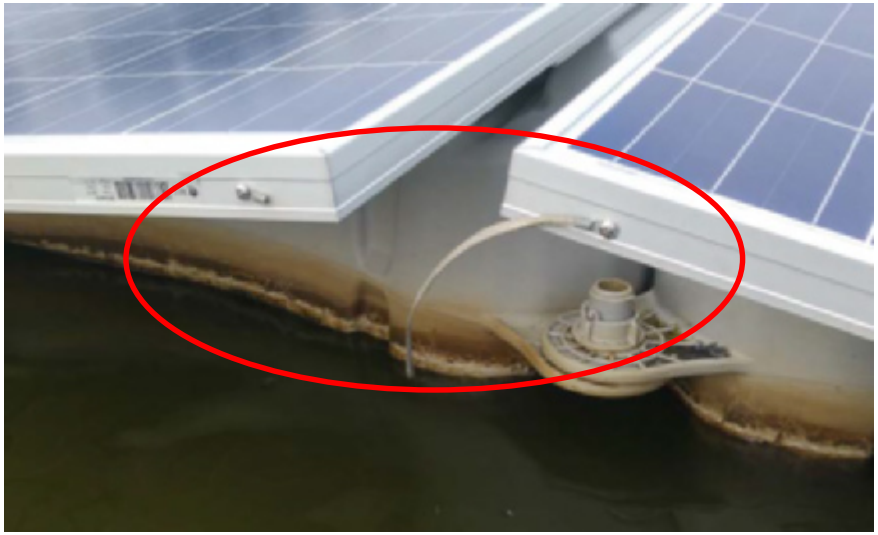
Snapped cables

Damaged sheath

- Recommendation
  - Proper cable routing and calculation
  - Proper bank fixation: e.g. “L” shaped brackets

Breakage of connecting parts

- Mechanical stress
  - At the joints of rigid structures
  - On equipotential bonding tape/wire
  - At the earthing tape connection for grounding



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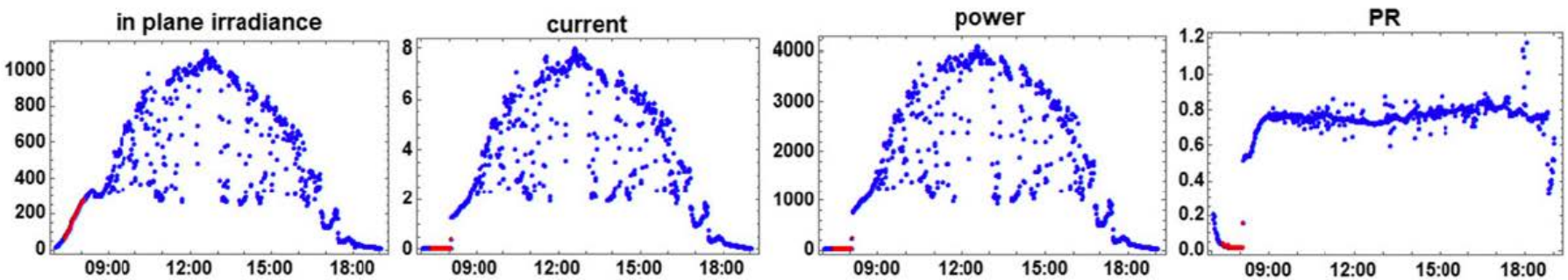
Insulation resistance issues

Inverters starting late

- Insulation faults observed for some systems
  - The insulation resistance (R_{iso}) is low for some floating PV strings.
  - Inverters measure R_{iso}. When R_{iso} does not meet the preset threshold, inverters do not start.
  - Result: inverters start late (till the R_{iso} limit is passed) and thus loss of energy.



Insulation resistance issues

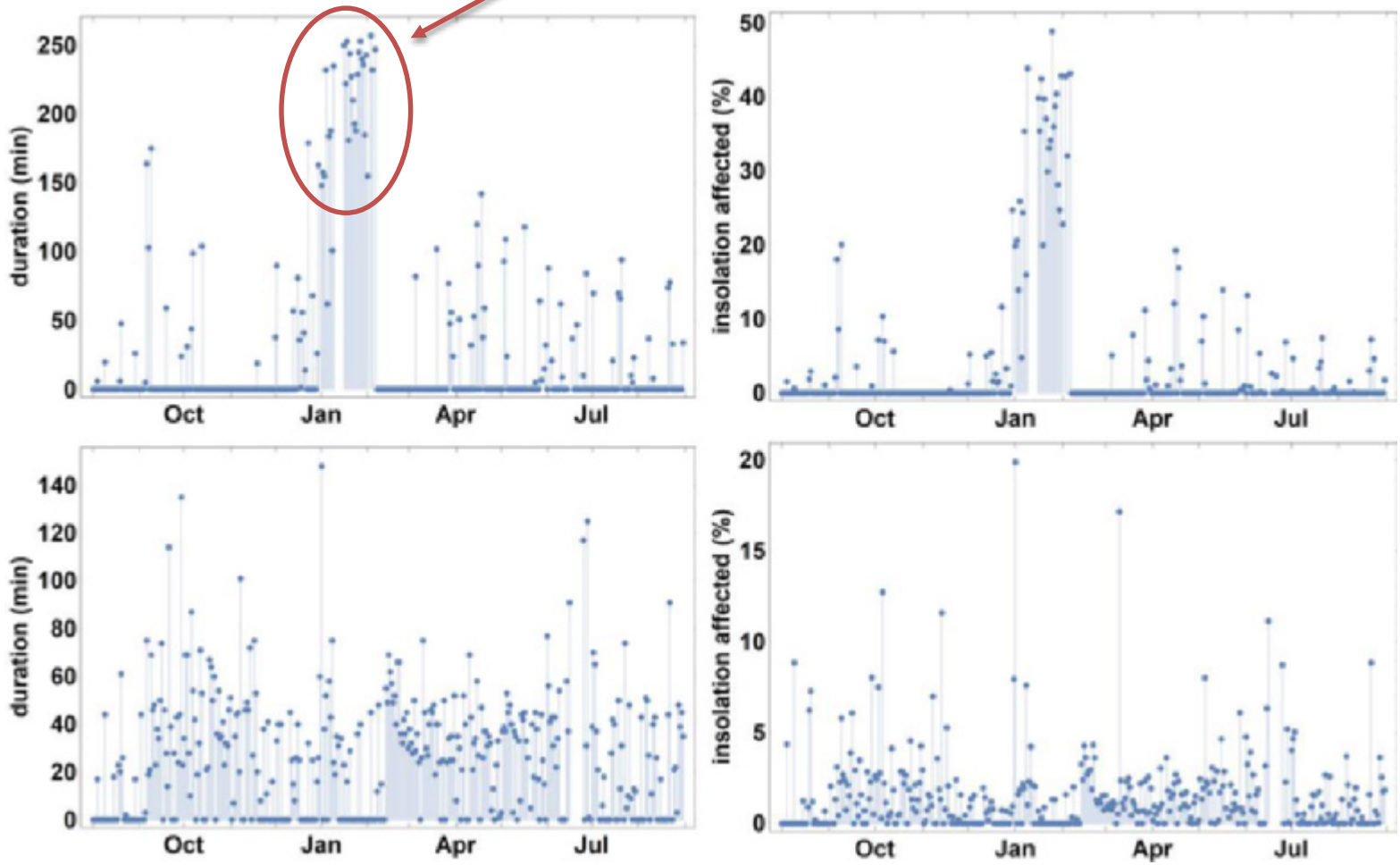
Inverters starting late

- Cases and observations

Cables dropped into water

Inverter/ String A

Inverter/ String B

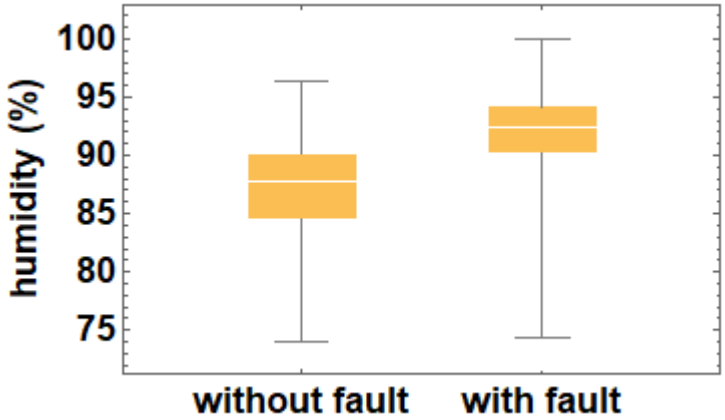


Insulation resistance issues

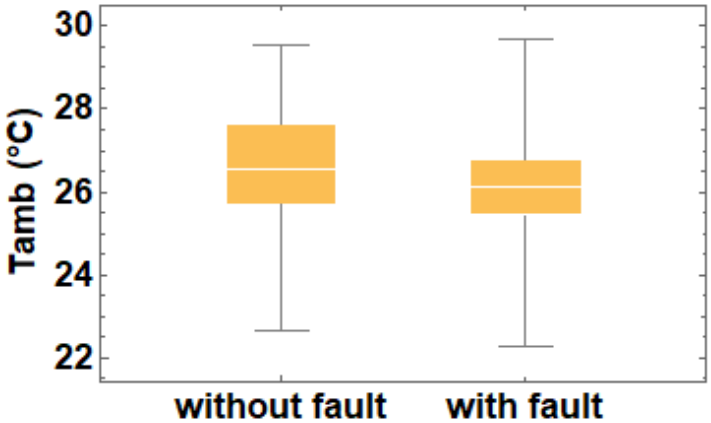
Inverters starting late

- Correlation with humidity or rain

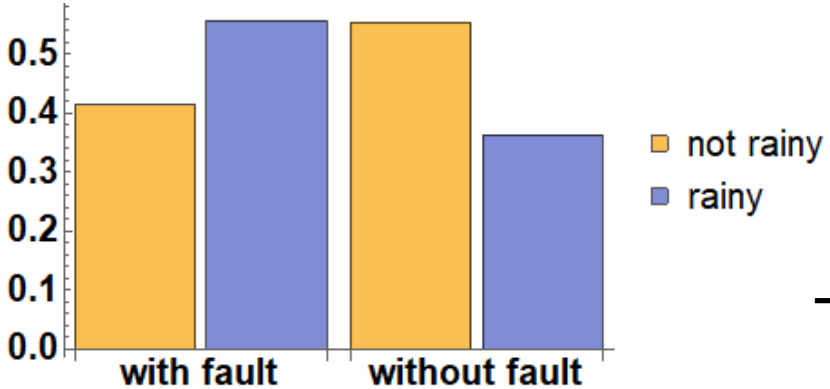
Humidity



Ambient temperature



frequency



Rain and higher humidity → more likely to have faults

→ Moisture/water resistant cables?

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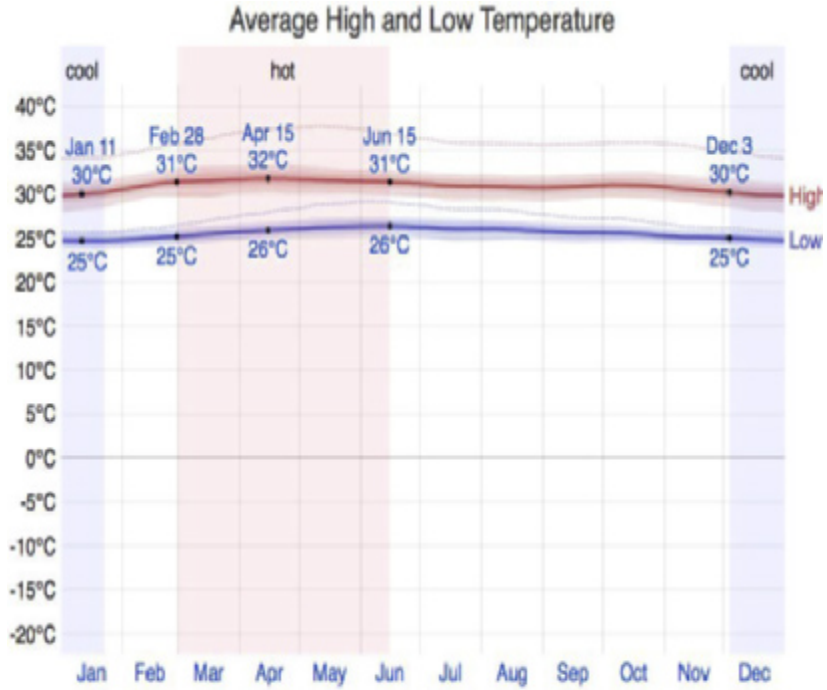
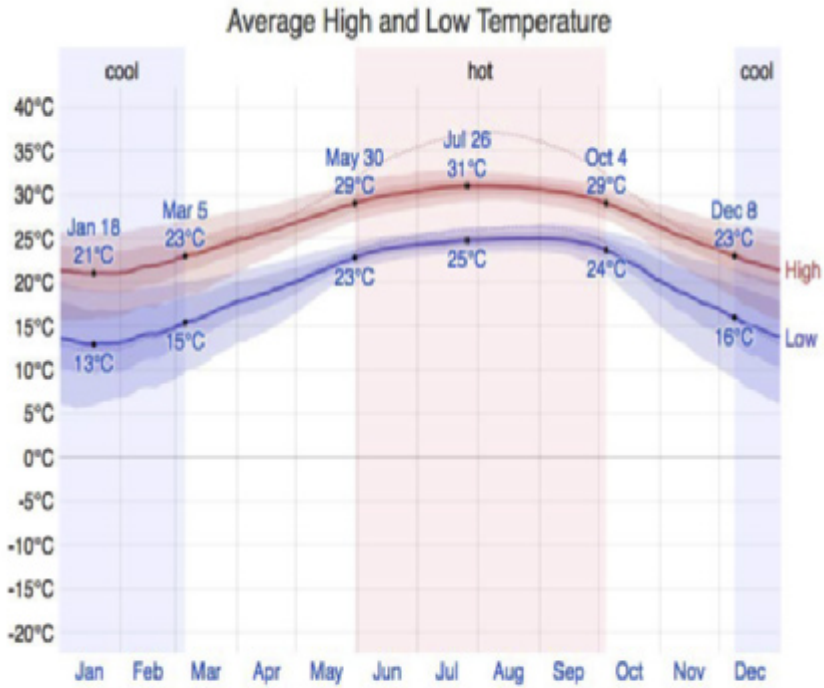
Stress of PID

Ambient temperature



The daily average high (red line) and low (blue line) temperature, with 25th to 75th and 10th to 90th percentile bands. The thin dotted lines are the corresponding average perceived temperatures.



The daily average high (red line) and low (blue line) temperature, with 25th to 75th and 10th to 90th percentile bands. The thin dotted lines are the corresponding average perceived temperatures.

Singapore
- Uniformly high temperature

Florida
- Seasonal

Peter Hacke, IFSS 2018

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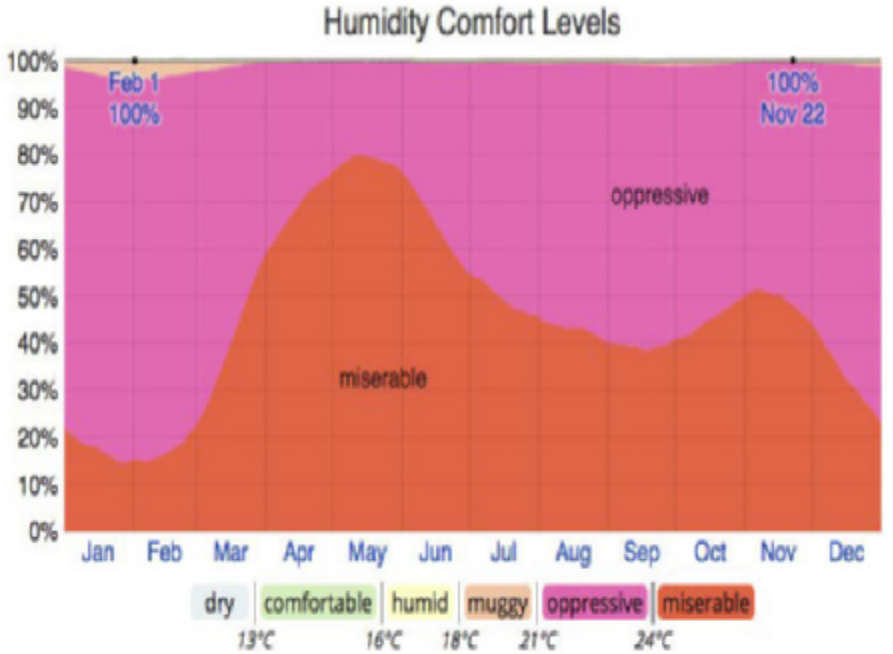
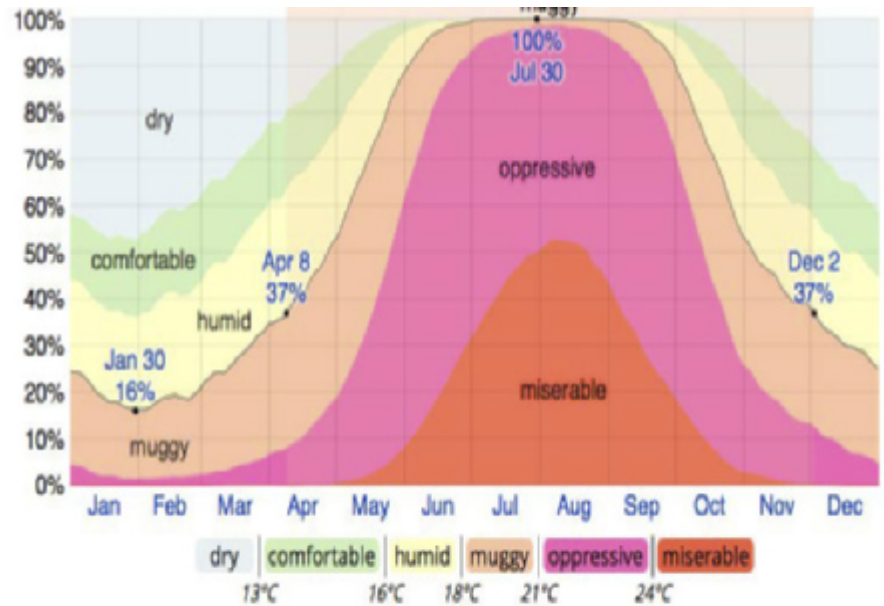
Stress of PID

Humidity



The percentage of time spent at various humidity comfort levels, categorized by dew point.



The percentage of time spent at various humidity comfort levels, categorized by dew point.

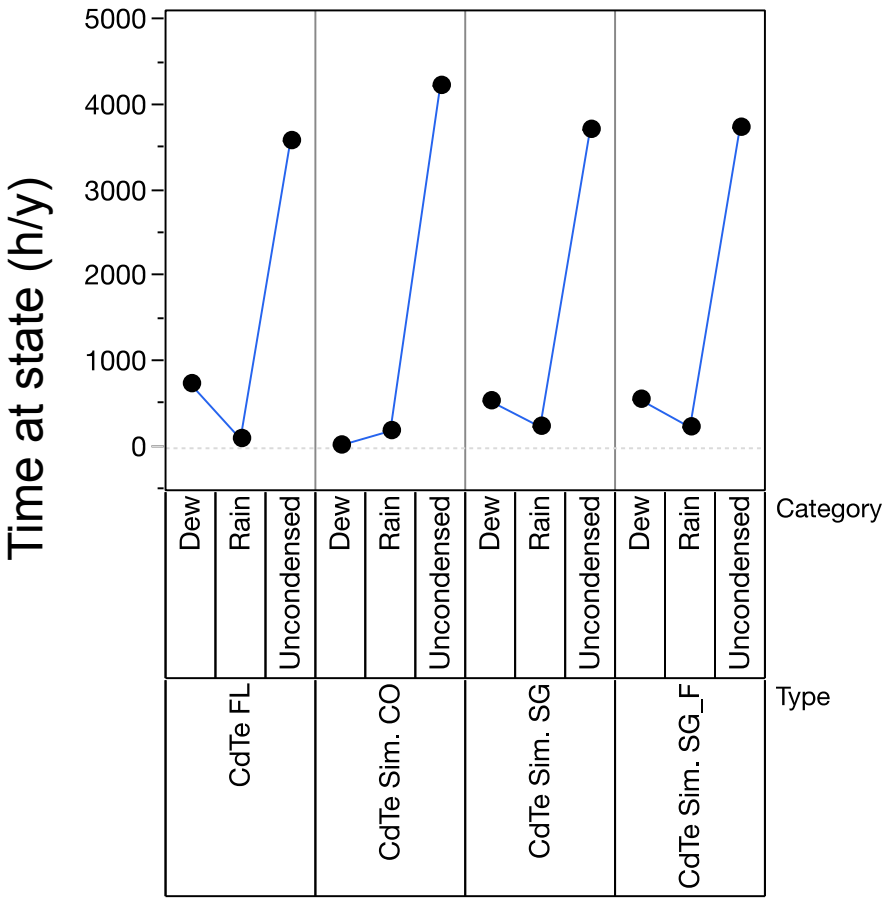
Singapore
- Uniformly high dew point

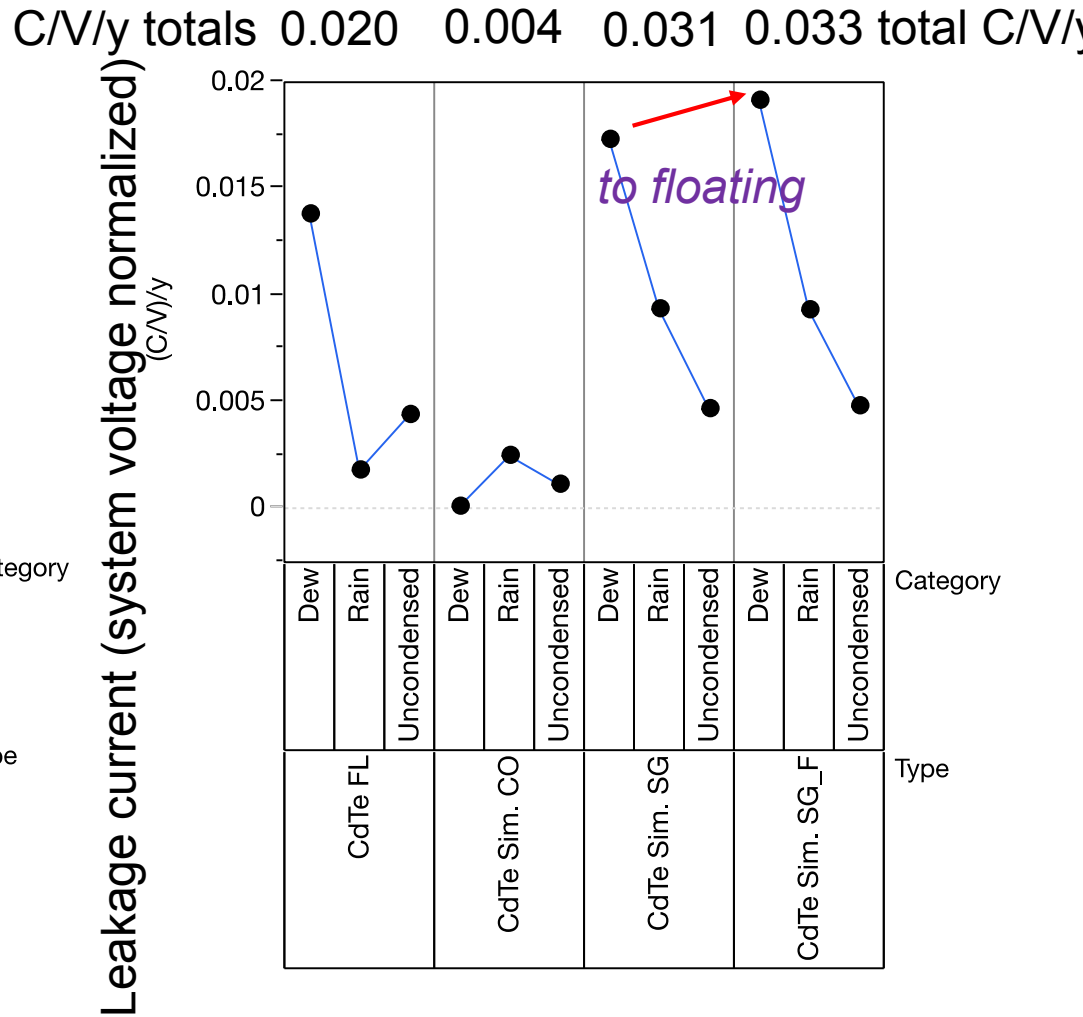
Florida
- Seasonal

Peter Hacke, IFSS 2018

Stress of PID

Coulomb charge transfer (modelled results)





Peter Hacke, IFSS 2018

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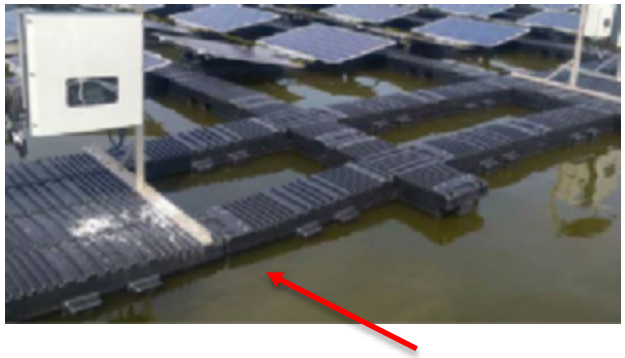
Loss of buoyancy

- Damage during installation
  - Punctured by nails
  - Dragging on rough surface
  - Float walls may be thin and fragile
- Foams may shrink or absorb water

- Recommendation:
  - Quality control of floats
  - Careful installation
  - Replacement of affected floats in time during O&M



Moisture/water ingress

- Electrical boxes and cabinets are generally exposed
- Constant movement
- Slanted installation
- Needs high quality protection (IP65 or above)
- Keep insects out as well

Water ingress and mild corrosion

Cable connector burnt

Module breakage

- Small amount of bowing observed for frameless modules
- An instance of module breaking due to O&M personnel falling onto the panel during cleaning.
- Recommendation:
  - Better maintenance walkway
  - Proper skill training for O&M personnel and improved the SOP (standard operating procedure)

Animal visits

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Soiling – from bird droppings

- Bird droppings observed on floating PV modules
  - Partial shading
  - Reduced performance, less energy yield
  - Cell reserve biased, hot spots, => can lead to accelerated module degradation

Singapore floating PV Testbed

- Possible solutions
  - Part of the O&M routine (i.e. immediate actions / cleaning)
  - Barrier methods
  - Non-barrier methods
    - Ultrasonic, Sonic Repeller
    - Visual Scare Device

Queen Elizabeth II reservoir, UK

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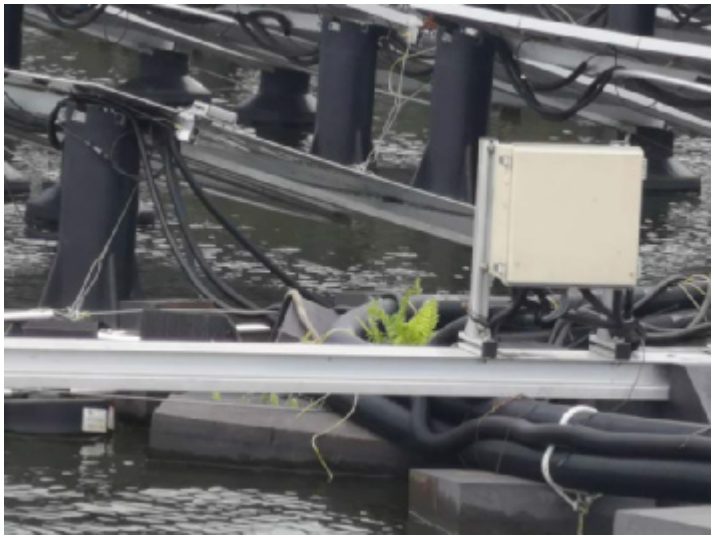
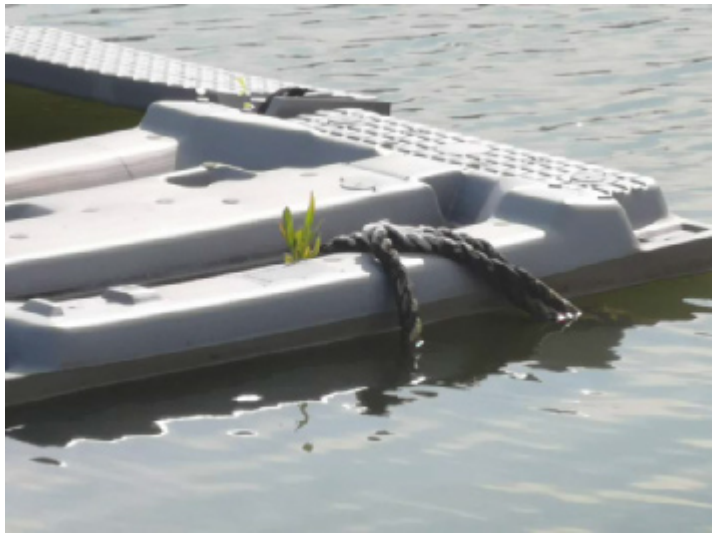
Vegetation growth

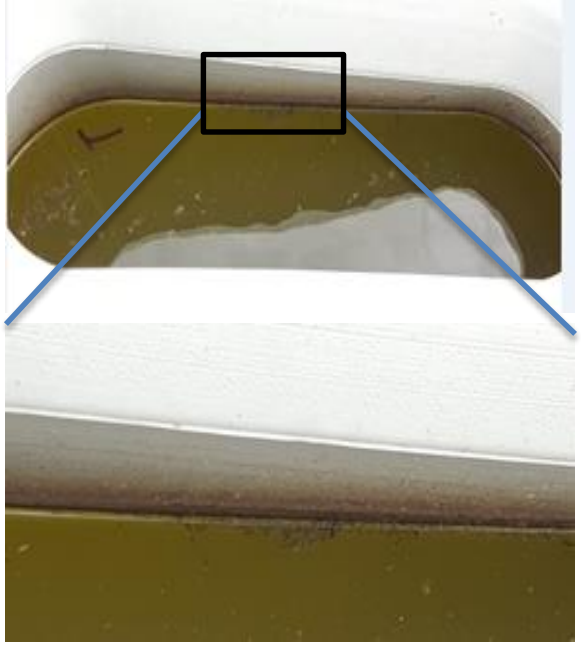




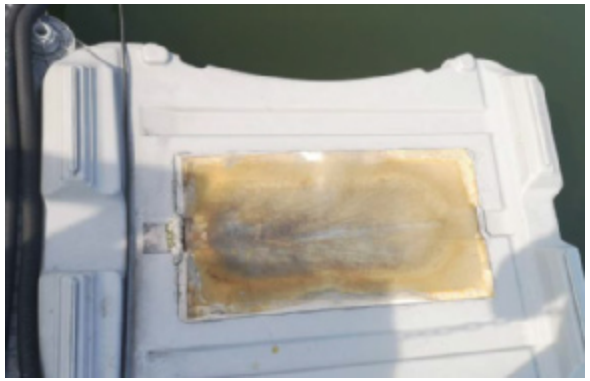
Biofouling and insects

Midges

- Midge exuviae found in the water pocket area
  - Stagnant water
  - Along the perimeter of the floating island
  - Floats mounted with PV modules are fine (pocket covered)



- Recommendation: cover exposed pocket of stagnant water



Biofouling and insects

Algae growth

- Thick algae blanket on submerged membranes
- Potential food source for birds
- Midge egg masses and larvae found on the algae mats grow on the foam structures

- Recommendation
  - Regular cleaning
  - Use better foams with smoother surface

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Summary

- Floating PV is a fast-growing segment with TW-scale potential
- Constant movement puts challenge on cable management and maintenance of connecting parts
- High humidity environment leads to more insulation resistance issues
- Calculation shows that significant PID stress is present, but further work is needed to better evaluate the exact impact
- Animals, insects and biofouling may need to be addressed for operation and environmental considerations
- Component quality is important for reliable operation
- Issues are not inevitable, but proper system design, workmanship and good O&M practices are important.

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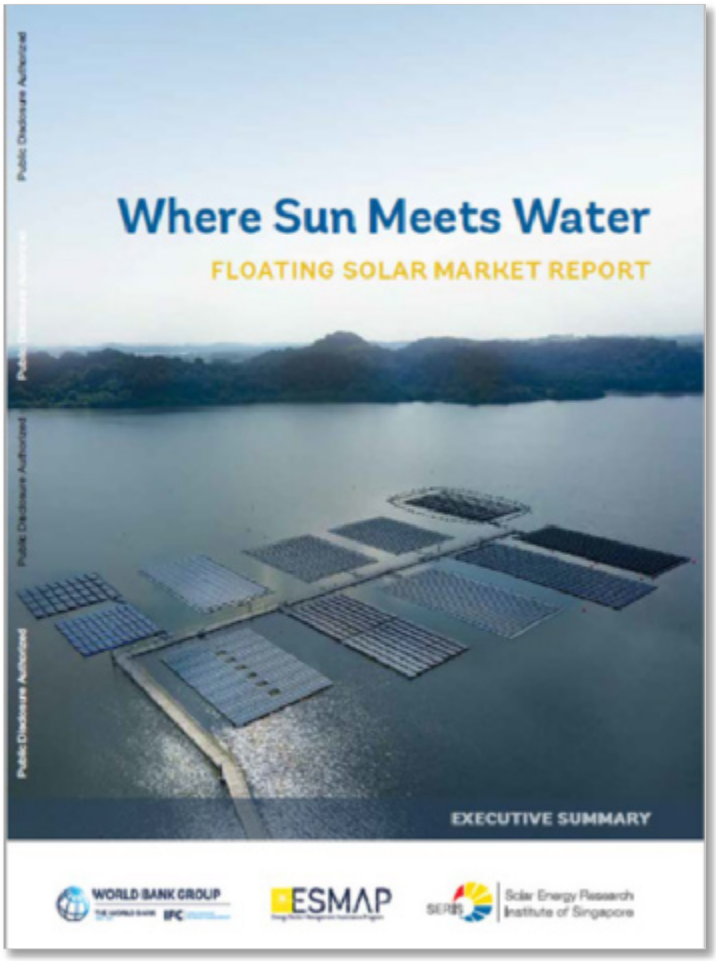
Collaboration with the WBG-ESMAP



- Floating Solar Market Report

  1. Rationale
  2. Technology overview
  3. Market potential and opportunities
  4. Economics
  5. Policy and regulatory framework
  6. Suppliers/EPCs

Publication: 1Q 2019

- Practitioner Handbook

  1. Project development phases
  2. Best practices and guidelines
  3. Environmental and social considerations

Publication: 2Q 2019

THE THIRD

INTERNATIONAL FLOATING SOLAR SYMPOSIUM

30 Oct 2019 – 31 Oct 2019

Marina Bay Sands Convention Centre, Singapore

1 Nov 2019

SERIS (Solar Energy Research Institute of Singapore) Workshops, lab tour and visit to the world's largest Floating PV testbed

INTERNATIONAL FLOATING SOLAR SYMPOSIUM

PART OF THE ASIA CLEAN ENERGY SUMMIT CONFERENCE & EXHIBITION

PART OF THE SIEW SINGAPORE INTERNATIONAL ENERGY WEEK

Don‘t hesitate to contact us:

thomas.reindl@nus.edu.sg

More information at
www.seris.sg
www.solar-repository.sg

We are also on:

AC Coupled Battery Storage

Mohammad Bozchalui, PhD, PE

Director of Products,

Energy Storage Solutions & Grid Services

NREL PVRW

February 28, 2019

Enphase Global Footprint: 4GWdc, 820k+ Systems, 120 Countries

Deliver technology solutions that make clean energy affordable, reliable, and accessible to all.

Market Position

ENPHASE.

Enphase Cycle of Quality and Reliability

sicZert

Certificate

Certificate No.: ZQ 23030617940720

Enphase Energy

1420 N. McDowell Blvd.
Pataluma CA 94954-6515
USA

enphase ENERGY

Research, design and development, manufacturing control, sales, customer support and testing of residential, commercial and utility grade solar micro inverter systems and associated energy management services

DIN EN ISO 9001:2015

- Enphase completed ISO9001:2015 and IS014001:2015 certification in July 2017 to the updated ISO standards. 2018 ISO surveillance audit also completed.

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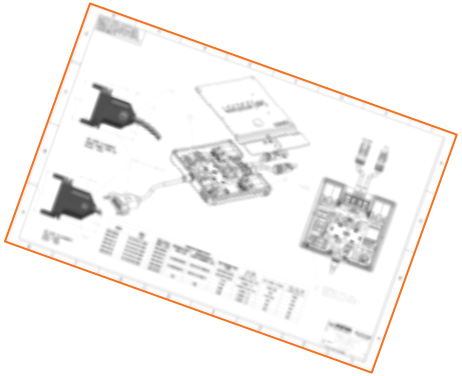
Quality & Reliability Begins in Product Design & Supplier Selection

Product Design

- Clear requirements for unit reliability
- Component selection
- Component verification
- Component use
- Rigorous thermal and environmental design



Supplier Quality

- Automotive standard implemented at component suppliers.
- Actively implementing elements of AIAG APQP & ISO TS16949
- Production Part Approval Process (PPAP):
  - Design record and specification requirements are understood
  - Process is able to produce product consistently during volume production.

AIAG: Automotive Industry Action Group
APQP: Advanced Product Quality Planning

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Enphase Product Lifecycle Testing

Design for Reliability	Evaluation of Design Limits	Environmental Conditioning	Long Term Reliability Testing	Manufacturing Test	Field/Ongoing Reliability Testing
Hardware Verification Test	MEOST/HALT Testing	UV Testing	Damp Heat Test	In-Circuit Test	Ongoing Reliability Testing
Software Verification Test		Salt/Fog Testing	Thermal Cycling Test	Functional Test	Failure Analysis
Reliability Modeling		Acidic Atmosphere	Grid Stress Testing	Hi-Pot Test	Predictive Model Verification
Component Qualification		Shipping/Handling		Gang/Systems Test	

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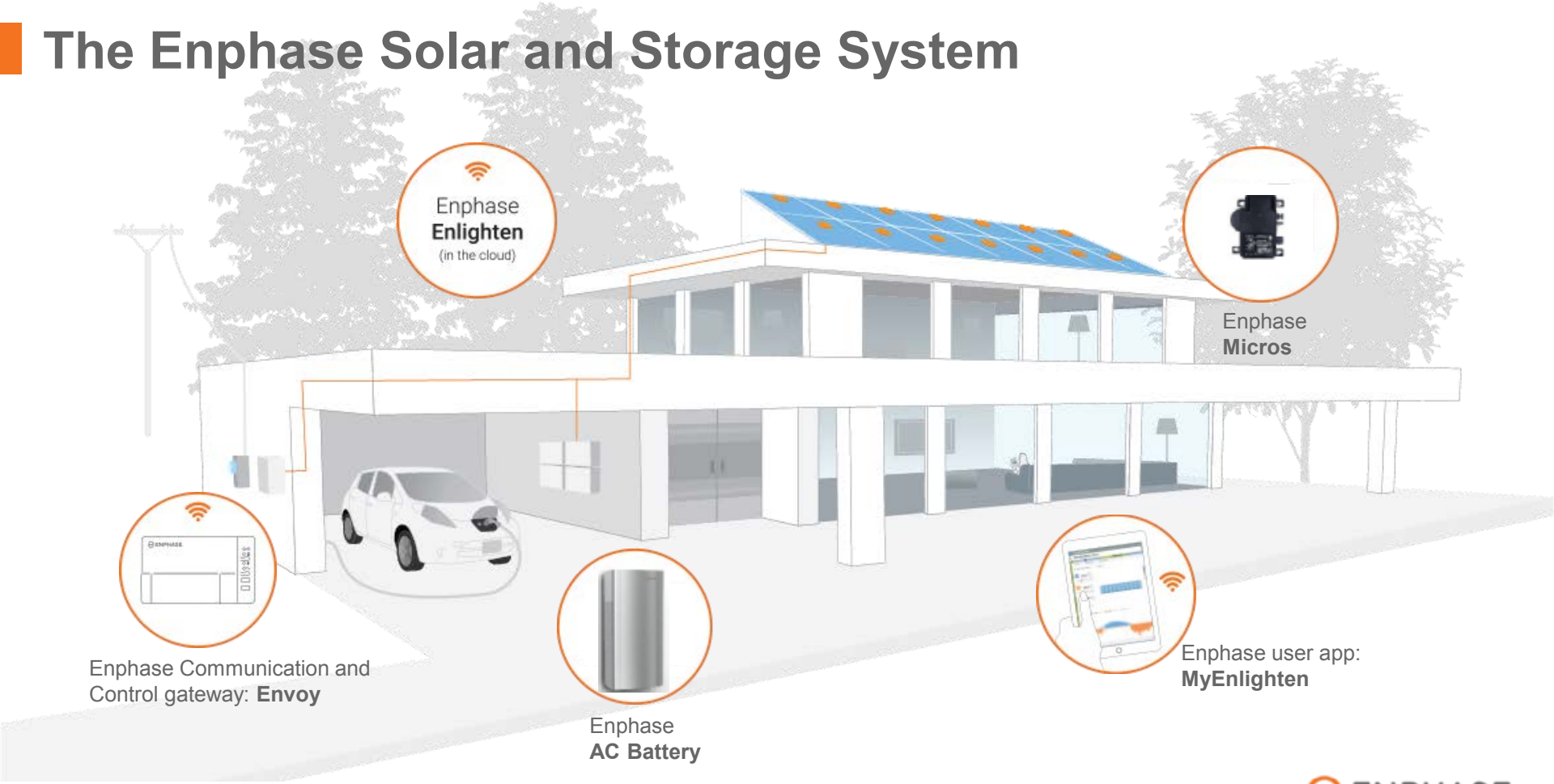
The Enphase Solar and Storage System



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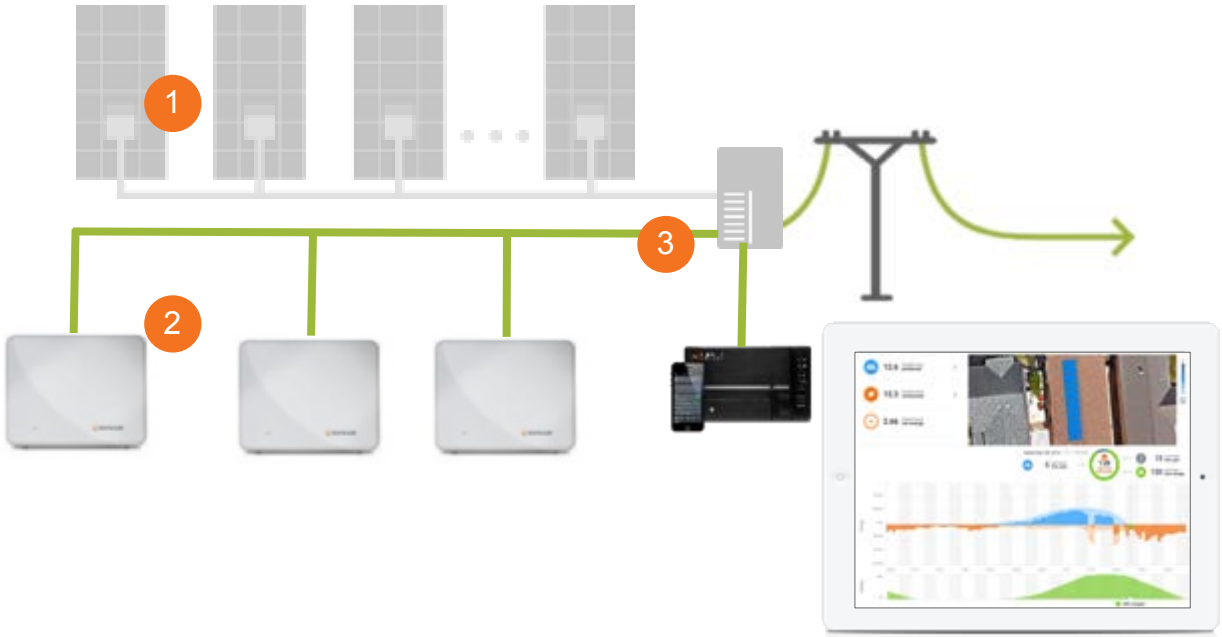
AC Coupled Architecture

1. PV Micros / AC Modules on the roof
2. AC Battery with integrated Micros
3. AC connection to panel/combiner



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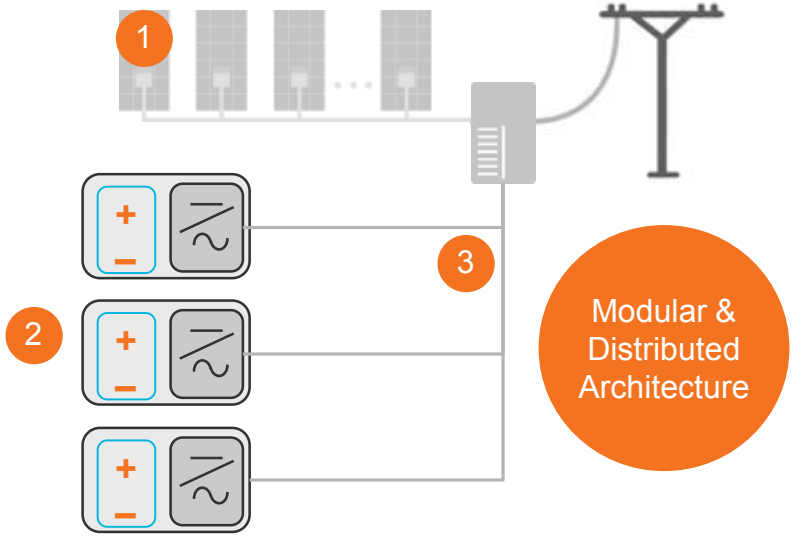
Reliability, Availability, and Serviceability

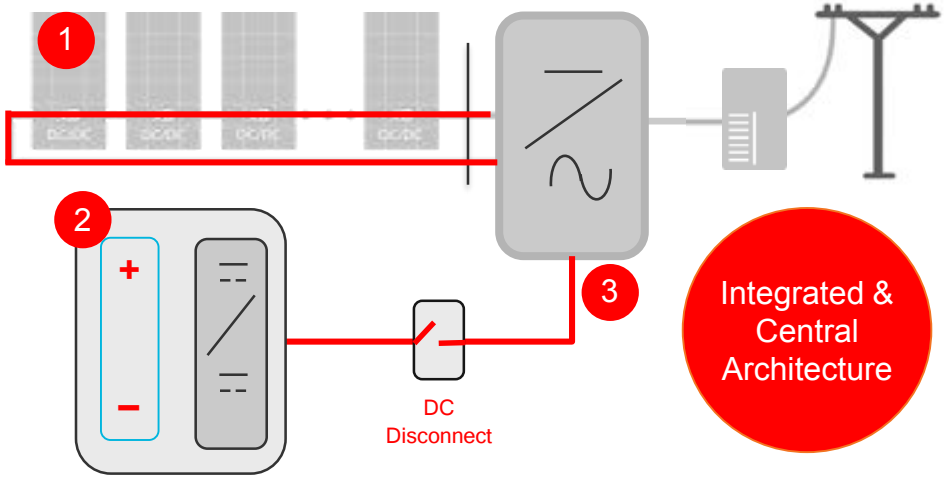
AC-Coupled Modular Battery

1. PV Micros / AC Modules on the roof
2. AC Battery with dedicated Micros
3. Inverters are not single point of failure for the system



DC-Coupled Battery

1. DC optimizers on the roof
2. DC Coupled battery
3. String inverter is single point of failure for the entire system (Battery and PV system)



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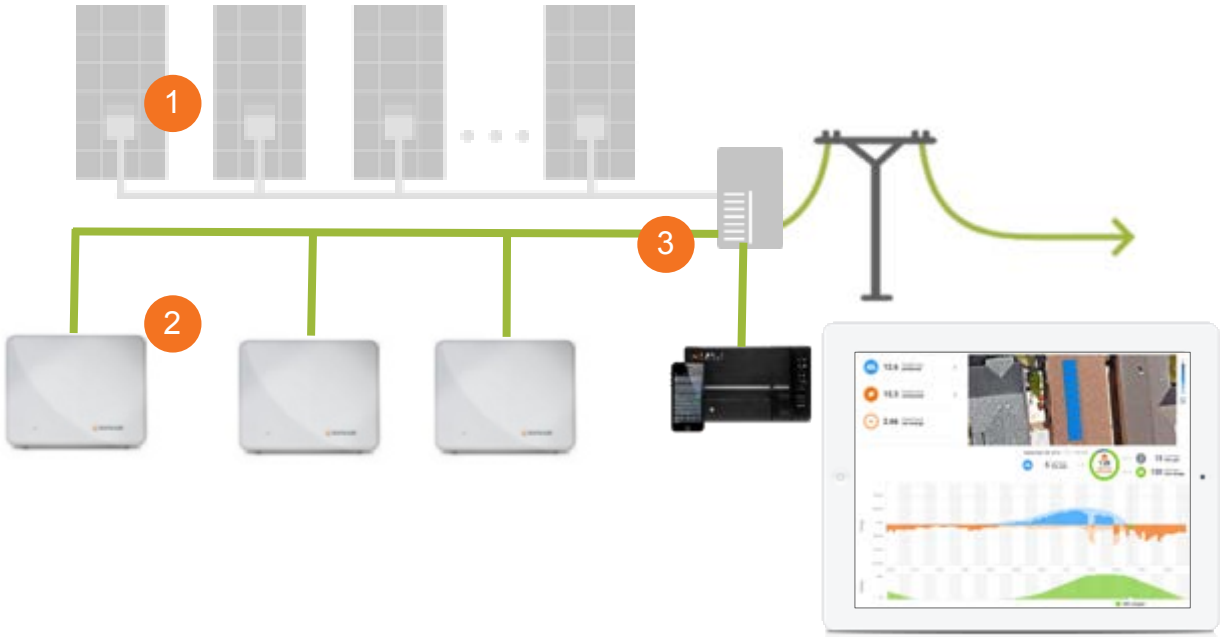
AC Coupled Architecture

- Simple system integration
- Modular design, expandable
- Higher system reliability



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Enphase AC Battery Storage Products

AC-Coupled, Modular, and Expandable Battery Storage Architecture

ACB 1.0

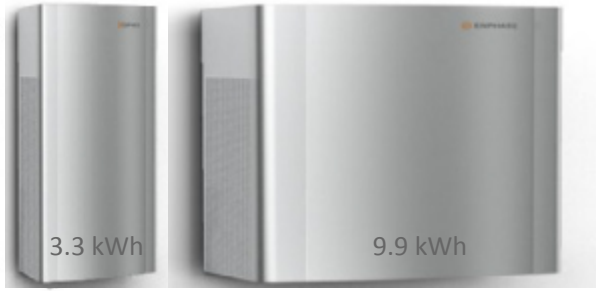
- First Generation
- 1.2 kWh Modular System
- Grid-tied operation
- ToU optimization
- EMEA, APAC, NA

Shipped Over
25 MWh Till Date

ACB 1.5

- Second Generation
- 1.2 kWh Modular System
- Grid-tied operation
- ToU optimization
- Upgraded BMS
- EMEA, APAC

Q1'19
Customer Availability



Encharge

- Third Generation
- 3.3 kWh Modular System
- Grid-tied operation
- ToU optimization
- Full Backup/off-grid operation
- IQ8 based system
- EMEA, APAC, NA

Q4'19
Customer Availability

2016 2017 2018 2019 >2020

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Enphase Encharge AC Battery

Features

- 3.3 kWh energy capacity, 1.28 kW power
- Integrated 4 microinverters
- Depth of discharge: >95%
- 96% round-trip efficiency for the battery
- LFP** chemistry
- Warranty: 10 years or 4000 cycles*
- Indoor and Outdoor Installations
- Modular and expandable

Notes: **Lithium Ferrous Phosphate // *Conditions apply. See Limited Warranty for terms and exclusions.

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AC Coupled Solar and Storage Systems

Solar PV	Enphase AC Coupled
Component Reliability	High (+99.7%)
Design, installation, and system integration	Simple
Environmental Rating	NEMA 6
Operating Life	25 Years

AC Battery Storage	Enphase AC Coupled
Impact of System size on its Reliability	Improved reliability
Battery Chemistry	LFP
Battery Safety	Higher thermal stability
Installation	Indoor/Outdoor

Solar + Storage System	Enphase AC Coupled
Warranty	One stop shop
Composite System Reliability	High
Expandable	Yes
Serviceability	High

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NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Recycling of PV Modules – Insights from Techno-Economic Analysis Informing Development of an R&D Roadmap

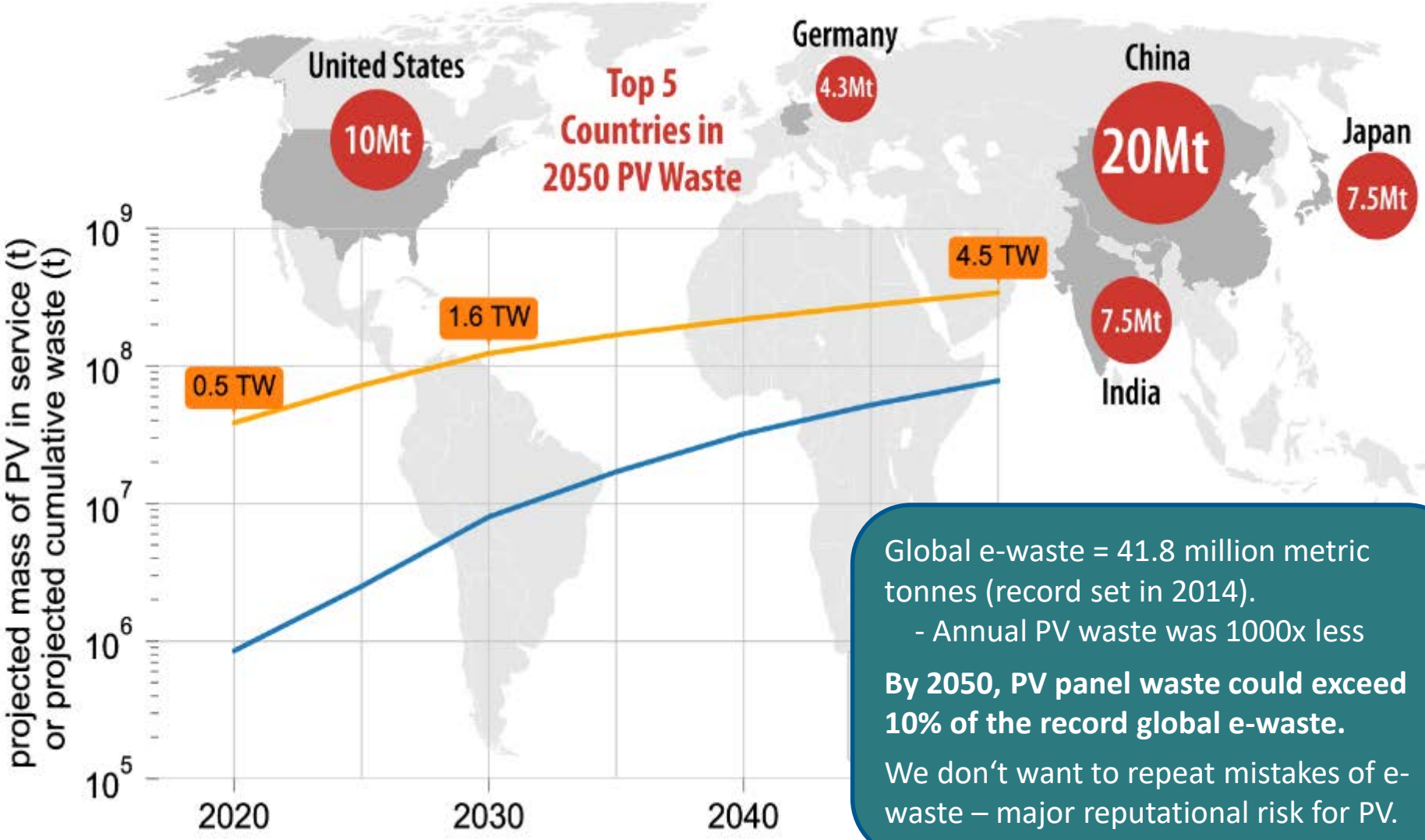
Garvin Heath, PhD

Photovoltaic Reliability Workshop (PVRW) 2019

February 28, 2019

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.

Low Volumes Now, PV Waste Will be Significant Challenge in Future



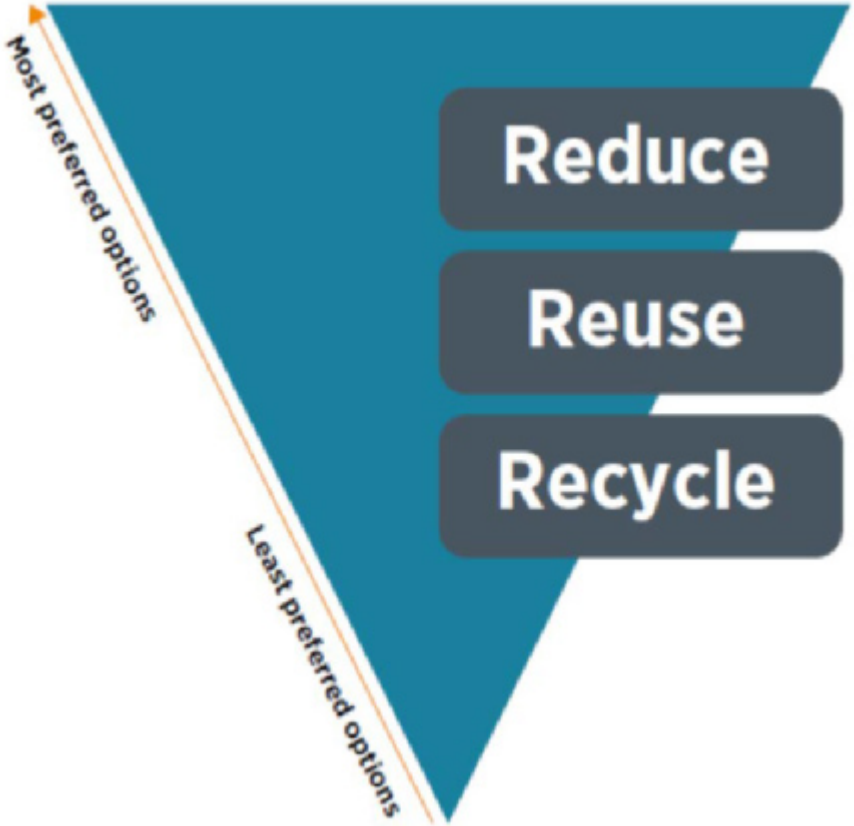
Global e-waste = 41.8 million metric tonnes (record set in 2014).
- Annual PV waste was 1000x less

By 2050, PV panel waste could exceed 10% of the record global e-waste.

We don't want to repeat mistakes of e-waste – major reputational risk for PV.

What Do We Do with PV Waste? The 3 Rs of Waste Management

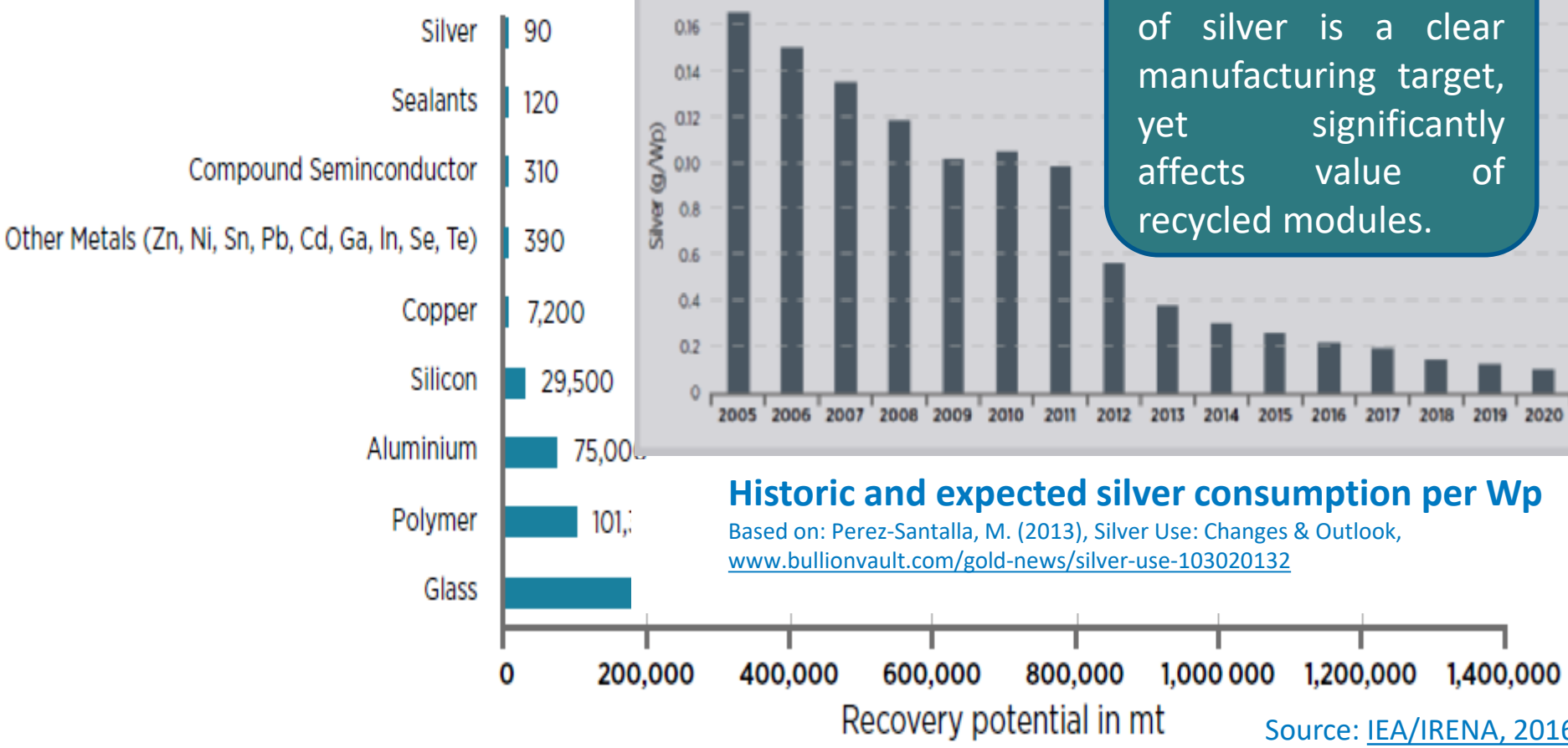
- PV R&D has set priority topics for material use **reduction** or substitution for different components commonly used in today's PV panels (e.g., Si, Ag)
- **Reusing** modules (potentially preceeded by repairing) is conceivable, but practically and economically challenging
- **Recycling** processes for thin-film and crystalline silicon PV panels have been developed and to some extent implemented on industrial scale (outside US mostly), but more development is needed
- Significant recovery potential for different material streams can be realized through ***high-value recycling*** which is not common today



Source: IEA/IRENA, 2016

Why Recycle Modules? ... Recovery of Valuable or Toxic Materials

Cumulative technical potential for end-of-life material recovery (under the regular-loss scenario and considering anticipated changes to module design, like dematerialization)



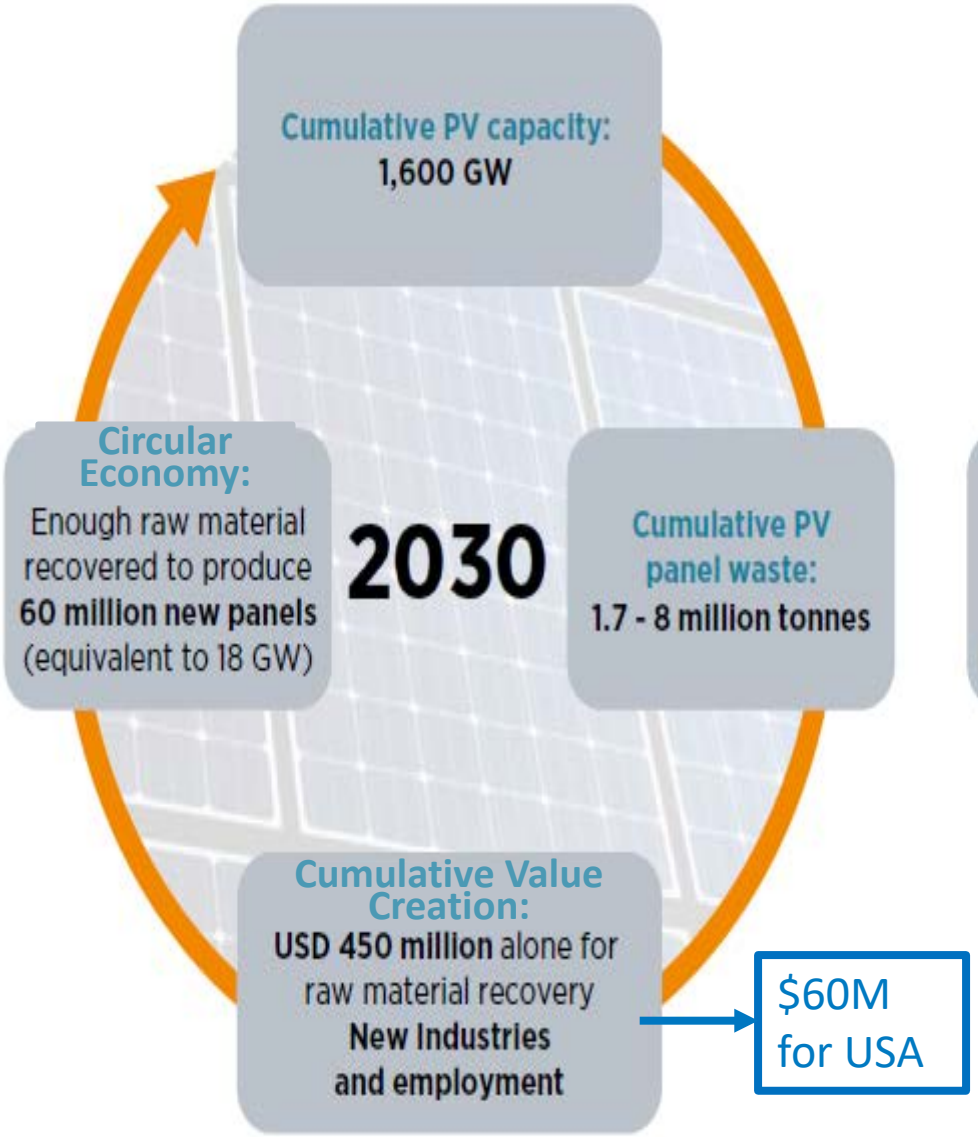
Reduction of the use of silver is a clear manufacturing target, yet significantly affects value of recycled modules.

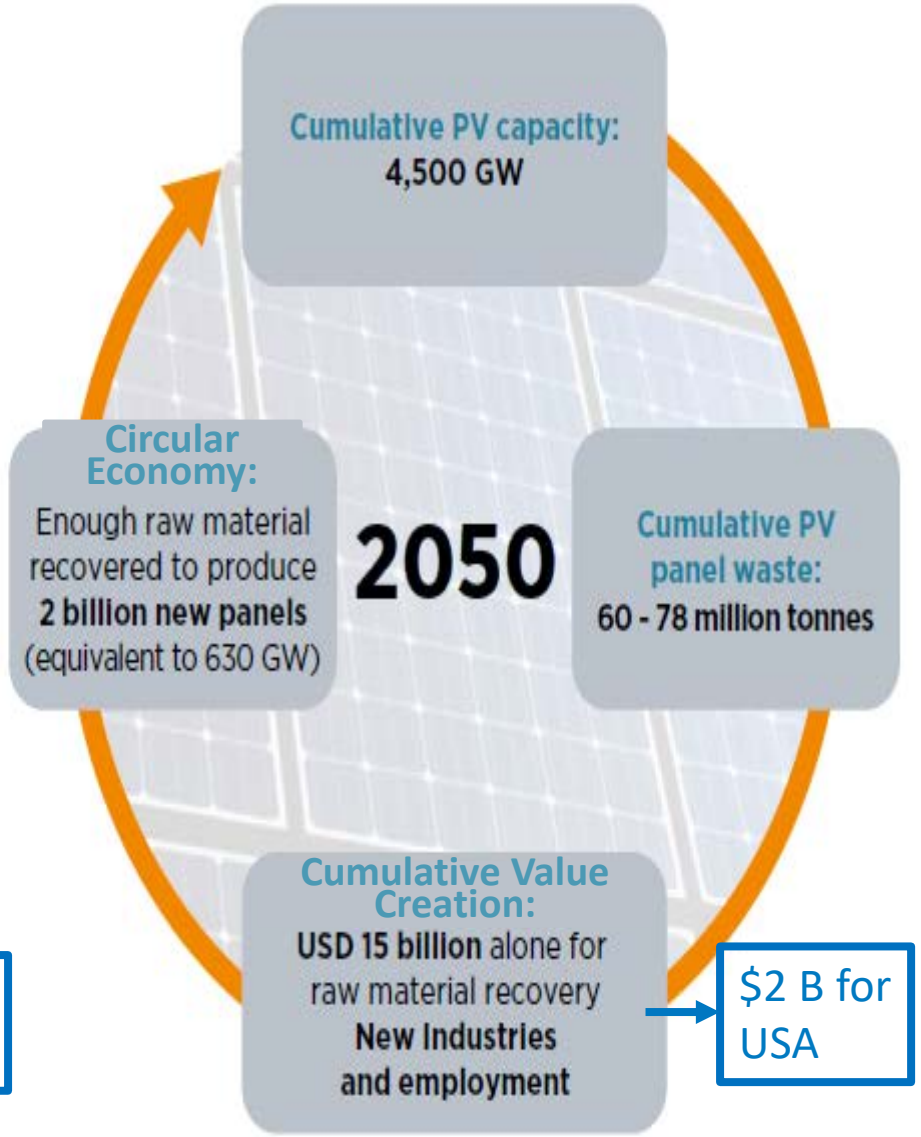
Historic and expected silver consumption per Wp

Based on: Perez-Santalla, M. (2013), Silver Use: Changes & Outlook, www.bullionvault.com/gold-news/silver-use-103020132

Source: IEA/IRENA, 2016

Potential Value Creation – A New Waste Management Industry?





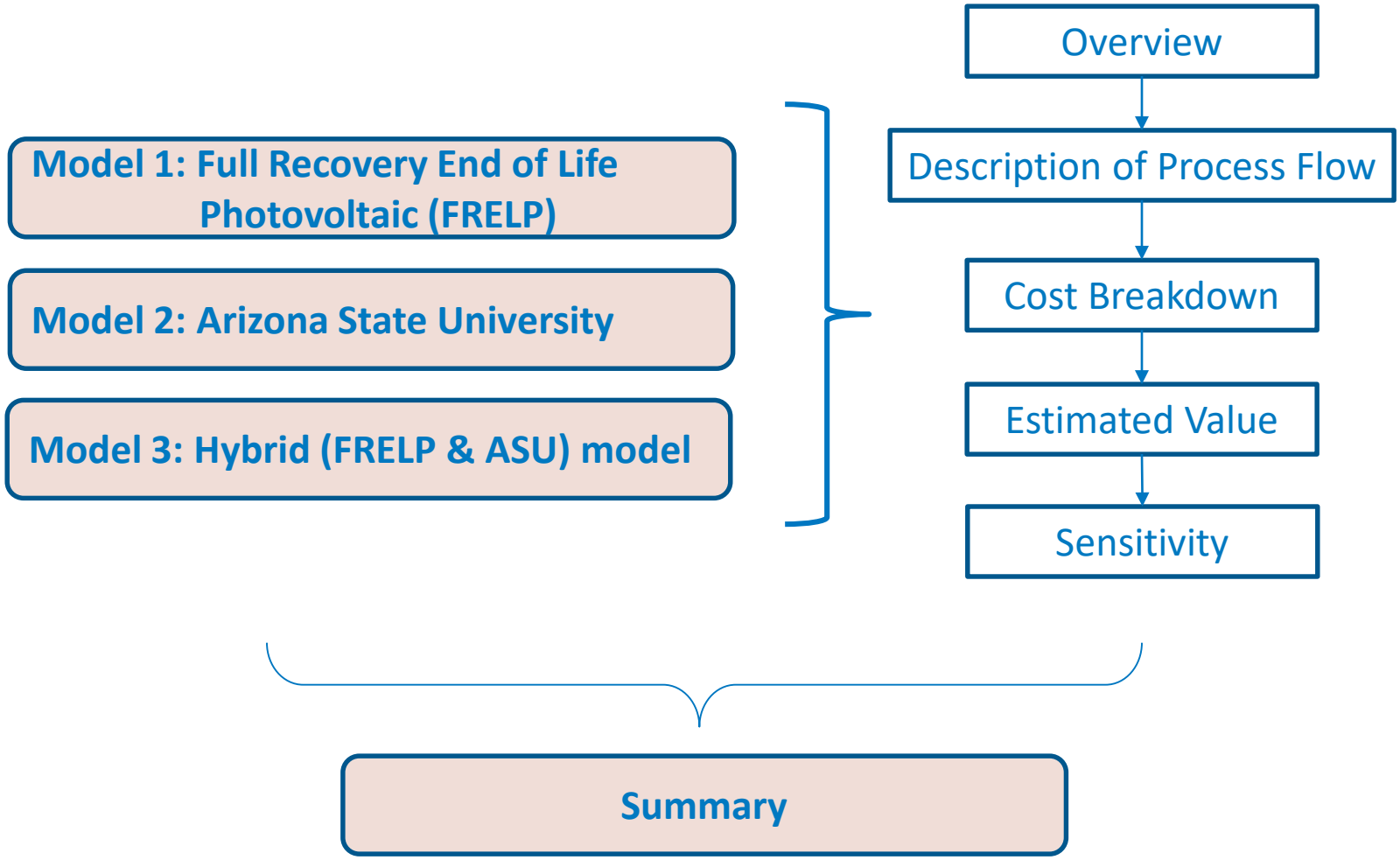
Source: IEA/IRENA, 2016

Trends in PV Recycling Technologies

Takeaways

1. US is far behind other countries especially in public sector support
2. Most effort to-date has been focused on easiest material targets and not integrated to recover all toxic and valuable materials in one, integrated process ("high value recycling")
3. No one process has emerged as preferred, and "high value recycling" has yet to be established in the US
4. A recycling R&D roadmap could focus efforts toward economical and effective high-value recycling technologies, especially for c-Si PV

Techno-Economic Analysis of Advanced Recycling Processes to Discern Cost Drivers and Identify R&D Targets

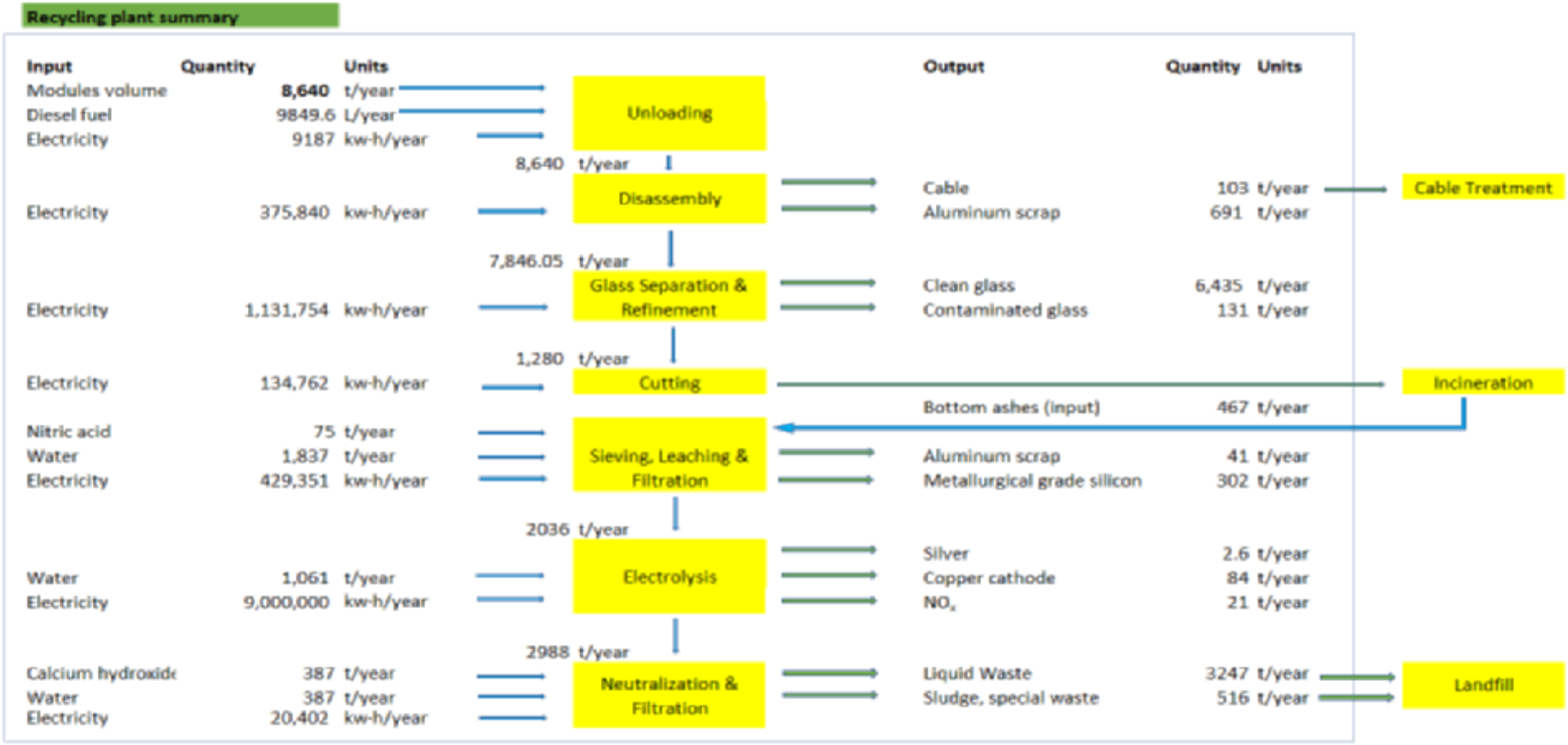


Simplified Process Flow – Example of pilot-scale facility in Italy (FRELP)

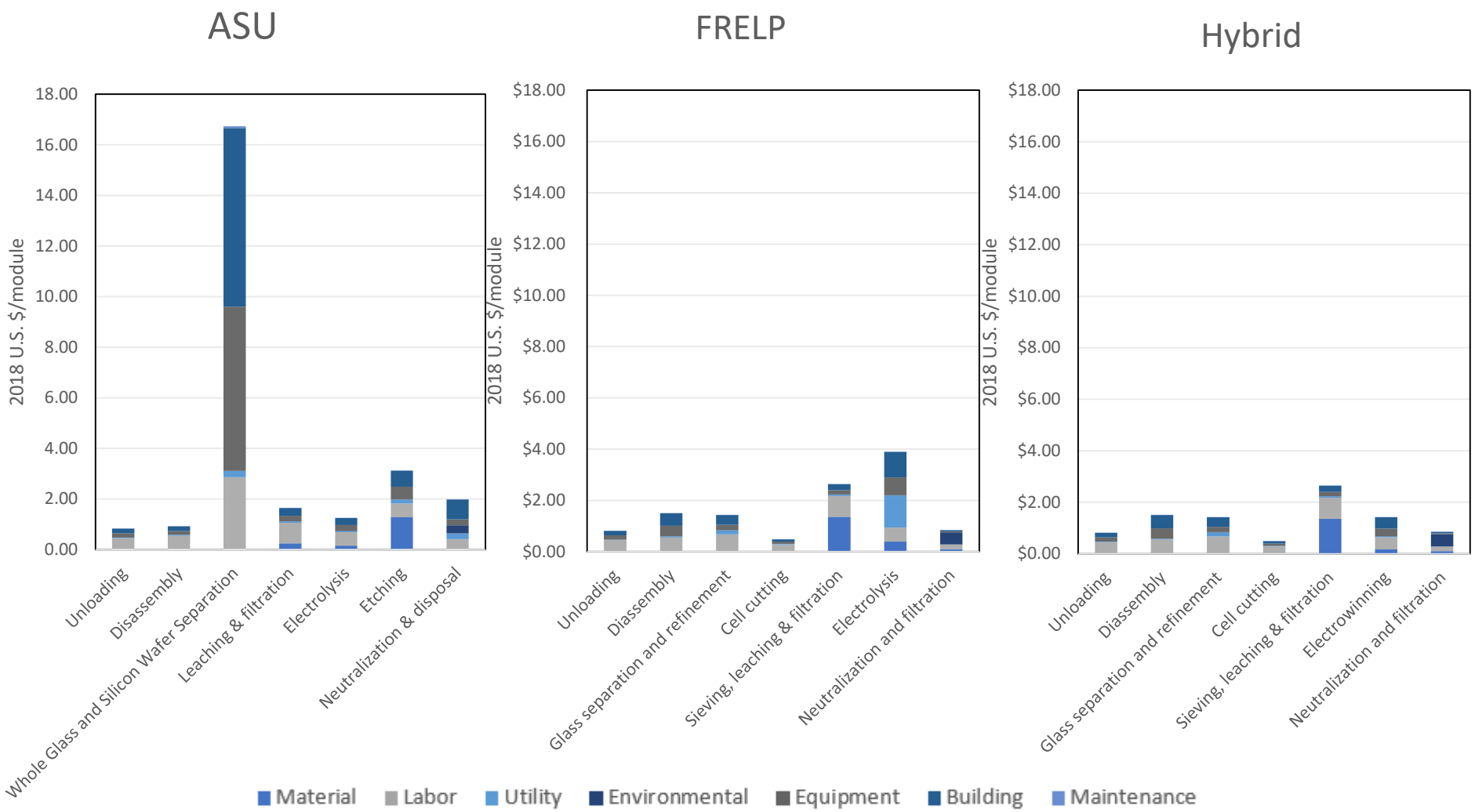
Step	Processing Name[1]	Description[1, 2]
1	**Unloading**	Removal of modules from shipping packaging and staging for processing
2	**Disassembly**	Removal and sorting of frames, cables, and junction box from each module
3	**Glass Separation and Refinement**	Removal of glass from backsheet by knife cutting after an infrared furnace has weakened polymer bond between glass and backsheet
4	**Cell Cutting and Incineration**	Size reduction of solar cells (on-site) followed by removal of organic binders (EVA and Tedlar® layer) from cells through incineration (off-site)
5	**Sieving, Leaching, & Filtration**	On the bottom ashes returned from the incinerator, screening is used to remove aluminum metals followed by a wet chemical leaching processing to dissolve silver and copper and prepare the appropriate electrolyte solution for electrolysis, while a filtration process is used to separate undissolved particles (metal silicon) from the leaching solution.
6	**Electrolysis**	Wet electro-chemical material refinement process (electrowinning, fusion and electrorefining) to collect precious and non-precious metals (copper and silver)
7	**Neutralization and Filtration**	Process to neutralize remaining waste materials and separate into materials to send to a standard or toxic waste landfill.

Detailed Process Flow – NREL's Bottom-Up Manufacturing Cost Modeling Approach Applied to Recycling

- Track required inputs (energy, consummables) for each step and compute the outputs of emissions, wastes, and materials recovered.
- Assign cost to each step – OpEx and CapEx – estimated based on literature review, industry interviews, academic research, and material/equipment quotes.
- The figure below depicts the mass flow of material required for processing 24 t/day or 1297 modules/day (i.e., pilot scale)

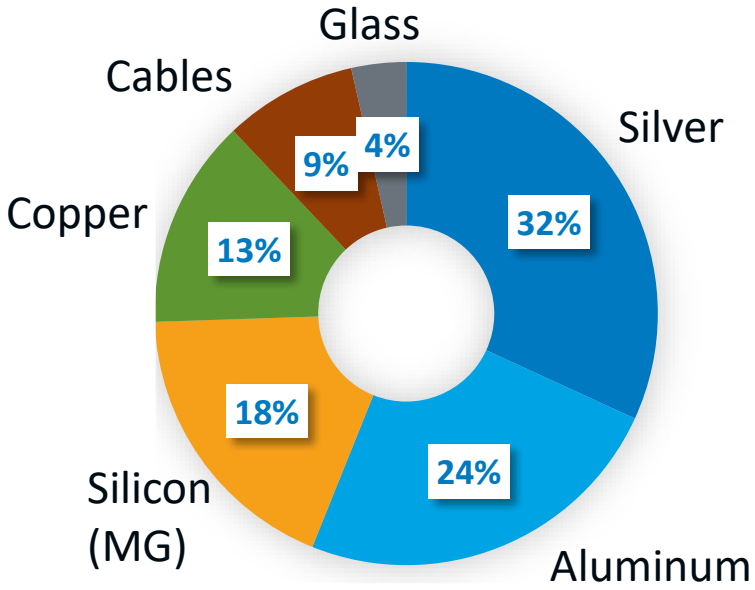


Cost Breakdown by Processing Step



FRELP Revenue from Material Recovery

Revenue	Market Rate	Unit	Revenue $/module
Silver	15.5	$/toz	2.72
Aluminum scrap	0.6	$/pound	2.07
Silicon[7]	1.1	$/pound	1.57
Copper	2.9	$/pound	1.15
Insulated cable	1.51	$/pound	0.73
Glass cullet	20	$/ton	0.30
Sum			8.54

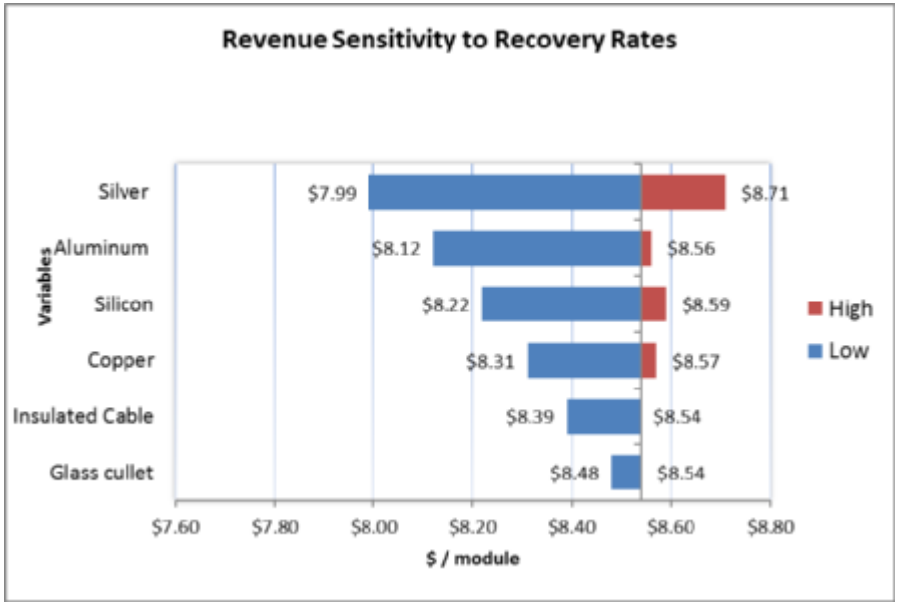


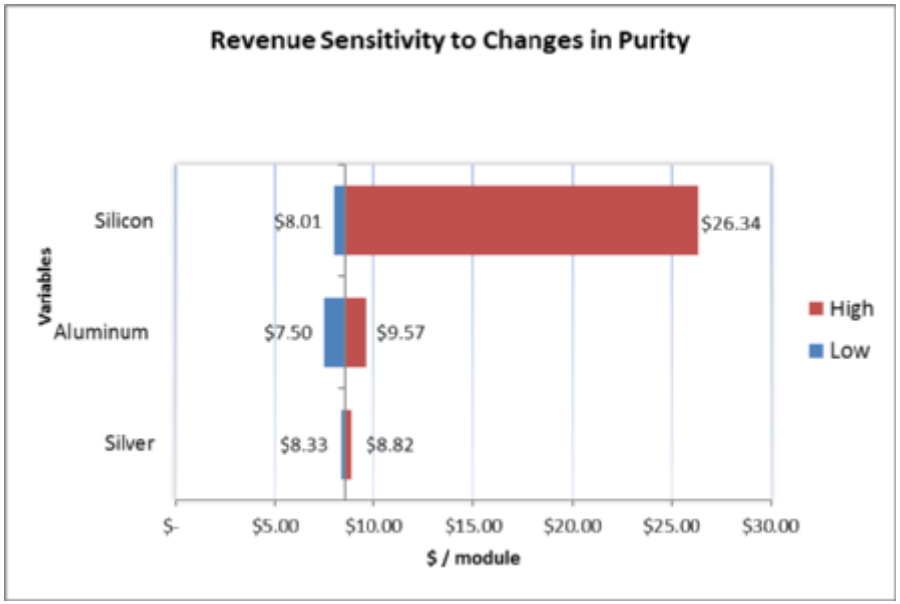
Notes: a) Market prices estimated based on commodity prices (copper, silver), quotes from recycling companies (glass, Al) and a USGS report (silicon)
b) The purity of the silver is assumed to be 99%. To refine silver from 99% to 99.99%, approximately $0.15/toz is charged[9]. The revenue shown above includes this cost.
c) Silicon is assumed to be metallurgical grade (not solar-grade).
e) Recovery rates: glass 98%, Ag 94%, Cu 97%, Si 95%, Al 99.4%;

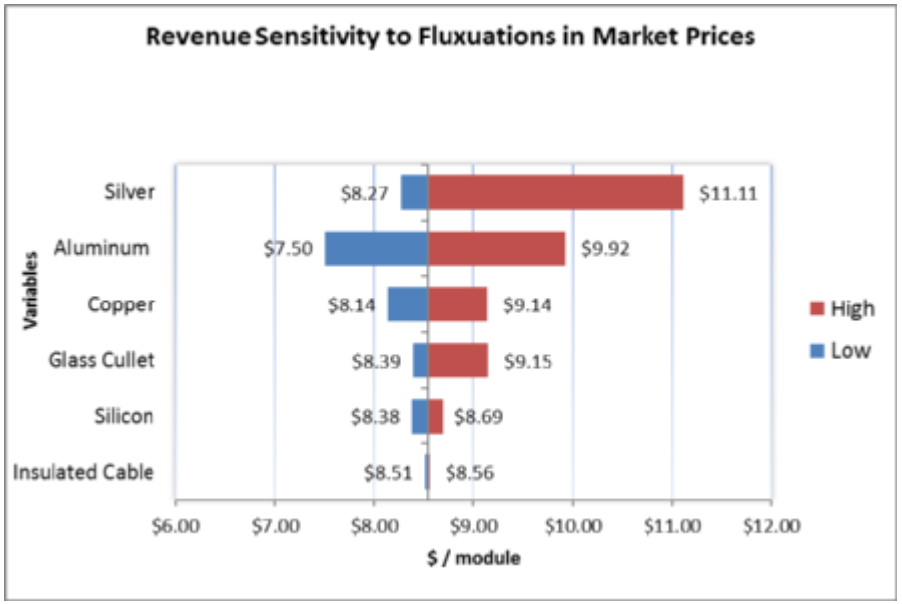
- There are additional points of value as well:
  - Reduced costs of alternative treatment, e.g., reduced landfill fees as well as costs of properly classifying the material waste.
  - PV recycling infrastructure would be a domestic industry, not offshored: jobs, direct and indirect/induced economic impact

Revenue Sensitivity Analysis: Purity, Recovery Rate, Market Price

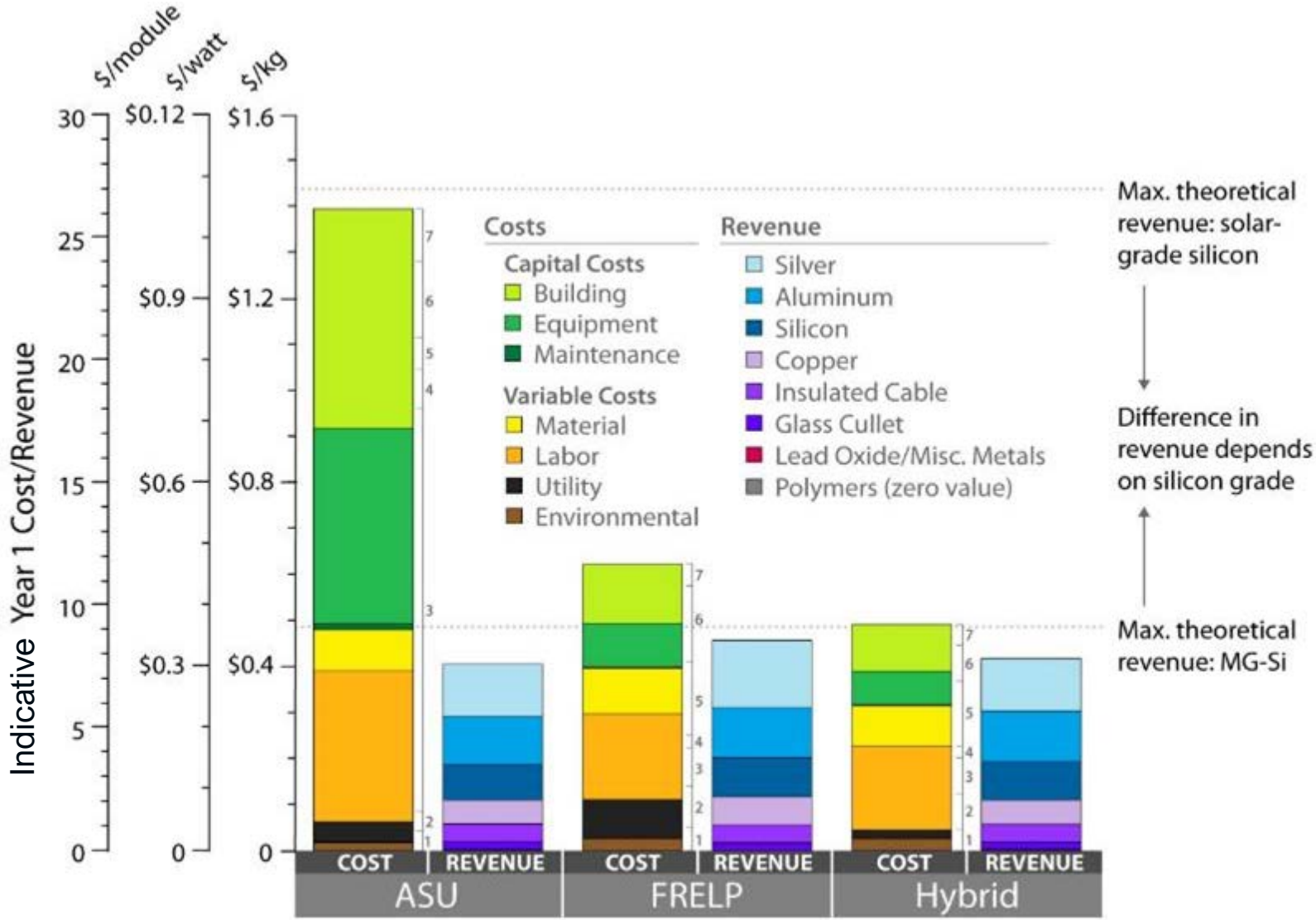
Parameters for the base case ($8.54 / module)			
Product	**Recovery**	**Purity**	**Market price**
Insulated Cable	100%	N/A	$1.51/lb
Silver	94%	99%	$15.5/toz
Copper	97%	N/A	$2.9/lb
Aluminum	99.4%	Scrap	$0.6/lb
Silicon	97%	Metallurgical grade	$1.1/lb
Glass cullet	98%	N/A	$20/t







Indicative Year 1 Costs and Revenue – Surcharge is Required, Improvements to Yield and Purity Can Improve Economics



Note: Year 1 cost-revenue balance does not ensure long-term profitability – need to calculate Minimum Sustainable Price

Preliminary R&D recommendations

- Current recycling costs are high relative to landfilling or other options
  - R&D and industrial experience is needed to reduce cost, increase material recovery rates, increase purity and decrease contamination
- Science questions
  - What are the mechanisms and effect of contamination of Silicon wafers during use and through recycling processes? This influences what can be done with recovered wafers.
  - How much fluorine gas is produced from thermal treatment of modules and how does fluorine gas treatment effect design and cost of recycling processes? What are the tradeoffs for use of non-fluorinated backsheets?
  - Are there upgrading steps that could turn waste streams into value co-products?
  - Could the energy use, purity and recovery fraction from electrolysis be improved with pre-treatment steps?
- Analysis questions
  - What will be the market size for PV waste in the US in future years from multiple sources
    - Manufacturing scrap
    - Early retirement – disasters, repowering
    - True end of life (after 20-30 year lifetime)
  - What is the total value proposition of recycling as compared to reuse, repair, remanufacturing, or disposal?
  - How do costs and effectiveness compare between different recycling policy design options including consideration of collection systems through treatment and disposal?
  - What are limitations and challenges to circular economy of PV modules given current codes, standards, regulations?

Thank you!

Garvin.Heath@nrel.gov

Collaborators:

Tim Silverman[1], Hao Cui[2], Timothy Remo[1], Michael Kempe[1], Michael Deceglie[1], Dwarakanath Ravikumar[3], Parikhit Sinha[4], Cara Libby[5], Stephanie Shaw[5], Evelyn Butler[6], Teresa Barnes[1], Andreas Wade[4]

1 National Renewable Energy Laboratory
2 Colorado School of Mines
3 University of Michigan
4 First Solar
5 Electric Power Research Institute
6 Solar Energy Industries Association

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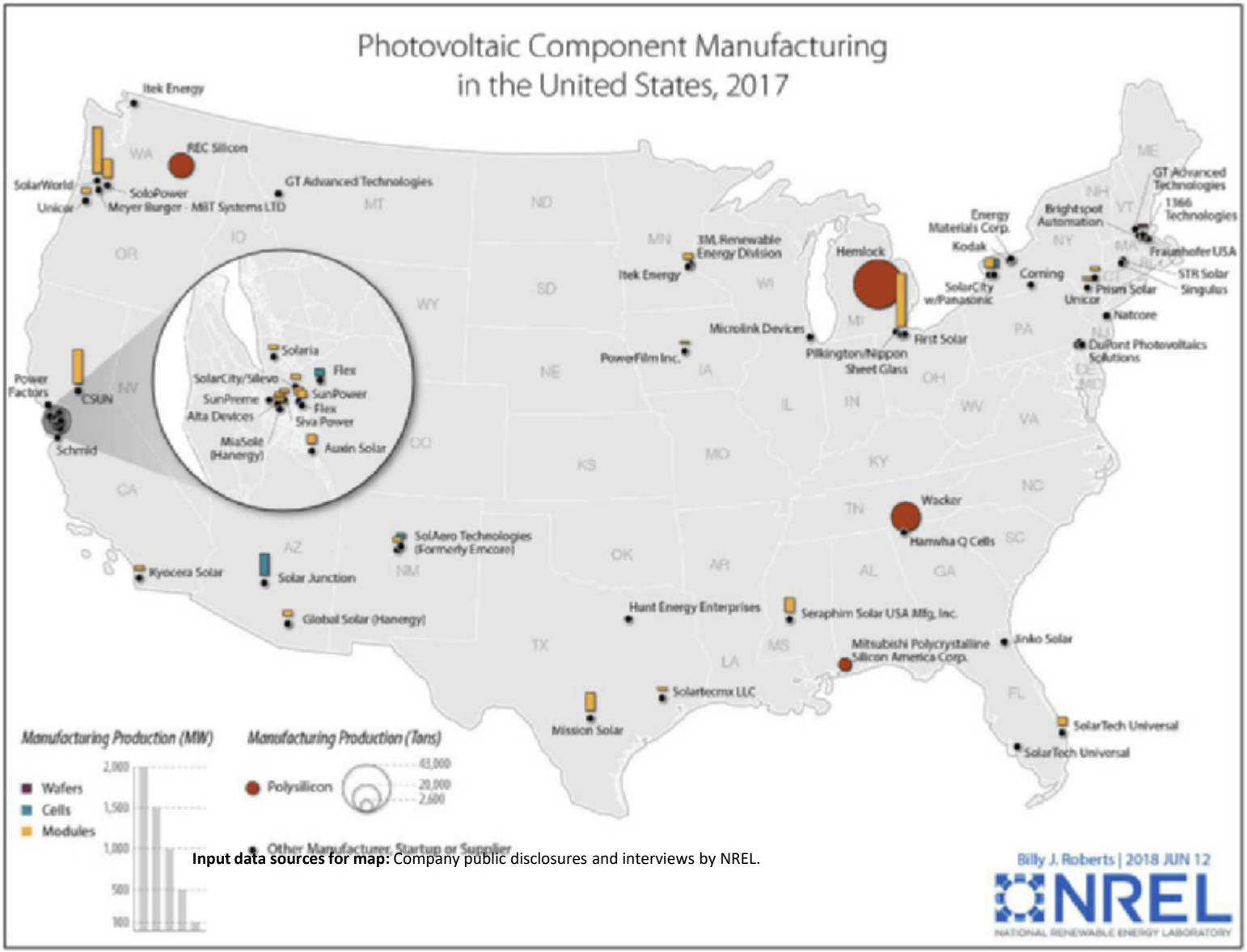
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Supplementary Slides

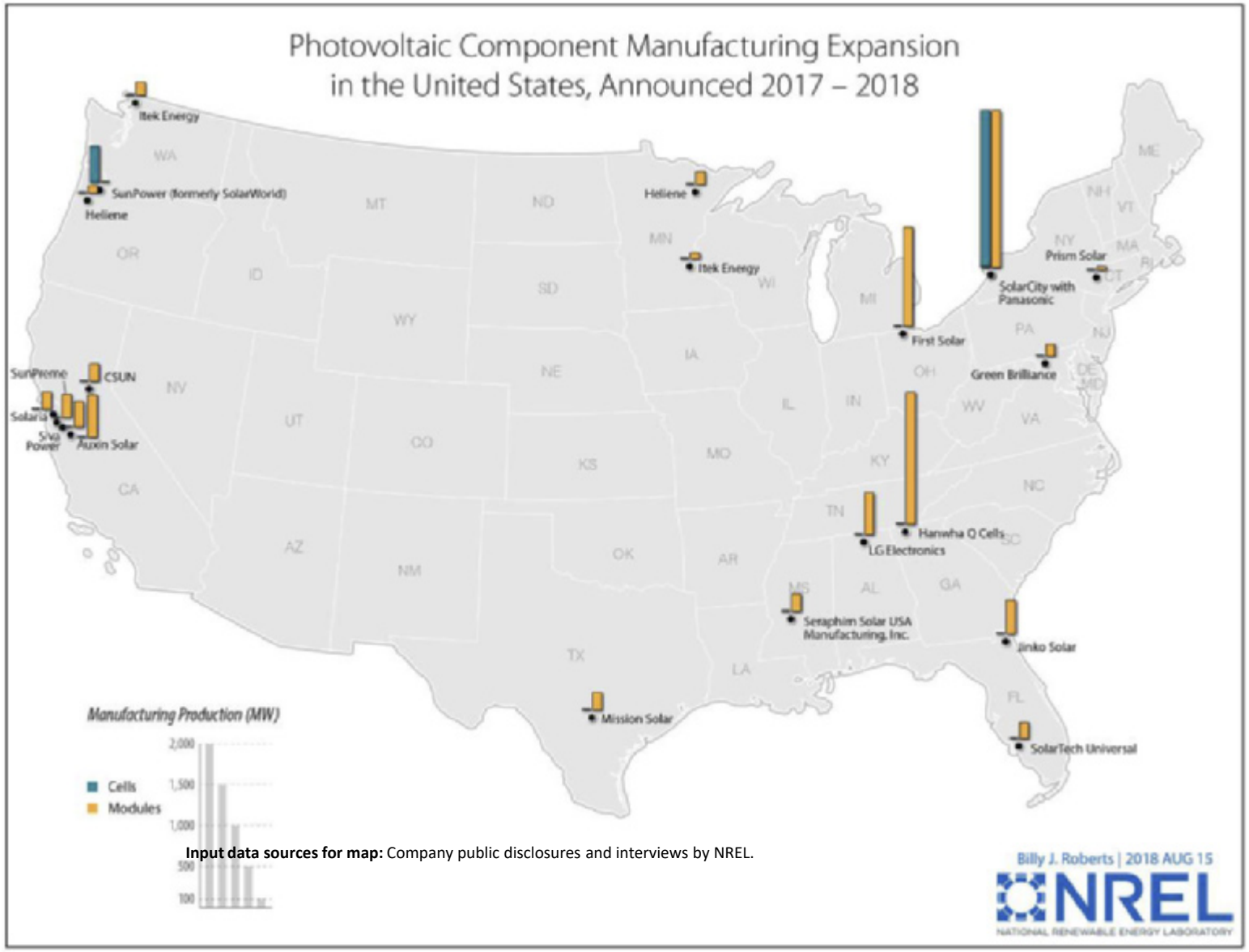
Growing PV Waste Source: Manufacturing Scrap

2017 Polysilicon, Wafer, Cell, and Module Capacities. Startup Companies, Materials, and Equipment Suppliers Locations.



Source: Michael Woodhouse, NREL

New Capacity Announcements Made in 2017 and 2018



Source: Michael Woodhouse, NREL

Extending the Value Chain – Cooperation Among New Partners Will Be Important to Create a Vibrant Industry

R&D Organisations

- Public and private institutions
- Producers

Repair/Re-use services industry

- Producers
- Independent services partners
- Producer-dependent contract and service partners (e.g. installation and construction companies
- Waste collectors and companies
- Pre-treatment companies

Recycling treatment industry

- Public waste utilities and regulators
- Waste management companies
- Pre-treatment companies
- Producers

Optimal PV recycling industry will integrate features and actors from energy and waste sectors

Source: IEA/IRENA, 2016

R&D Challenges

Waste Management and Recycling

Challenges are to prepare the technologies, systems and policies to manage decommissioning and disposal of end-of-life modules that can

- Minimize costs and
- Minimize environmental impacts, while
- Maximizing materials recovery.

Design for Recycling

Conversely, one way to facilitate economical recycling and maximize material recovery is to design new modules that

- Increase speed and ease of dismantling,
- Improve rate and purity of recovered materials, and
- Reduce waste.

A Market Pull for Recycling?
New Sustainability Leadership Standard for PV Modules

- "NSF 457" – Sustainability Leadership Standard for PV Module Manufacturing (ANSI standard, published December 2017)
  - Comprehensive framework for the establishment of product sustainability performance criteria and corporate performance metrics that exemplify sustainability leadership in the market with third party verification
  - Aims to enable easier specification of high sustainability performance in large purchase contracts of PV modules, alleviating individual purchasers from the arduous and complex task of defining sustainability performance for PV modules
    - Potentially adopted by Green Electronics Council as a new category within the successful EPEAT registry
  - Three tiers of performance: Bronze, Silver, Gold
    - Based on the principle that only leaders – those in the top third of the market – are expected to qualify to the standard at the Bronze level at the date of publication of the standard
    - Very few will qualify for Silver and Gold

(ANSI) NSF 457 Scope

Sustainability Performance Categories

- Substance Management
- Manufacturing Chemicals
- Preferable Materials
- Design for Recycling
- Product Packaging
- Responsible End of Life Management
- Water Use
- Energy Management
- Life Cycle Assessment
- Corporate Environmental Performance
- Corporate Social Performance
- Conflict Mineral Sourcing

(ANSI) NSF 457 Scope

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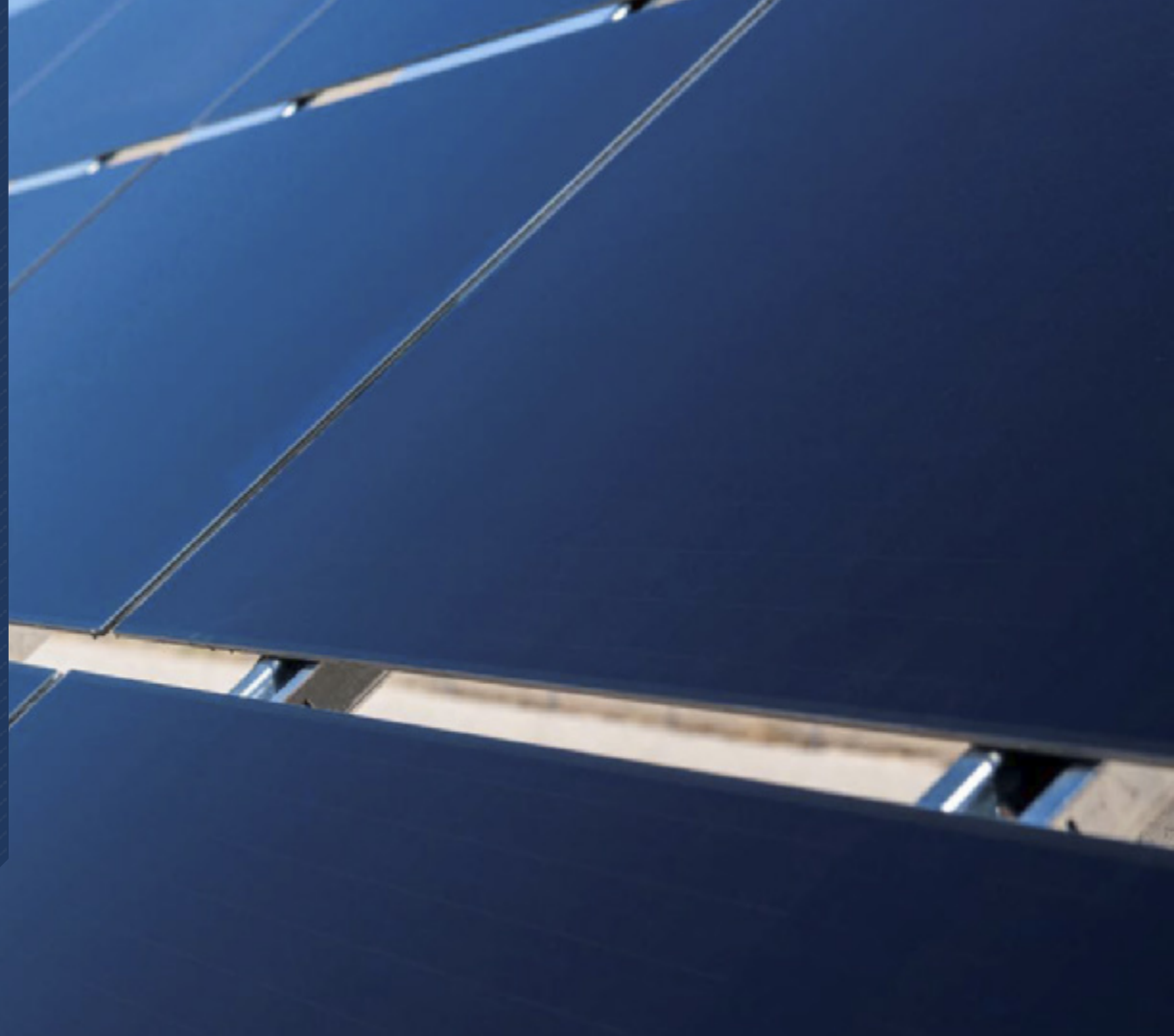
HIGH VALUE PV RECYCLING APPROACH

Parikhit Sinha
NREL PVRW 2019

First Solar®



FIRST SOLAR AT A GLANCE

Globally recognized for environmental performance and excellence

High-efficiency technology with a proven energy advantage

Lowest environmental impacts generating clean electricity with NO carbon emissions or air pollutants

Industry-leading global PV recycling program

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PROVIDING THE LEADING ECO-EFFICIENT PV TECHNOLOGY

SUPERIOR ENERGY YIELD

COST COMPETITIVE

LOWEST ENVIRONMENTAL IMPACT

- Higher energy yields at a competitive cost
- Smallest carbon footprint and air pollutants
- Lowest life cycle water use
- Fastest energy payback time < 1 year
- Industry leading PV recycling program
- Validated by 3rd party research and global peer reviews

Creating more value with less environmental impact.

Seitz et al., Eco-Efficiency Analysis of Photovoltaic Modules, Bavarian State Ministry of Environment and Health, 2013.

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FIRST SOLAR IS COMMITTED TO ENVIRONMENTAL STEWARDSHIP

- Providing value-driven energy solutions that protect and enhance the environment
- Committed to responsible product life cycle and end-of-life management
- Ensuring solutions to clean energy do not pose a burden on future generations
- Leading the industry with proven recycling solutions
- Fulfilling solar's promise as a clean and sustainable renewable source of energy

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WHY RECYCLE?

Recycling is in the power plant owner's best interests:

- Commercially attractive: recycling will likely be cheaper than disposal at EOL
- Landfill disposal will become increasingly costly and burdensome
- Global regulatory developments will continue to limit disposal options and move towards requiring recycling
- Mitigates risk of uncontrolled disposal
- Allows for recovery and beneficial reuse of valuable materials
- Reduces waste and the carbon footprint and energy payback time of PV modules
- Positive image: Demonstrates the power industry is responsible and self-regulating
- Supports scalability and overall sustainability of PV

Enlightened self interest…It is the right thing to do.

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CIRCULAR ECONOMY: BEYOND WASTE

TYPICAL RECYCLING RATES

AUTOMOTIVE
~75%

INFORMATION TECHNOLOGY
~45%

FIRST SOLAR MODULES
~90%

THE VALUE LOOP

SEMICONDUCTOR FROM MINING BY-PRODUCTS

THIN FILM PV MANUFACTURING

Resource-Efficient Manufacturing

DISPLACE GRID EMISSIONS

25+
Years of Deployment

FIRST SOLAR RECYCLING SERVICES

90% RECOVERY RATE

GLASS: Used to make glass products

ENCAPSULANT: Used to make rubber products

SEMICONDUCTOR: Reused to produce First Solar modules

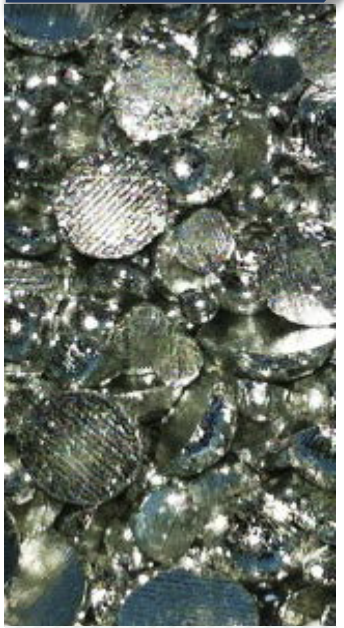
1Kg	40x	1,230 years
Of CdTe Semiconductor	Times it can be recycled	Years it can generate electricity

First Solar.

FIRSTSOLAR.COM/SUSTAINABILITY

FULLY INTEGRATED RESPONSIBLE PRODUCT LIFE CYCLE APPROACH

Material Sourcing



Converting mining byproducts into a stable semiconductor

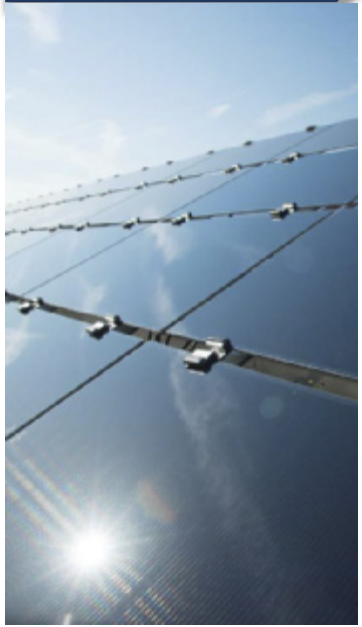
Product Design

Designed for high-value recycling

Manufacturing

Manufacturing with less energy, water, and GHG emissions

Product Use



Faster CO_2 reductions and greater return on energy invested

Collection & Recycling

Recovering over 90% of materials at end-of-life for new PV modules

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FIRST SOLAR PRODUCT DEVELOPMENT APPROACH

- Continuously improving our technology while ensuring recyclability
  - Recyclability is fully integrated in module design
  - Product development budget allocates funds for recycling process upgrades
  - Technology improvement projects are tracked through Change Management System (CMS)
  - Module improvement projects require timely implementation of recycling process upgrades

Ensuring the recyclability of our products is integral to our R&D process.

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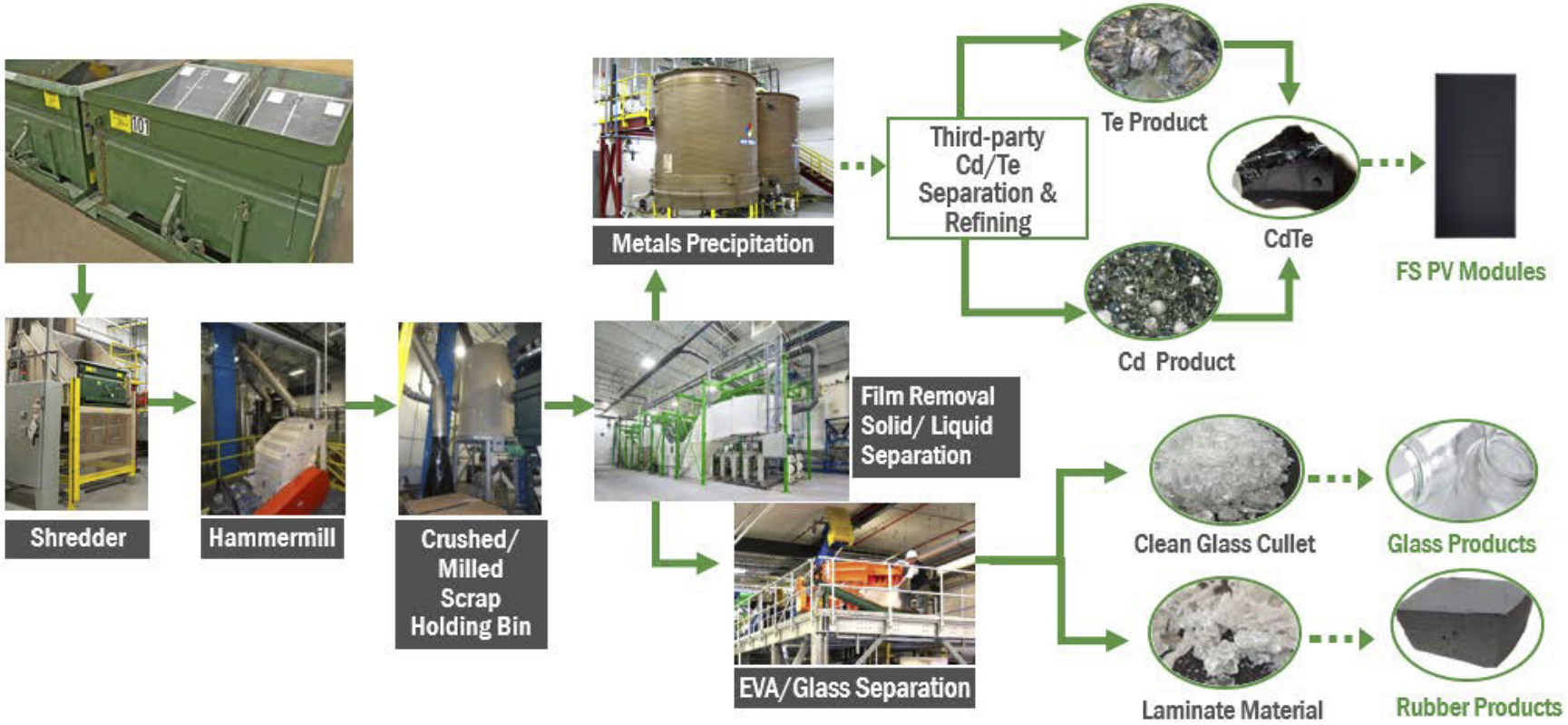
FIRST SOLAR MODULE RECYCLING PROCESS



+ 90% Recycling of Semiconductor Material and ~ 90% Recycling of Glass

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FIRST SOLAR'S RECYCLING PROCESS DESIGN PROGRESSION

V1 Recycling (2006)

- Based on the mining industry
- Batch process
- Moving glass and liquid from process to process
- Volume output – 10 tons/day
- Capital investment - $5M

V2 Recycling (2011)

- Based on the chemical industry
- Batch process
- Based on keeping the glass fixed and moving the liquids thru the material
- Volume output – 30 tons/day
- Capital investment - $7M

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THIRD GENERATION CONTINUOUS PROCESS RECYCLING (2015)

- More efficient 24/7 operations
- Compact plant with smaller footprint
- Increased daily recycling capacity from 30 tons to 150 tons/day capacity
- Requires 30% less capital, chemicals, waste and labor
- Achieves superior glass and semiconductor purity

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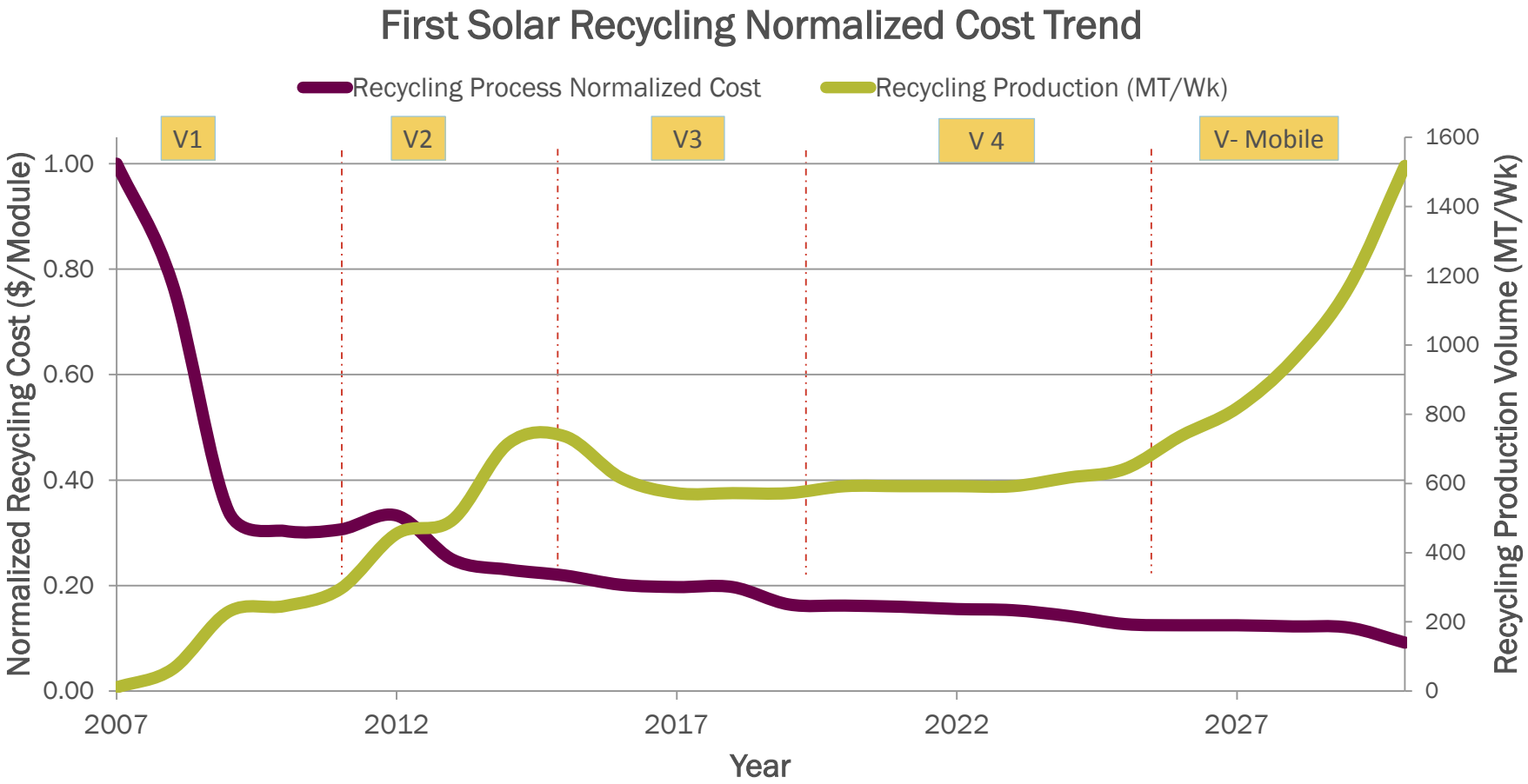
CONTINUOUSLY DRIVING DOWN COSTS FOR SUSTAINABLE PV RECYCLING



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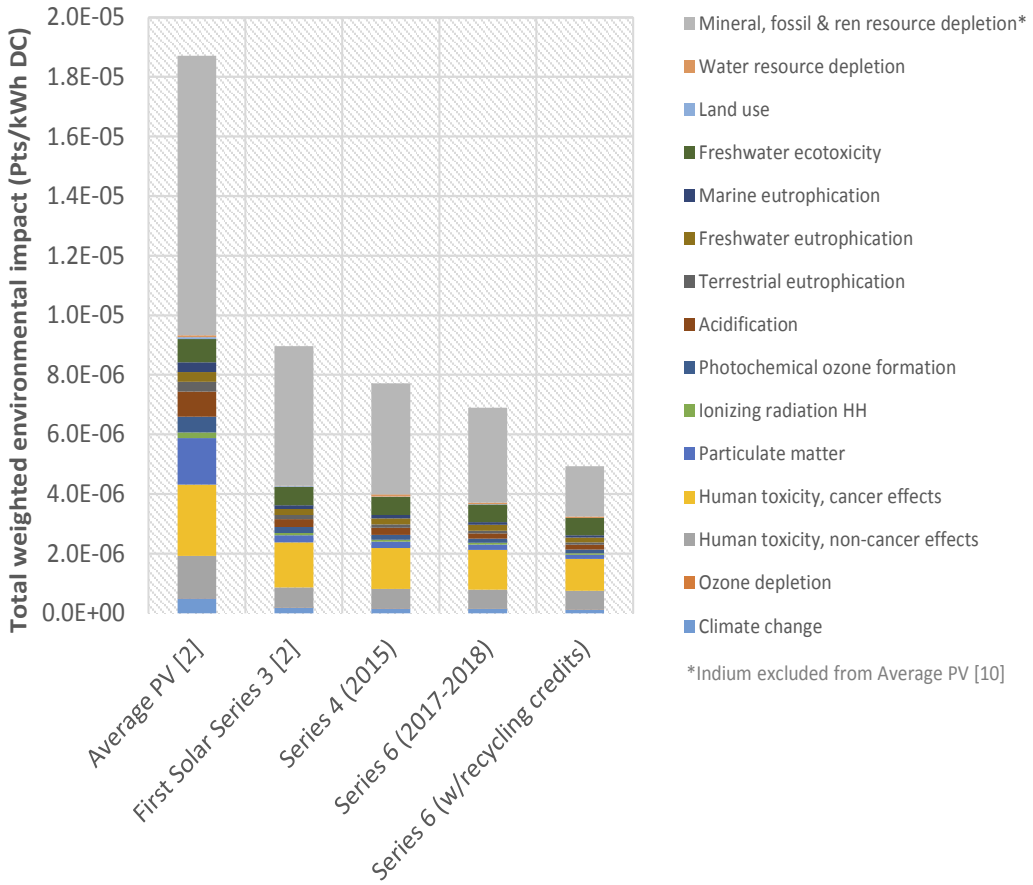
BENEFITS OF HIGH VALUE RECYCLING

Measures that enable and encourage circular economy and the decarbonization of the supply chain of electricity would help to effectively relieve some of the major hotspots by addressing resource depletion (through recycled content) and reducing emissions from fossil-fuel based electricity generation.



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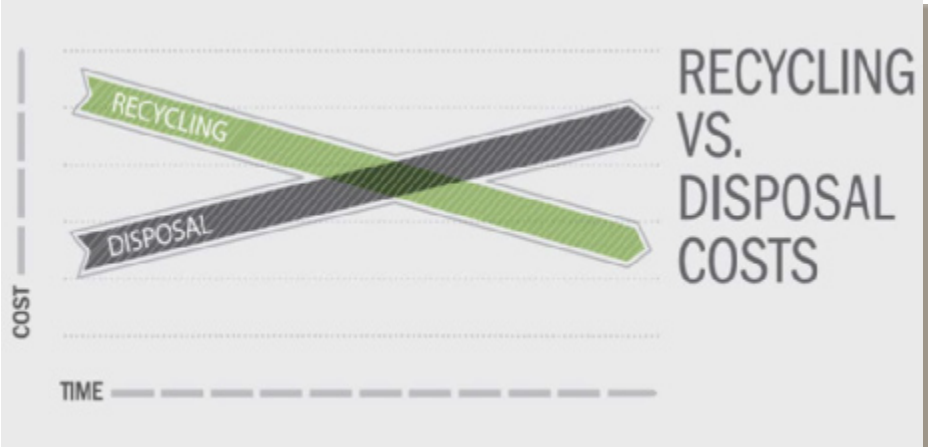
FINANCING PV RECYCLING: PRE-PAY VS. PAY-AS-YOU-GO

Pre-Pay / Pre-fund	First Solar RSA
Customer pays for EOL collection and recycling at time of sale and funds are placed in an independent trust fund	Customer contractually commits to recycling through an RSA with 2-year termed renewable pricing. EOL recycling is funded with later year project cash flows
✓ Convenient ✓ Effective for low volumes ✗ Inefficient use of customer cash flows ✗ Not cost-effective or scalable ✗ Not competitive	✓ Globally available ✓ Cost effective and scalable ✓ Optimized use of cash flows ✓ Convenient and comprehensive ✓ Flexible pay-as-you-go service ✓ Allows prices to drop as recycling costs decrease



Increased volumes of solar modules at end-of-life and greater experience in recycling, accompanied by rising disposal costs, will likely lead to recycling becoming more commercially attractive and result in higher volumes of collection and recycling.

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BENEFITS OF FIRST SOLAR'S RECYCLING PROGRAM

Environmentally Responsible

- Minimizes life cycle impacts and reduces carbon footprint and energy payback time of PV
- Maximizes resource recovery: over 90% of semiconductor material and 90% of glass

Commercially attractive

- No up-front fees: modules can be recycled using later year project cash flows
- Renewable pricing adjusts RSA price as recycling costs decrease

Globally Available

- Convenient way of helping you meet various regulatory and permitting requirements

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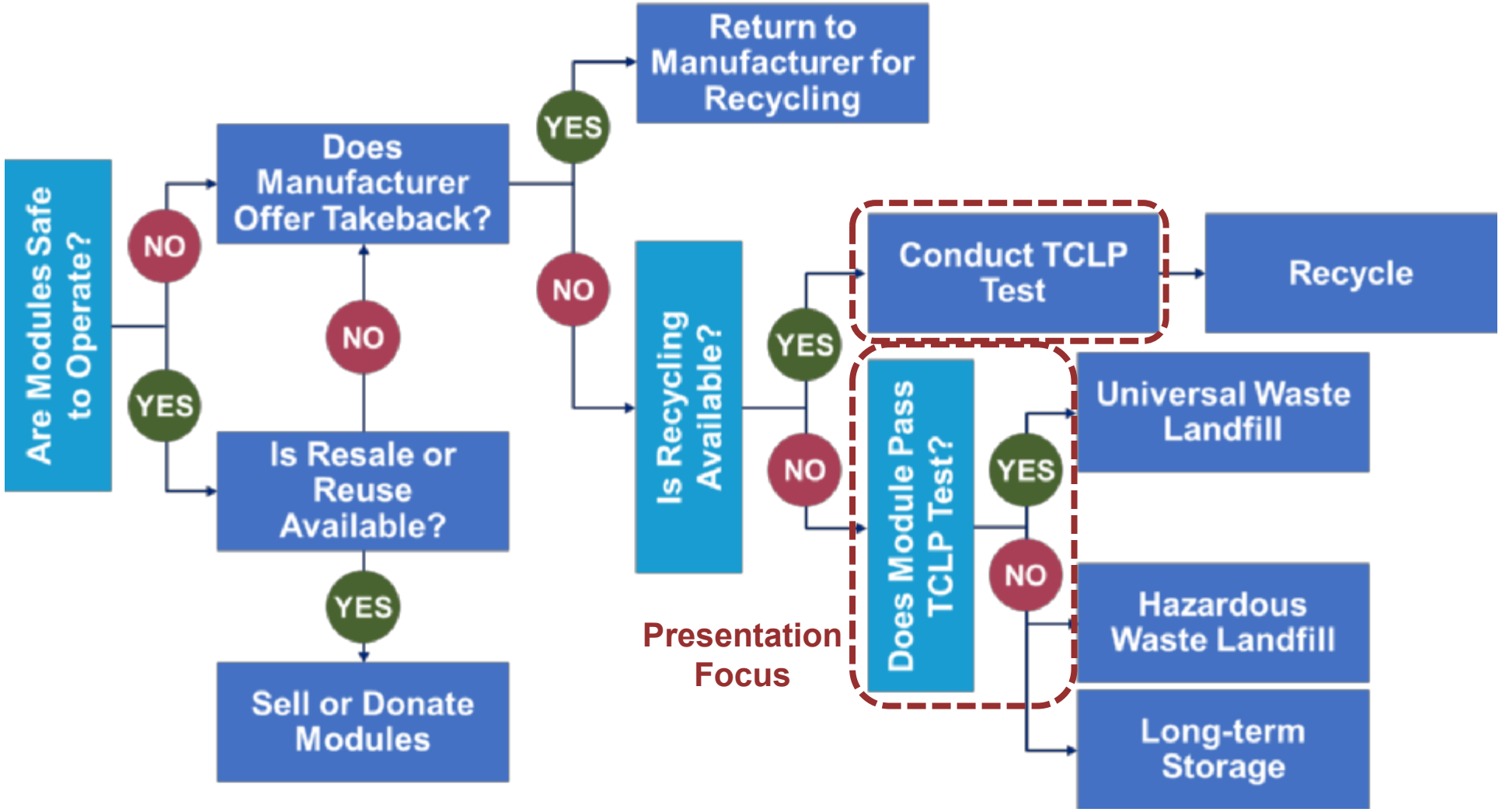
Assessing Variability in Toxicity Testing of PV Modules

GovindaSamy TamizhMani, Arizona State University
Cara Libby, EPRI

PV Reliability Workshop
Lakewood, CO
2019-02-28

End-of-Life Decision Tree



Proper disposal is important to avoid costly excavation/resurfacing of materials later for enhanced treatment

Background

- PV modules that contain hazardous materials like lead and cadmium have the potential to contaminate ground and surface water if elements leach out during landfill disposal
- Toxicity is determined using the TCLP (toxicity characteristic leaching procedure) test specified by Environmental Protection Agency (EPA) Method 1311
  - Landfill disposal is allowable if within toxicity limit of regulatory requirements
  - Recycle or hazardous waste disposal is necessary if the toxicity limit of regulatory requirements is exceeded

Sources of variability in test results:

1. ***Removal of representative sample pieces from the test module***
2. ***Analyte preparation by TCLP labs from sample pieces (assumed accurate)***
3. ***Elemental analysis (assumed accurate)***

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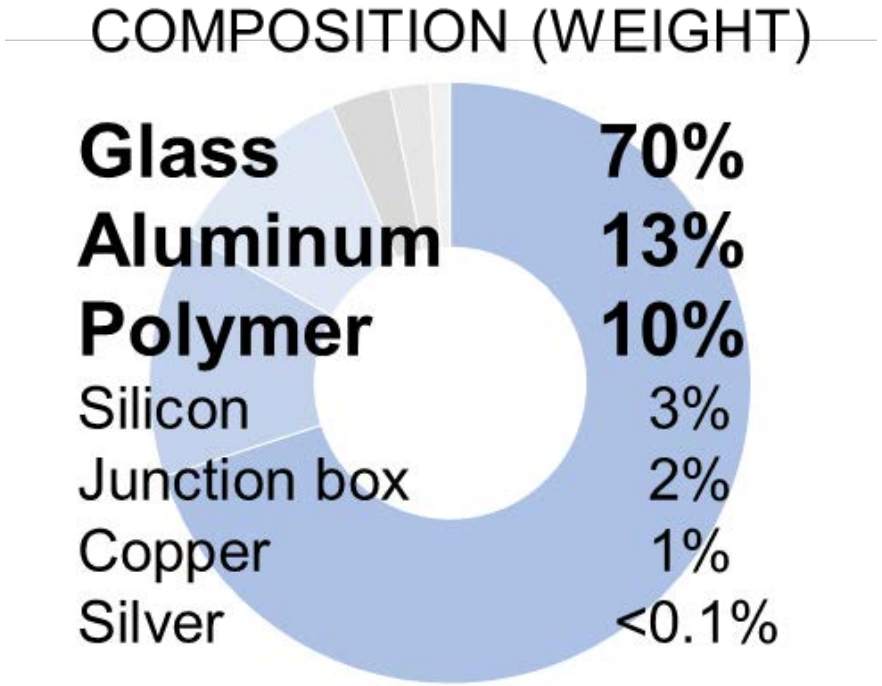
Are PV Modules Hazardous Waste?

- Modules consist largely of recyclable materials but may incorporate hazardous constituents
- Public data are limited on trace hazardous materials in c-Si modules
  - Older c-Si modules are known to exceed the TCLP test standard of 5 mg/L for lead
  - Lead solder content is typically less than 0.1% today



Toxicity testing is often required whether modules are being recycled or going to landfill or long-term storage

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EPRI R&D: PV Module Toxicity Testing

- Project Objectives
  - Identify and characterize potential sources of variation in PV module leach test results
  - Clarify extent to which module toxicity is a pervasive issue and barrier to disposal
  - Fortify and codify robust PV module sampling methods for toxicity testing
- Multi-phase collaboration with Arizona State University is examining factors that may influence TCLP results and pass/fail

Sources: EPRI, 3002014825; G. TamizhMani, C. Libby, S. Shaw, et al., “Evaluating PV Module Sample Extraction Methods for TCLP Testing.” PVSC/IEEE, 2018

Sources of Variability in Test Results

- Variability in removal of sample pieces from module laminate – *focus of this presentation*
  - 110 g (from 20 kg laminate) representative pieces
    - location of pieces on the module
    - particle size (< 9.5 mm)
    - 100% glass coverage: glass/encasulant/cell/encapsulant/backsheet interfaces are intact
    - extracting method (mechanical, waterjet, laser)
- Variability in TCLP analyte preparation
  - No further crushing: requirement in the agreement and instruction on the sample container
  - No reduction in number of supplied pieces: requirement in the agreement and instruction on the sample container
- Variability in elemental analysis
  - Which analytical/test method used

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Sources of Variation in Leach Testing Results

- Initial research suggests large variation in TCLP results:
  - Sampling location on module
  - Removal method
  - Amount of sample crushing
  - Test laboratory
  - Glass tempering

- Guidelines for module sampling and preparation are needed to reduce test variations

Photo credit: Eliza Hotchkiss, NREL

Module pass/fail depends on sampling protocols

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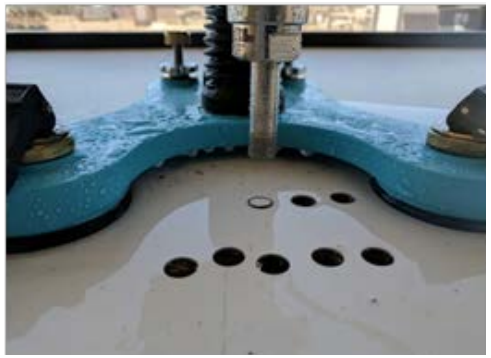
Pilot Testing: Sample Removal Effects on TCLP Results

Objectives:

1. Identify potential sources of variation in TCLP results due to module sampling and preparation methods
2. Develop a non-biased approach for a standardized sampling protocol for PV modules that produces precise and accurate toxicity test results (e.g., no false positives)

Approach

Investigated 4 mechanical sample removal methods & 1 water jet sample removal method

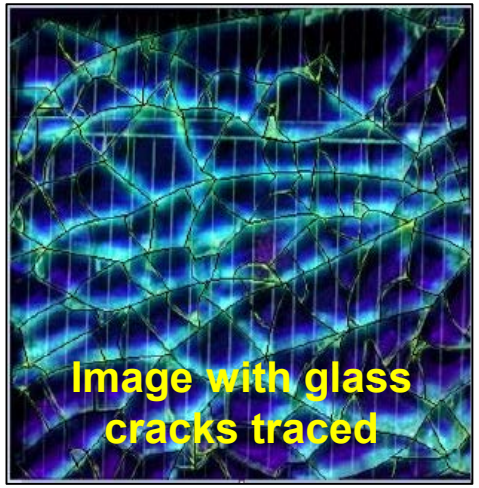


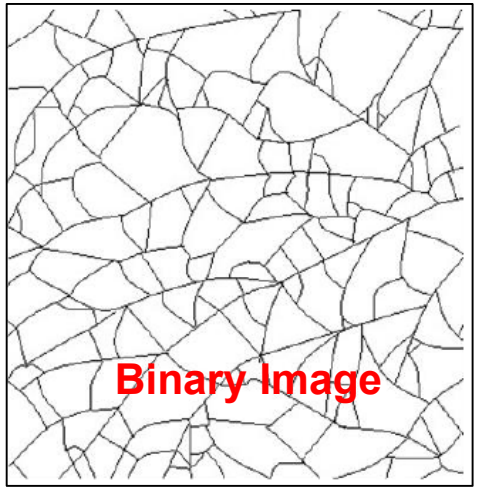
Robust toxicity sampling and testing needed

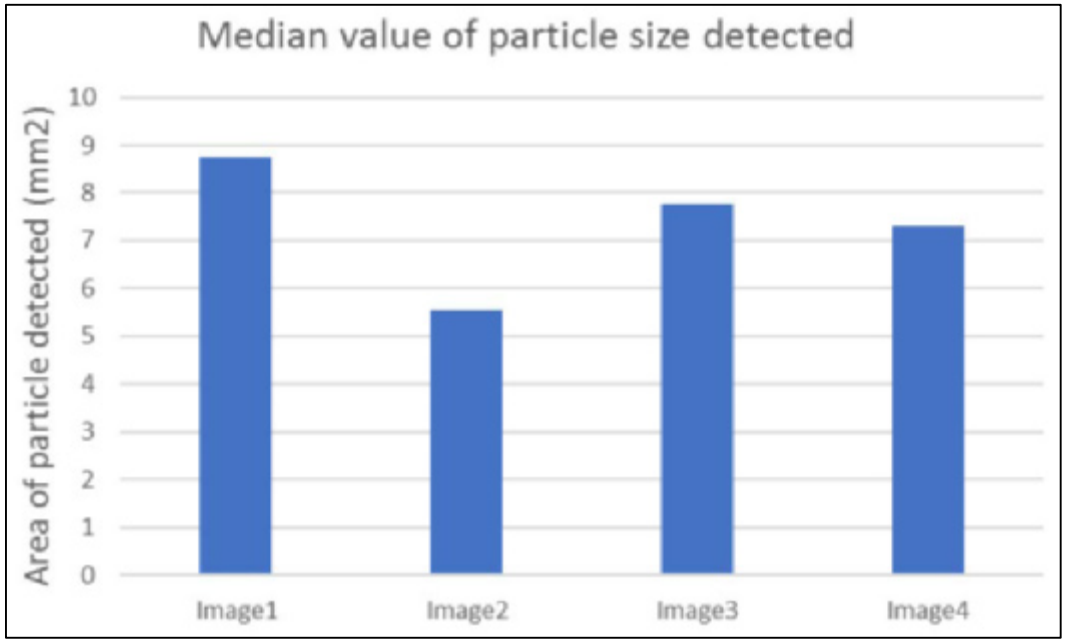
Particle Size and Area

EPA 1311: "Particle size reduction is required, unless the solid is smaller than 1 cm in its narrowest dimension (i.e., is capable of passing through a 9.5 mm standard sieve)".

To detect the glass particles' boundary lines without interference from the metallization fingers → Fluorescent dye is sprayed on broken glass superstrate → Cracks with dye are photographed and traced





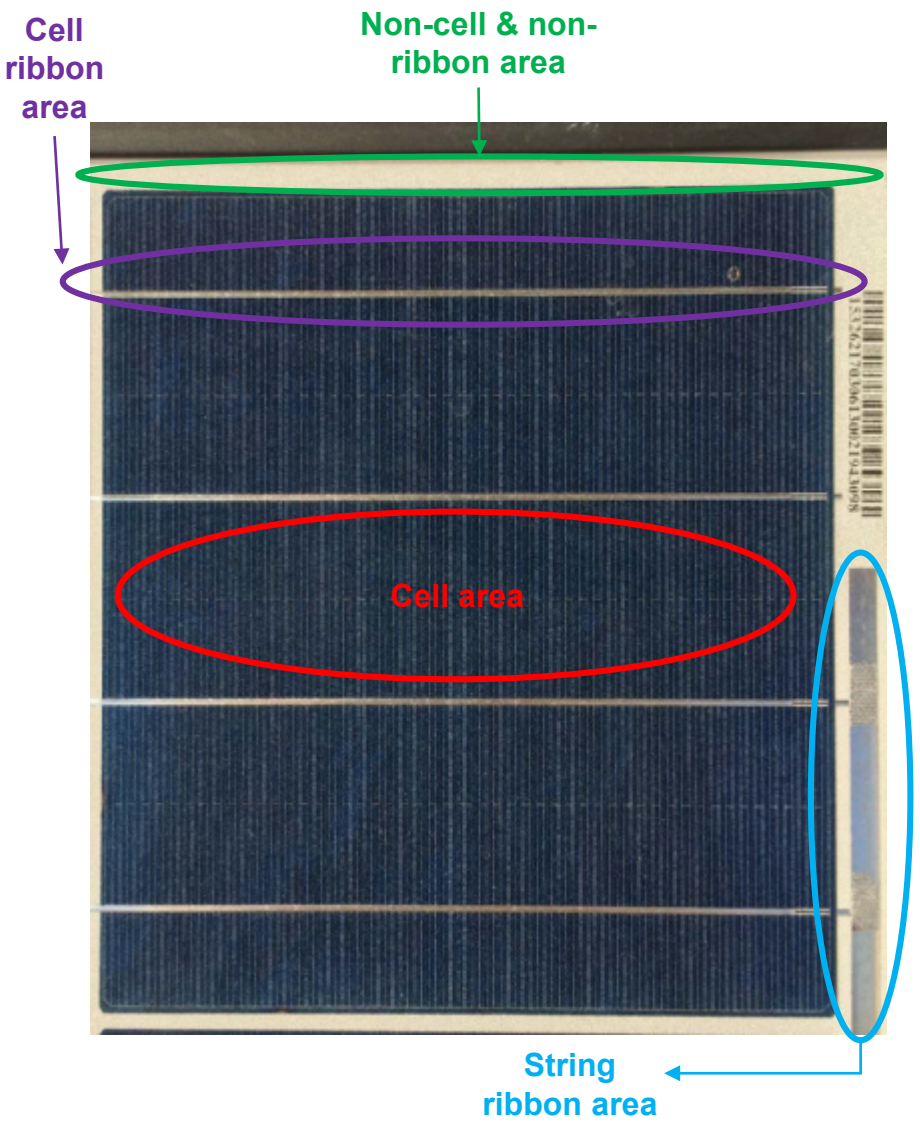


Sample Composition

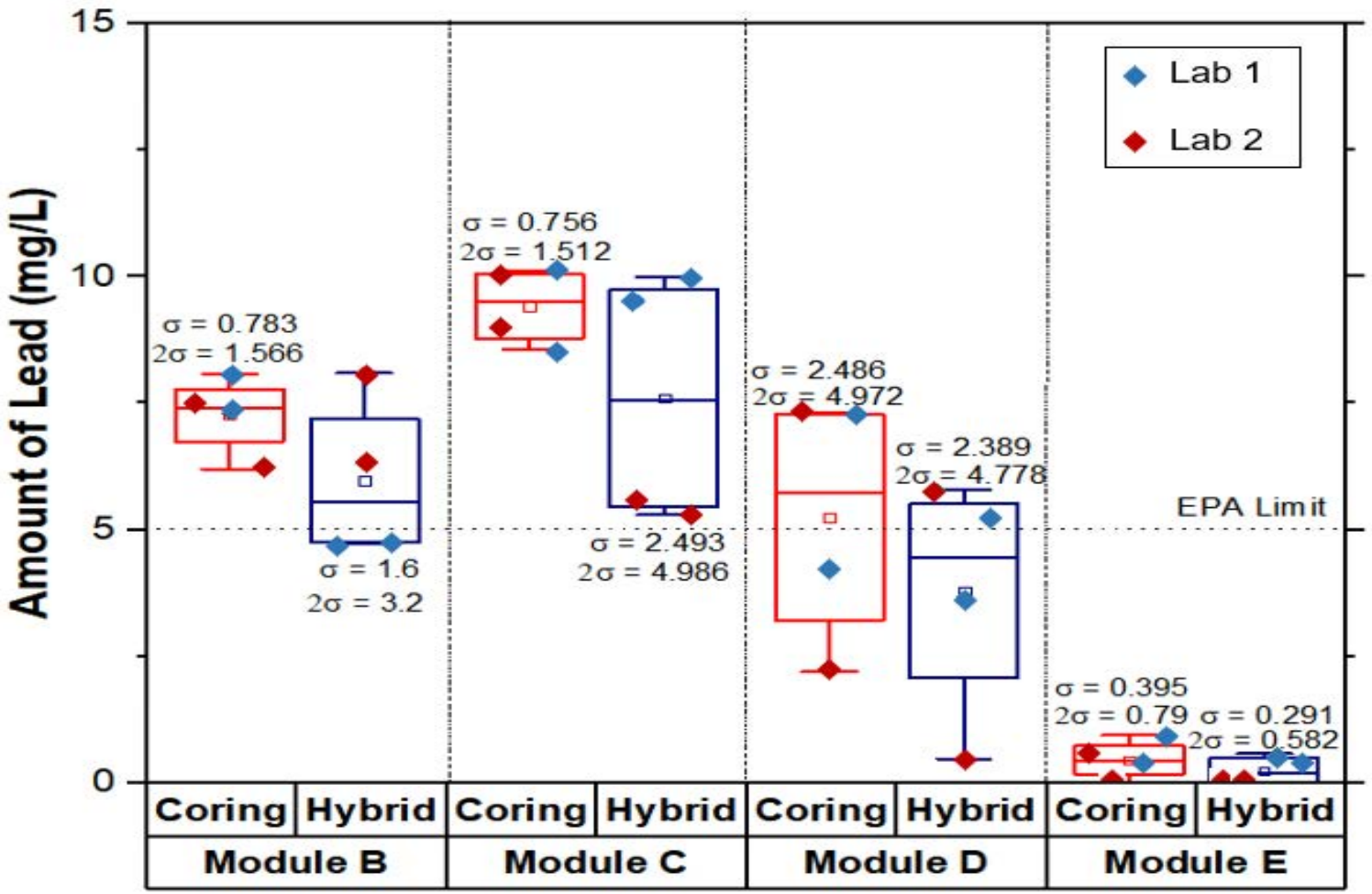
- Samples are composed of one or more pieces from each of the 4 categories within the module

- The number of pieces obtained from each of the 4 areas was determined based on the relative size and weight of each area

  1. Calculate the total laminate area: cell area + cell ribbon area + string ribbon area + non-cell & non-ribbon area
  2. Determine the average weight of pieces from each area
  3. Calculate the number of pieces required from each area to create samples of 100-110g each



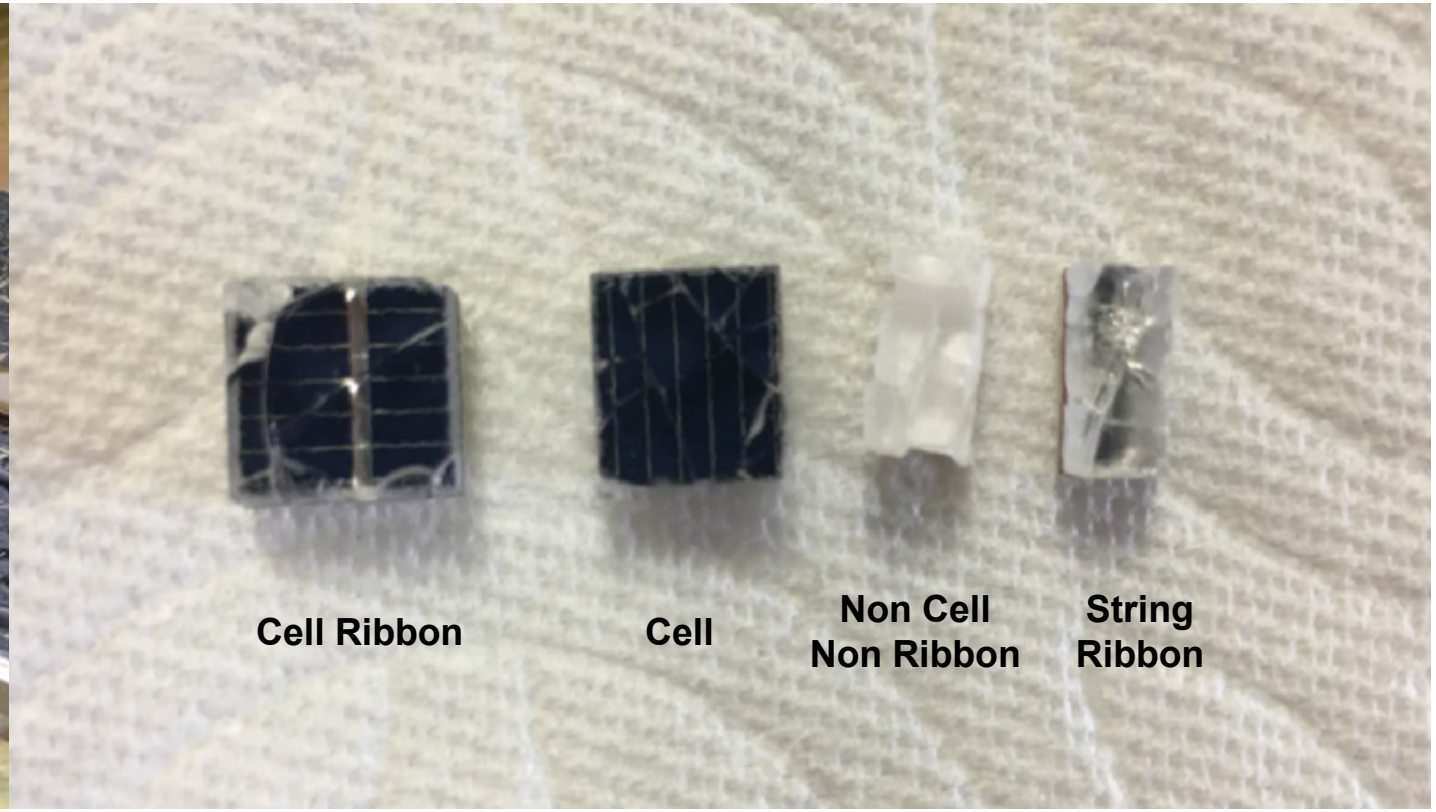
Variability in TCLP Results by Sampling Approach



- Minimal lead in Module E
- <20% variation in coring results for Modules B and C
- Lead variation sometimes was >50%, possibly due to more glass cracking (non-uniform glass tempering?)
- Greater variation observed for the hybrid approach, perhaps due cores put close together, leading to shattering

Additional improvements to reduce variability desired

Waterjet Sampling Alternative



Morphology of Coring Pieces:

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Shipment to Testing Laboratories

Post processing of waterjet-cut sample pieces:

1. Rinse in deionized water
2. Dry in oven at 50° C for 4 hours
3. Categorize based on module area
4. Weigh individually to determine average weight of pieces in each of the 4 area categories
5. Package samples according to weight calculation, label, and send to laboratories

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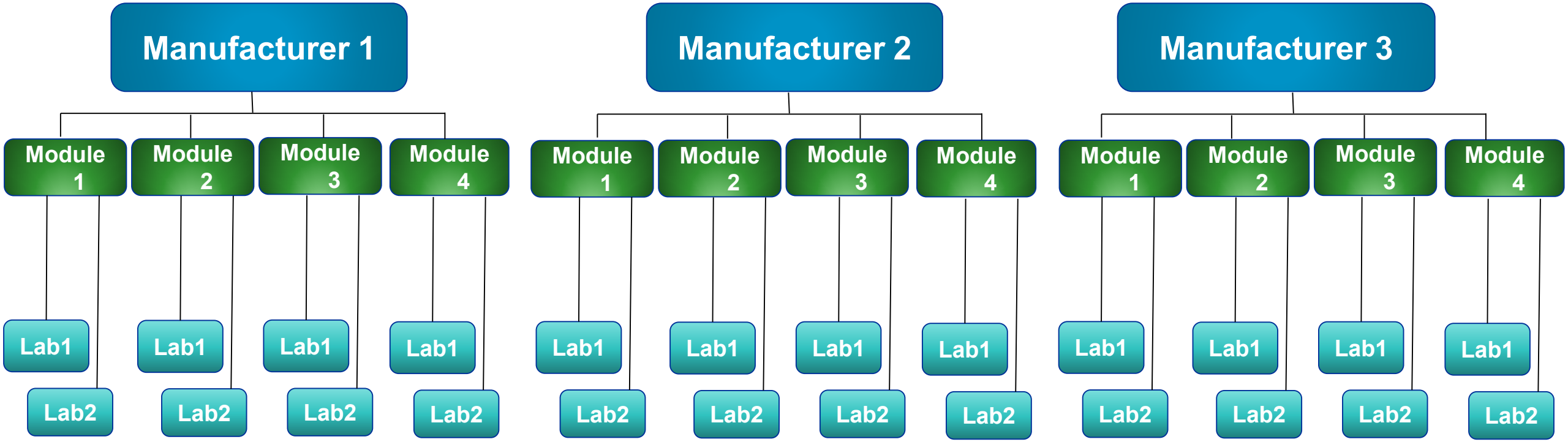
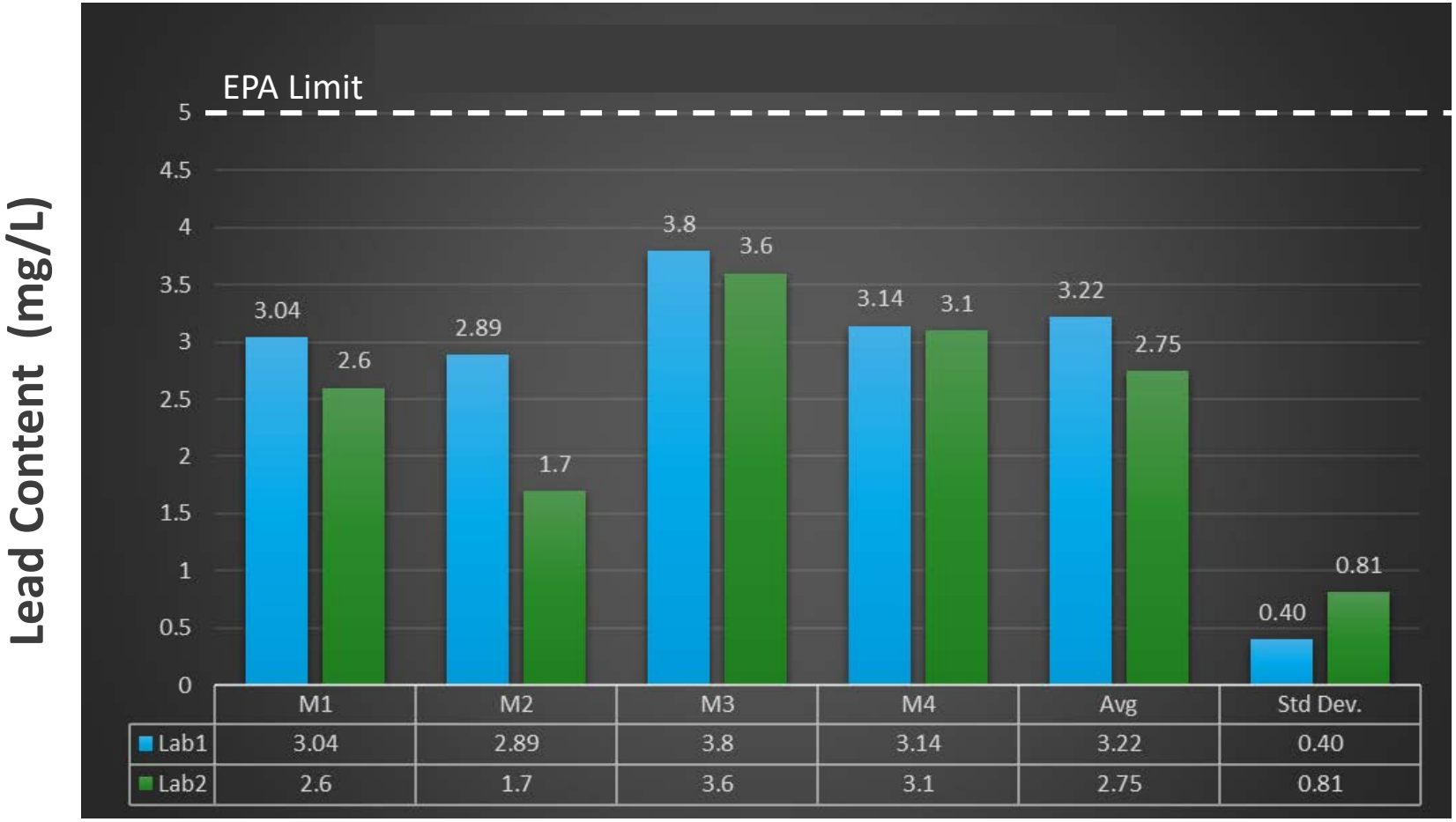
Variability Test with Waterjet Sampling Approach



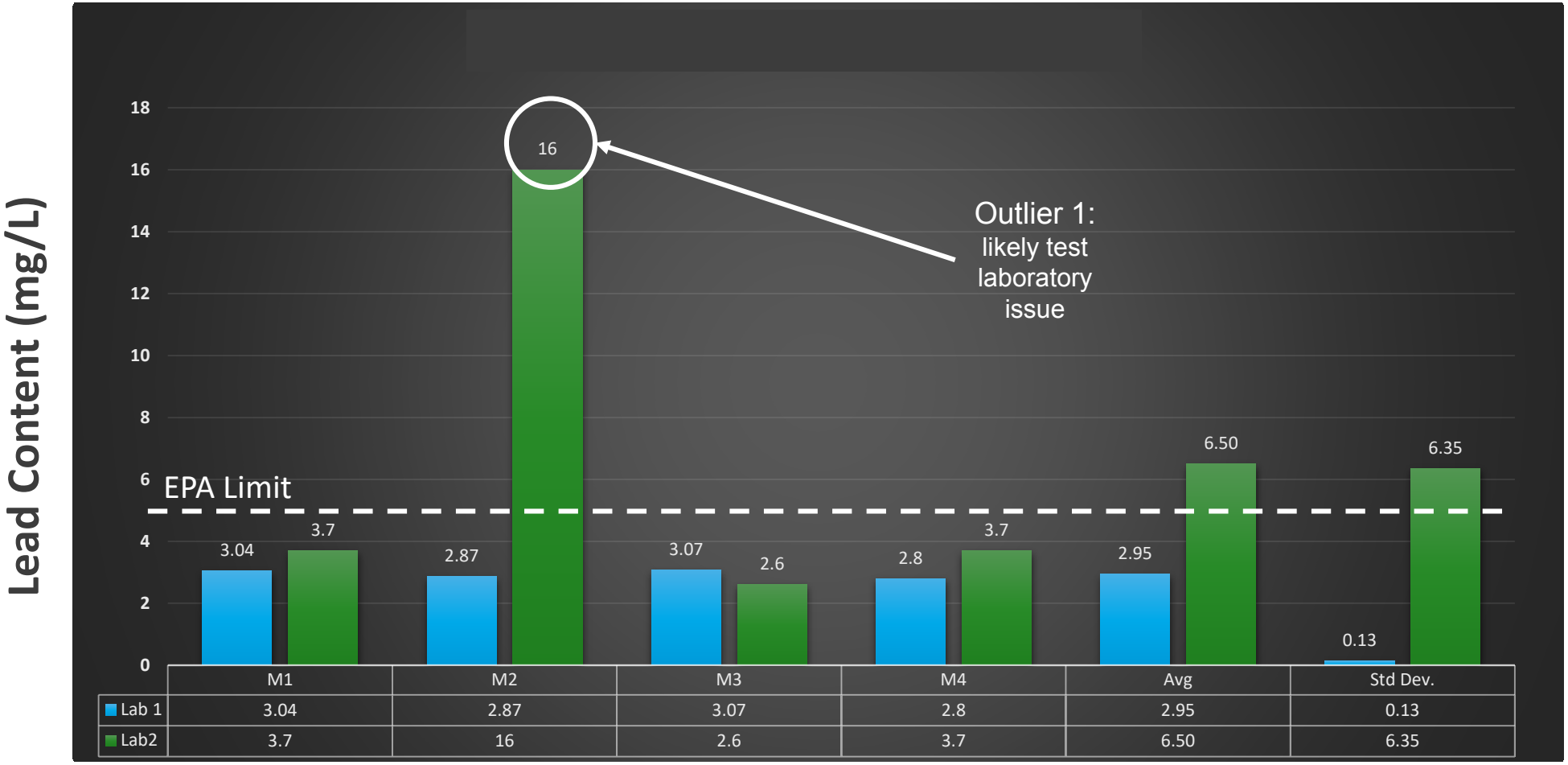
4 modules from 3 manufacturers analyzed by 2 test laboratories (n=24)

Variability by Manufacturer 1



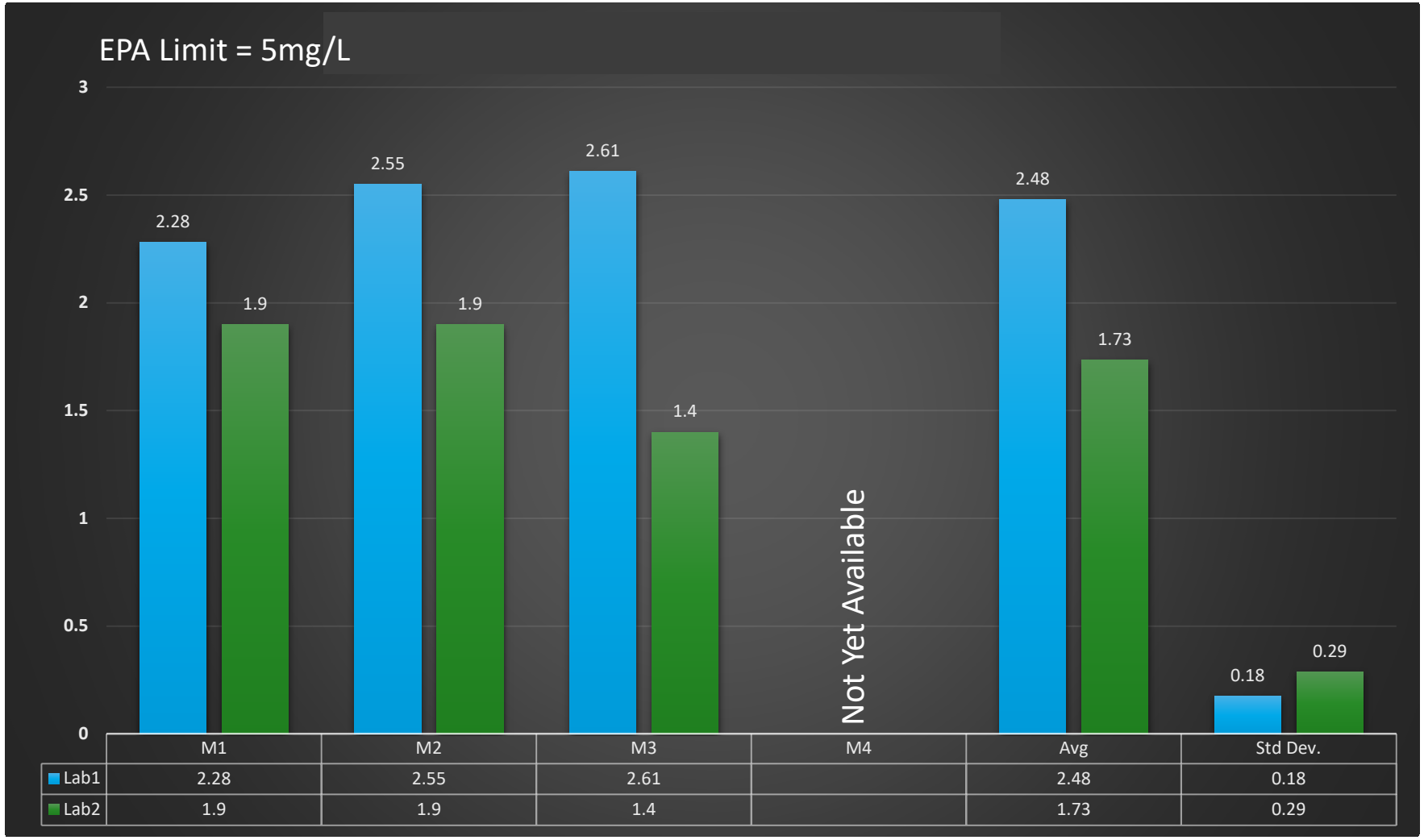
	M1	M2	M3	M4	Avg	Std Dev.
Lab1	3.04	2.89	3.8	3.14	3.22	0.40
Lab2	2.6	1.7	3.6	3.1	2.75	0.81

Variability by Manufacturer 2



	M1	M2	M3	M4	Avg	Std Dev.
Lab 1	3.04	2.87	3.07	2.8	2.95	0.13
Lab2	3.7	16	2.6	3.7	6.50	6.35

Variability by Manufacturer 3



	M1	M2	M3	M4	Avg	Std Dev.
Lab1	2.28	2.55	2.61		2.48	0.18
Lab2	1.9	1.9	1.4		1.73	0.29

Summary

- Waterjet method: Lab 1 standard deviation of lead content across modules was 4%, 7%, 12% for three manufacturers. Lab 2 was 17% and 29% for two manufacturers (manufacturer #2 not considered due to an outlier); this affected pass/fail verdict
- There is no, or very little, difference in lead content between the four modules for each tested manufacturer
- Waterjet extraction method yields more consistent sample surface morphology, and significantly faster sample removal times
- ***Assuming that no leaching of material*** occurred during the waterjet process, all modules from all tested manufacturers ***passed*** the TCLP toxicity tests
- However, coring results cannot be directly compared to waterjet results as different modules were used

➢ ***Clear and consistent sampling and preparation procedures are needed***

➢ ***Cheaper and more precise mechanical sampling method is needed***

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Together…Shaping the Future of Electricity

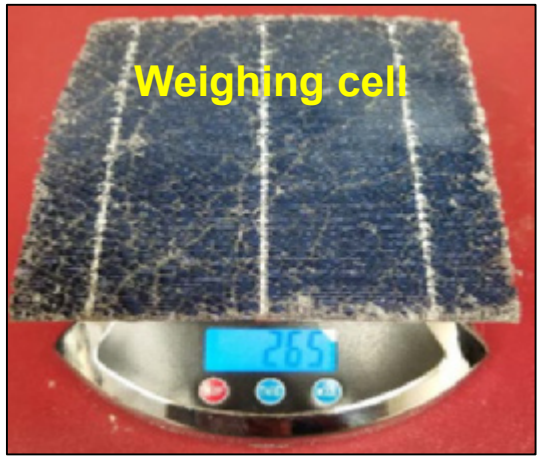
Contacts: manit@asu.edu, clibby@epri.com

Mechanical Sample Removal Methods

Removal Methods

Mechanical Methods

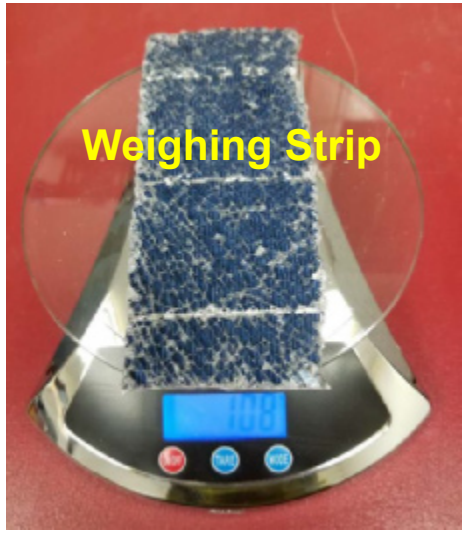
Cell-cut Approach



Issues:

- No lower particle size limit
- No orientation to cut pieces

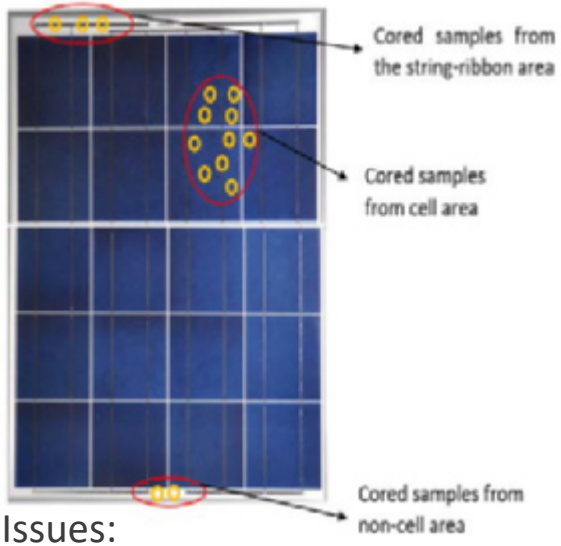
Strip-cut Approach



Issues:

- No lower particle size limit

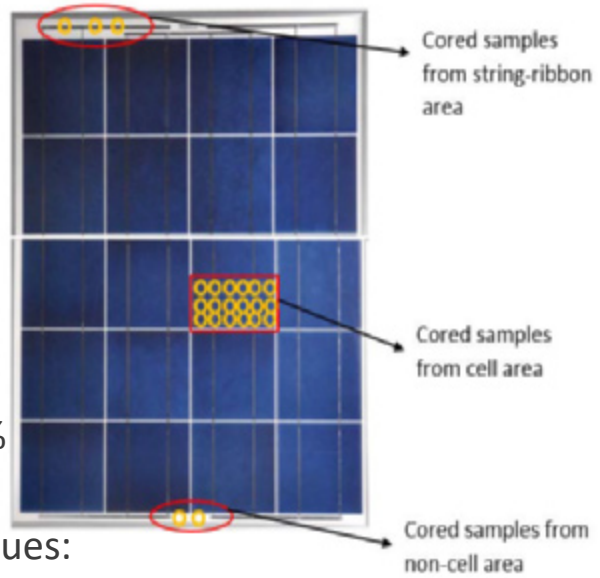
Coring Approach



Issues:

- Glass coverage is not always 100%
- Time consuming

Hybrid Approach



Issues:

- Glass coverage is not always 100%
- Powdery kerf loss

Waterjet Method *(see later slides)*

Comparisons – Sampling Approaches

	Coring	Waterjet
Pros	• Most precise among tested mechanical sampling approaches (but variability issue still significant, ~30%) • No material leaching during sample removal	• Lower variability • Less time consuming • 100% glass coverage on all particles
Cons	• Most time consuming mechanical method • 100% glass coverage could not be obtained in all the pieces	• More costly and module shipping cost may also add up • Waterjet facility might not be easily available everywhere • Material leaching is yet to be confirmed

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Poster Session III (Thursday) Poster Awards

1st Place: #84 M.U. Saleh, "Detection and localization of disconnections in PV strings using SSTDR"

2nd Place: #24 L. Kazmerski, S.C. Silva Costa, A.S.A.C. Diniz, C. Brasil Maia, C. Dias Campos, D. Senna Braga, M. Machado Viana, P.P. Brito, V. Camatta, E.M.C. Barboso, F. Costa, L.R. de Oliveira Cruz, and S. de Morais Hanriot, "Comparative studies of the effects of soiling of PV modules and systems in tropical and subtropical climate areas in Brasil"

3rd Place: #90 H.H. Ng, "25-year low-cost flexible frontsheet"

Design Advancement of an Indoor Soil Deposition Chamber: A Road to Standardization

Z. Hammond[1], T. Curtis[1], L. Simpson[2], and G. TamizhMani[1]

[1]Arizona State University Photovoltaic Reliability Laboratory (ASU-PRL)
[2]National Renewable Energy Laboratory (NREL)

1. Introduction

- An indoor, in-situ soil deposition chamber has been developed at ASU-PRL to simulate PV module soiling in the field
- Improvements have been made to the soil deposition chamber to aid others in building their own test setup and contribute toward the development of an international standard
- The improvements are divided into the following categories: *design improvements, cost reduction*, and *new features*

Fig. 1. Indoor Soil Deposition Chamber

2. Design Improvements

- **Soil Dispersion Box**
  - Dust particle clumping has been observed as a result of prolonged exposure to high-level humidity within the chamber prior to dispersion
  - To prevent clumping, a soil dispersion box was created to allow the soil to be kept outside the chamber until time for dispersion
  - Compressed air enters through the front side of the dispersion box while a cam lock keeps the drawer in a closed position

Fig. 2. Soil Dispersion Box

- **Oven-door & Viewing Window**
  - Past versions of the indoor soil deposition chamber had magnetized and/or Velcro fastened doors. These designs degraded after repetitive use, leading eventually to cracked and damaged acrylic sheets
  - A hinged door with a bolt latch was constructed to ensure a more permanent solution and function as a viewing window for operators
  - Silicone seals line the edges of the door, preventing the flow of dust or contaminants from entering or exiting

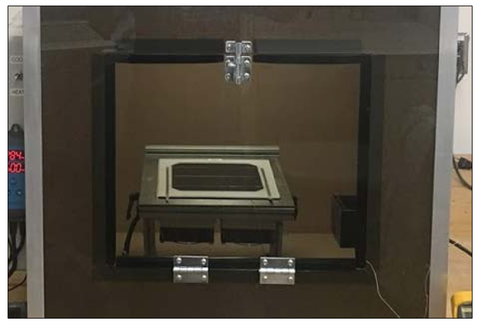

Fig. 3. "Oven-style" Door

- **Shutters to Protect LED During Testing**
  - In the original chamber, the top sheet had to be replaced with an LED-integrated sheet after the soil deposition was completed for Isc measurements
  - The new design includes two shutters that can slide open and closed, protecting the LED light from dust and moisture during dispersion

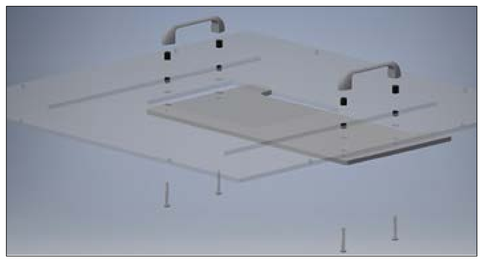

Fig. 4. Shutter Design

3. Cost Reduction

- **Extruded 90° Angled Aluminum Frame**
  - The replacement of 80/20 frame profiles with 90° angled aluminum framing reduced material costs dramatically while providing improved structural integrity

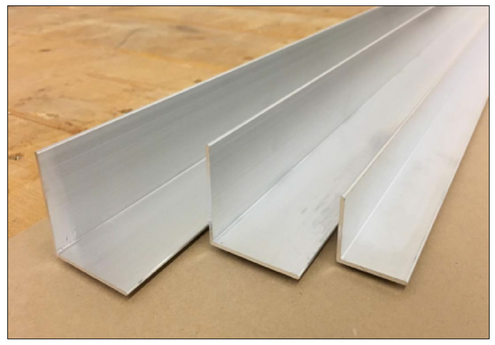

Fig. 5. Angled Aluminum Frame

Fig. 6. Full-Spectrum Laser System

- **Laser-cut Acrylic Sheets**
  - A Full-Spectrum Pro-Series Laser System was used to automate cutting operations, decreasing build time and labor costs

4. New Features

- **Compressed Air Connection**
  - As opposed to the original chamber, which used nitrogen gas, the new setup includes an adaptor that connects to standard air compressors

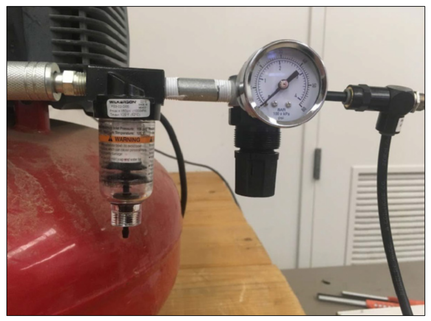

Fig. 7. Air Compressor Assembly

- **Exterior Enclosure Box**
  - The new design features an easily accessible electrical enclosure box attached to the side of the chamber, housing the temperature controller, power supply and Peltier wiring
- **Single Peltier Element for Heating/Cooling**
  - A single 12 V, 31 W Peltier replaced the four elements used in past models
  - The new Peltier connects directly into a temperature controller that can be operated manually or on a laptop

Fig. 8. New Peltier Element

5. Future Improvements / Conclusion

- More design changes can be made to improve accuracy, lower costs, and ensure reliability. Some recommendations include an optimized dispersion box to minimize leftover dust, or a solenoid valve to further automate the dispersion process.
- Designing artificial soil deposition chambers for widespread use and accessibility provides a road to standardization and further soiling research

Acknowledgments: This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under Solar Energy Technologies Office (SETO) prime award number DE-AC36-08GO28308 (NREL's SuNLaMP project).

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

Capability 5: Field Deployment for Reliability

Bruce King
Sandia National Labs

SAND2019-1774 C
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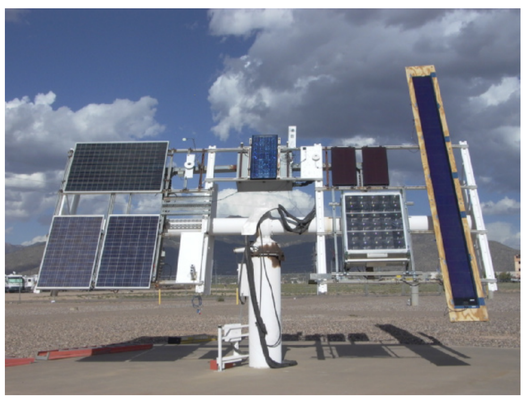
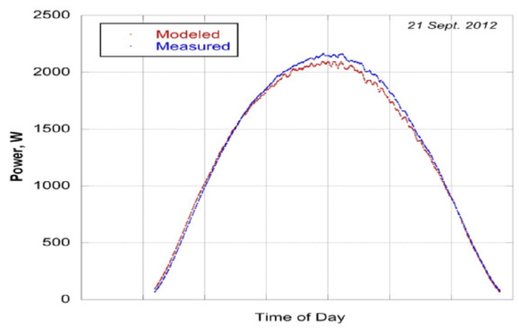
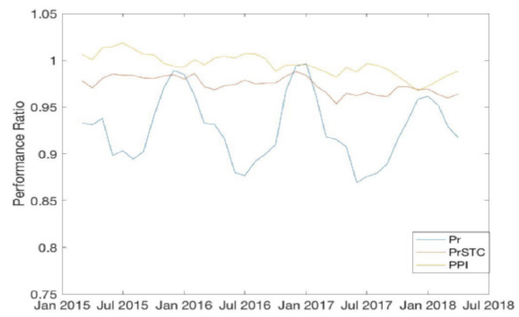
Fielded PV Systems Research





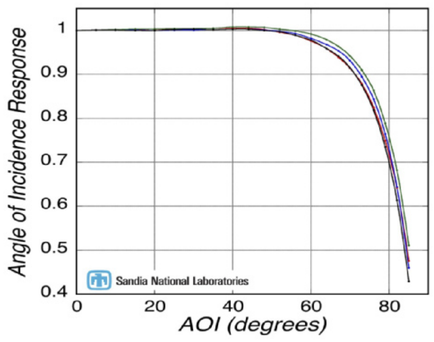


- Tracker Testing - Full electrical performance (IV curves, temperature coefficients, angle of incidence)
- System Instrumentation - DC Voltage and Current, In-situ IV curves, local irradiance
- Combine measured PV system performance with modeled power predictions
  - Evaluate system reliability and degradation rates
  - Evaluate technology improvements
  - Validate energy yield calculations

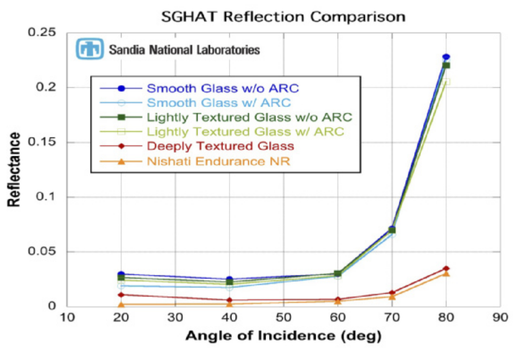
Emerging Technology Characterization Examples

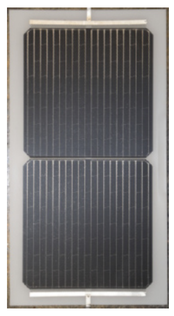
Roofing Products - BIPV

Influence of Coatings on Angle of Incidence

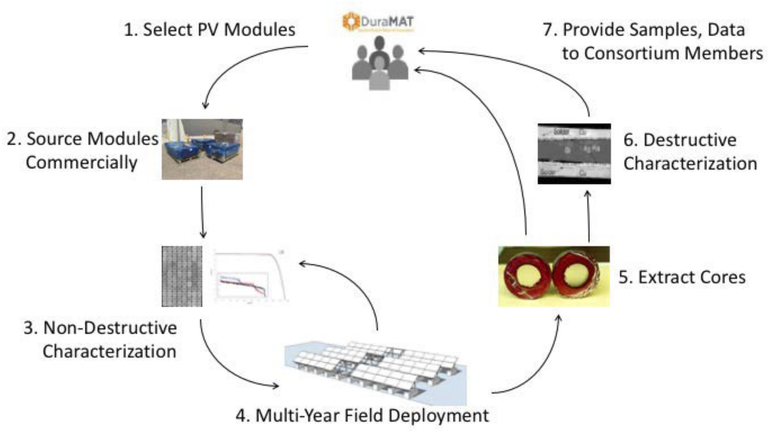


Optimization of Novel Packaging Methods





Field-Aged Module Library



1. Engage **DuraMAT stakeholders** to identify relevant commercial PV modules for long-term field aging
2. **Source Modules** from commercial vendors
3. **Non-destructive characterization** prior to deployment and annually throughout project
4. **Multi-year field deployment** alongside operational sister systems (PV Lifetime)
5. Extract **sample cores** from pristine modules and annually from fielded modules
6. **Destructive Characterization** to identify materials baseline and degradation
7. Provide **sample cores and data** to DuraMAT Stakeholders

Group	Manufacturer	Model	Cell Type	Status
1	Jinko	JKM270PP-60	Multi-Si	Installed
	Canadian Solar	CS6K-300MS Quintech	Mono-Si	Installed
	Hanwa Q-Cells	Q.Peak-G4.1 300	Mono-Si	Installed
	LG	LG320N1K-A5	Mono (N)	Installed
	Panasonic	VBHN330SA17 HIT	HIT N-type	Installed
2	Mission Solar	MSE300SQ5T	Mono PERC	Installed
	TBD			

Non-Destructive Field Evaluation Capabilities

Field Electroluminescence

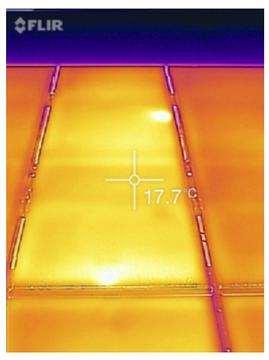
- Acquired fieldable EL camera from Brightspot Automation (7/18)

Additional Capabilities under consideration:

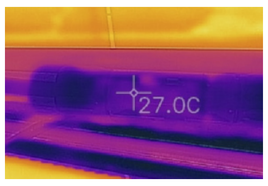
- Hand-held FTIR (commercial)
- Hand-held RAMAN
- Reflectivity
- Flash/Reflected UV imaging (under development)

Infrared (IR) Imaging (existing capability)

- FLIR A6700 Mid-Wave IR camera for high end inspection (1-5 μm)
- FLIR One Long-Wave IR for quick inspection (8-14 μm)



Module Hotspot



Normal Connector

Failing Connector

Field LED Flash Tester

- LED simulator for in situ IV characterization
- Full-size, up to 72-cell modules
- AAA
- 30 m/s pulse
- Expected delivery FY19

U.S. DEPARTMENT OF ENERGY · NREL NATIONAL RENEWABLE ENERGY LABORATORY · Sandia National Laboratories · BERKELEY LAB · SLAC NATIONAL ACCELERATOR LABORATORY

LETID TESTING IN QUALIFICATION STANDARDS: PROCEDURES, KINETICS, AND SEPARATION OF B-O DEGRADATION FROM LETID

Q CELLS
Engineered in Germany

NREL Workshop 2019

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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: mainly mc PERC, up to ~13% but also Cz PERC

It is planned to address LETID in the new edition of the qualification standards (IEC 61215 & IEC 61730). How to modify procedures in order to detect and separate the different effects is currently under discussion. A round robin is ongoing to establish appropriate conditions.

CHARACTERISTICS OF LETID

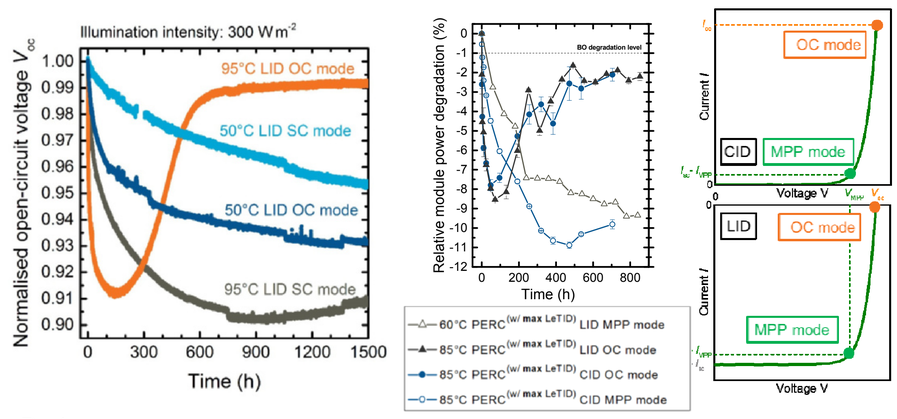

Fig. 1:
(left): light induced LETID degradation over time for different temperatures and injection levels (OC=open circuit, SC=short circuit, MPP=maximum power point)
(center): same, but induced by injecting current instead of illumination
(right): illustration of injection level conditions in dark, i.e. current induced (top) and light induced conditions (bottom).

Characteristics of LETID

- Occurs at temperatures >50 °C
- Characterized by degradation of Isc, Voc, Pmpp followed by slow recovery over time
- Caused by excess carriers → can be induced either via illumination or current injection
- Is a slow process - hundreds of hours in lab & up to many years in field for full cycle whereas B-O LID happens in timescale of only a few days
- Speed depends on injection level and temperature
- Can be present in Cz and mc-Si for all wafer materials

LID & LETID IN Cz-PERC

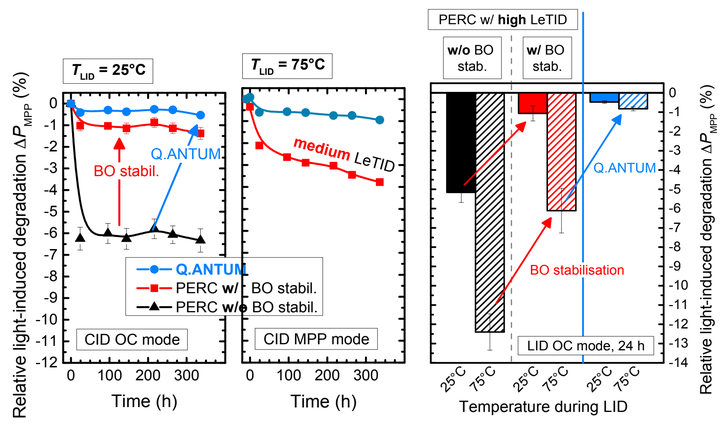

Fig. 2: LID and LETID in Cz PERC: BO-LID @25°C (left), LETID @75°C (center), and avoidance in Q.ANTUM (right)

- LETID also occurs in p-type Cz PERC
- LETID cannot be avoided by BO stabilization
- Q.ANTUM prevents B-O LID and LETID

OUTDOOR RESULTS CYPRUS VS LAB

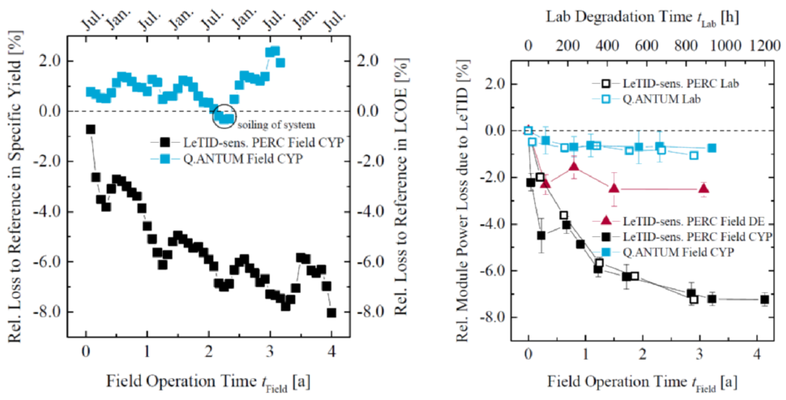

Fig. 3: (left) Relative specific yield loss over time in years for LETID sensitive mc-Si (black) and Q.ANTUM modules (blue) at Cyprus, i.e. Southern Mediterranean, test site.
(right) Comparison between relative module power loss due to LETID for sensitive (black) and Q.ANTUM (blue) as measured in lab setup (upper legend) versus outdoor results from Cyprus (black, blue) and Germany (red) test sites.

LONG TERM STABILITY

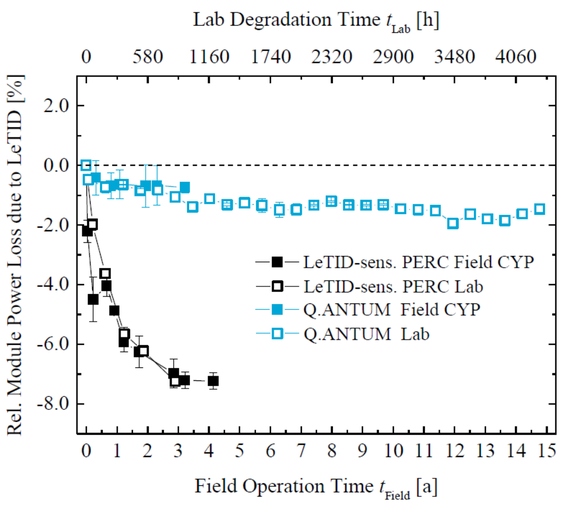

Fig. 4: Degradation over time for LETID sensitive (black) and Q.ANTUM (blue) modules. Correlation between field degradation in Cyprus (solid) and lab data (MPP mode 75°C, open symbols).

- Anti LETID of Q.ANTUM is long term stable

LETID IN QUALIFICATION TESTING

Implications of B-O LID for qualification testing

- BO-LID and LETID both can be present in Cz
- LETID testing should be included in qualification for Cz and mc modules
- Separation of the two effects is crucial as B-O is included in gate 1 requirement (modules might be down-labelled) and might thus produce a wrong LETID signal

➢ initial stabilization should be performed before LETID test leg

Current active edition of IEC 61215 and IEC 61730:

- Initial stabilization misses LETID, as process is slow at 50°C and stability criterion fulfilled before LETID maximum is reached
- Allows for alternative stabilization method to be qualified → current induced degradation can be used

Draft of new edition of IEC 61215 :

- Separate test leg to identify LETID susceptibility (2 modules)
  - **Use current instead of light** to stress module in order to minimize cost and effort
    Injection level comparable to maximum power point conditions.
  - **Determine minimum** in degradation curve
    → several rounds of current stress until minimum reached
  - Use a **temperature that allows test in reasonable time** without risking to miss minimum.

  Climatic cabinet with power sources to inject current into modules

  Current level $I_{test} = I_{sc} - I_{mpp}$

  Stress 1 week at a time, Pmpp measurements in-between
  Repeat until <1% change

  75 °C
- If modules are susceptible (power loss >5%), all modules must be driven through whole cycle until fully recovered and stable (using higher current (Isc), and possible higher T) before going into the other qualification sequences

B-O LID DURING LETID TESTING

Kinetics of B-O LID and LETID during LETID sequence

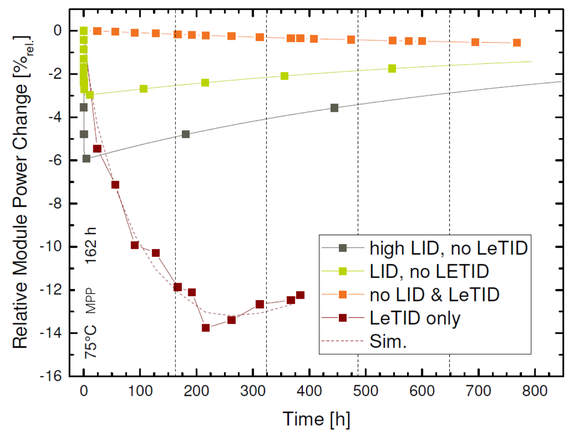

Fig. 5: Relative degradation [%] over time [h] for LID sensitive and LETID sensitive modules during LETID test sequence at 75°C

- During LETID sequence, B-O degrades fully, leading to an additional signal of up to 5%, thereby failing LETID insensitive modules falsely

Kinetics of B-O LID and LETID including preconditioning

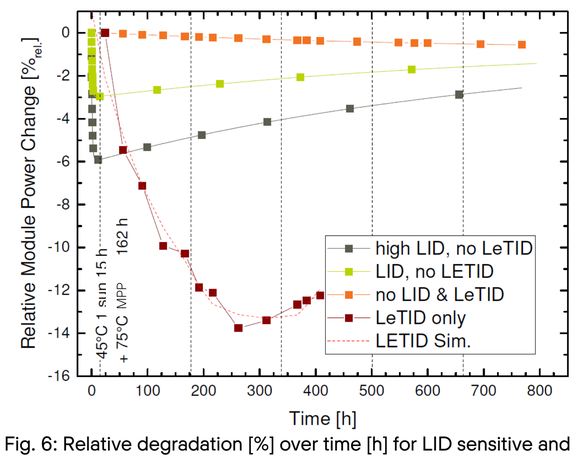

Fig. 6: Relative degradation [%] over time [h] for LID sensitive and LETID sensitive modules during LETID test sequence at 75°C

- False fails can be avoided by adding a light soaking <50°C before the LETID test sequence to fully degrade B-O before test
- 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

➔ 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
- Q.ANTUM permanently suppresses LID&LETID
- LETID testing can be done more efficiently using current induced degradation
- Module Qualification should include testing for LETID for both multi- and monocrystalline modules
- Test conditions proposed : 75°C mpp injection level preceded by initial stabilization <50°C
- B-O LID can significantly influence results and cause false fails in LETID testing when initial stabilization is omitted
- The error from B-O recovery during the LETID sequence is very small (usually <0.5%).

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ACKNOWLEDGEMENTS
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LEADING THE WORLD'S SUSTAINABLE ENERGY FUTURE

Junction-Box Terminal Resistance-Welding Development

Michael Bauer (FS), Tim Frech (EWI), Joe Lindgren (FS), Qiuwan Wang (FS)

2019 NREL PVMRW

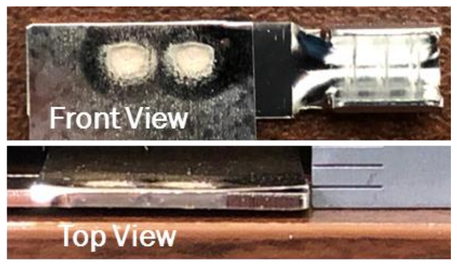
Proud Member of EWI

Our Technology

- First Solar is a leading global provider of photovoltaic (PV) systems using advanced module and system technology.
- Series 6 modules set a new industry benchmark for reliable energy production, optimized design and environmental performance.

Background

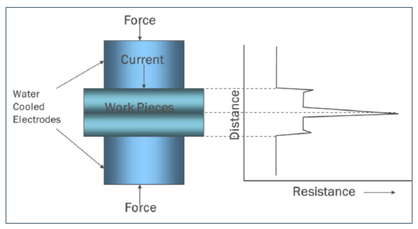
- The Junction box is an important component in the solar panel. It encloses connections that conduct the power from the solar panel and protects them from the environment.
- Evolved from soldering in the Series 4 module to resistance spot welding in the Series 6 module, which has further improved process and yield.
- Worked with Edison Welding Institute (EWI) on the development of a weld process to achieve good weld strength, reduced electrode sticking & weld expulsion, and improved electrode life.
- The selection of weld electrode material and the material compositions of the junction box terminals are crucial to achieving a good solid-state weld.
- The components in the plating material that would induce bad weld performance were identified and eliminated, thus improving the production welding process.



Junction-Box Connection

Introduction

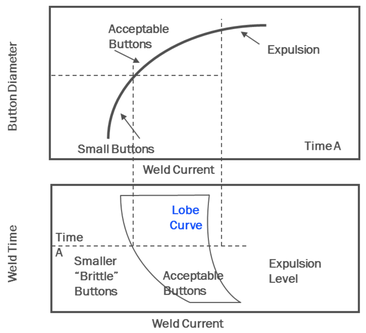
- Resistance welding is joining the materials by applying pressure and passing current. It's cost effective as no other material is needed to make a bond.
- The weld is formed at the interface, where it has the highest resistance due to physical contact.

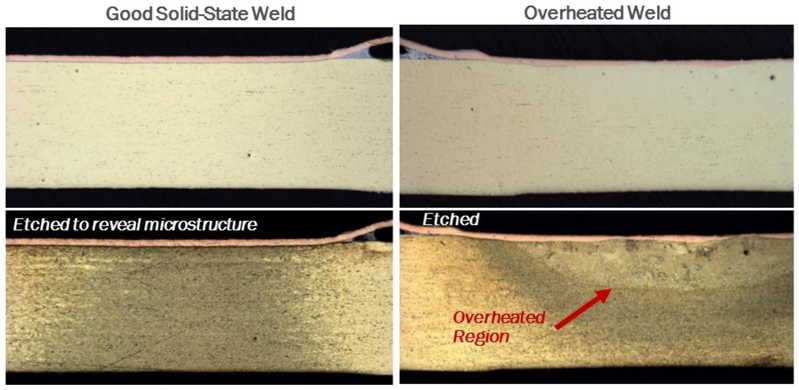


- Solid-State welding has no fusion zone, i.e. no melting occurred at the interface.
- Resistance welding of copper directly to copper can be difficult due to the high thermal conductivity.

Resistance Welding Development

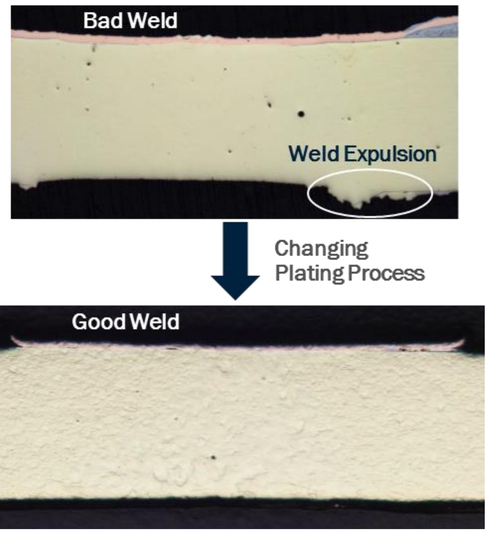
- Metrics included weld strength, button size, observation of electrode sticking and weld expulsion.
- Optimized weld process was developed utilizing lobe curves and through weld electrode selection.
- Created a robust process to achieve a good solid-state weld of the junction-box connection despite a thermal mass differential between components.
- Enabled expulsion-free process window
- Improved yield by 0.2%
- Expected electrode lifetime increase enabled by 35% heat reduction





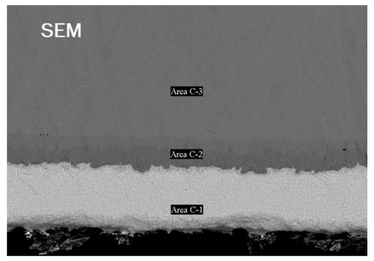
Junction-Box Terminal Material Selection

- Several analysis techniques were used to identify the components in the material that would induce bad welds.
- Plating compositions of the junction box terminals were proven to affect the weld quality.



Analysis Techniques

OM, SEM-EDS, ICP-MS and XPS



SEM Image of Junction-Box Terminal for Plating Analysis

PID TESTING OF BIFACIAL MODULES: HOW TO ADAPT TEST PROTOCOLS IN QUALIFICATION STANDARDS TO AVOID POLARIZATION ARTEFACTS

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➔ MOTIVATION

PID is an important failure mode with potentially high impact on energy yield. Serial interconnection of modules in strings in a pv system lead to high voltage stress between grounded module frame / glass surface and the cells inside the modules. A test for PID-s based on IEC TS 62804 is planned to be included into the next edition of the qualification standard IEC 61215. Bifacial modules exhibit an artificial degradation due to polarization effects in this test protocol. This polarization effect is temporary and can be easily reversed. Data from field installation and laboratory tests show that this artefact does not occur in field installations. A modification of procedures is unavoidable to obtain realistic qualification results.

CHARACTERISTICS OF PID

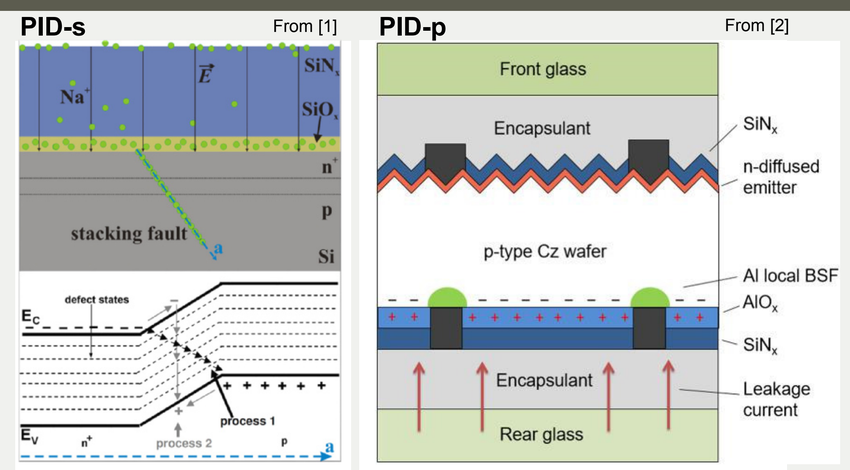

Fig. 1 (left): Schematic drawing of a solar cell cross section. An electric field between cell and glass surface causes drift of Na^+ ions towards the Si interface. Diffusion into stacking faults causes shunts in the pn-junction = PID-s [1]. (right): In bifacial modules the electric field attracts positive charges to the passivation/antireflection stack on the rear side of bifacial PERC cells and reduces field effect passivation and consequently performance = PID-p (polarization) [2].

Characteristics of PID-s

- Electric field between glass and solar cell leads to Na^+ ion drift/diffusion into junction and consequently power degradation
- Characterized by degradation of FF and Isc driven by shunting (Rshunt reduction)
- Shunting of p-n junction caused by sodium ions occupying stacking faults in silicon [1]

Characteristics of PID-p in bifacial modules

- Power decrease (mainly) for rear side illumination of bifacial modules characterized by Isc-loss
- Caused by accumulation of positive charges at the rear side passivation/anti-reflection stack which decreases field effect passivation [2] due to polarization
- Fast degradation under voltage stress, further stress leads to slow power recovery due to field inversion near the silicon passivation interface

PID TESTS IN STANDARDS

Two equivalent methods in current version of IEC 62804-1:

- A: testing in damp heat using an environmental chamber:
  - Module temperature: 60 °C (or 85 °C)
  - Chamber relative humidity: 85 % rH
  - Dwell time: 96 h
  - Voltage: module rated system voltage and polarities
- B: Contacting the surface with conductive foil as electrode:
  - Module temperature: 25 °C
  - Relative humidity: less than 60 % rH
  - Dwell time: 168 h
  - Voltage: module rated system voltage and polarities

Method A of 62804-1 is currently proposed for IEC 61215:

- Module temperature: 85 °C (still under discussion)
- Chamber relative humidity: 85 % rH
- Dwell time: 96 h (under discussion)
- Voltage: module rated system voltage and polarities

PID-p ARTEFACTS IN LAB TESTING OF BIFACIAL PERC MODULES

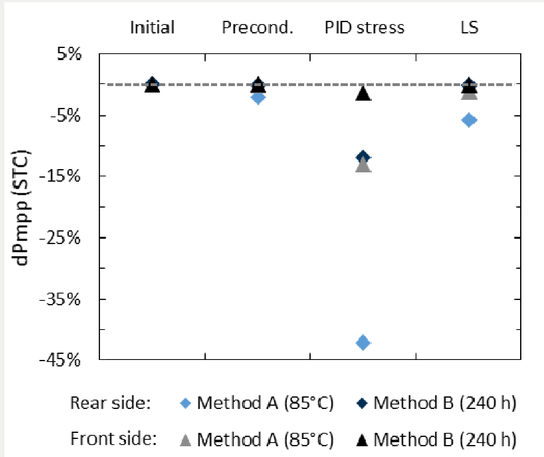

Fig. 2: Relative module power degradation due to PID-p on bifacial modules for PID test conditions and following regeneration with light soak of about 0.8 kWh at 50 °C.

Characteristics

- Both, method A (climate chamber) as well as method B (Al foil) show significant power loss for bifacial modules due to polarization of the rear passivation layer.
- Power loss is much more pronounced for rear illumination, but also significant for front side STC power due to the influence of the increased recombination at the rear side.
- Effect is reversible by a short sequence of illumination on the rear side (0.8 kWh).

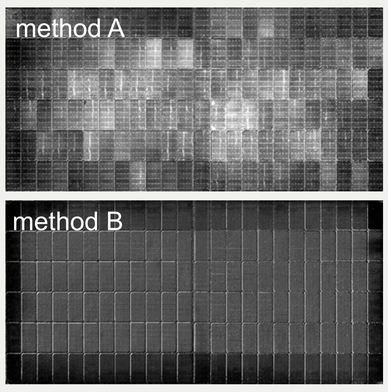

Fig. 3: Relative module EL intensity loss due to PID-p on bifacial modules for method A and method B.

KINETICS: FAST RECOVERY

Recovery under illumination:

- Illumination of rear side accelerates recovery from PID-p
- Modules recover within minutes under illumination at elevated temperature (see Fig. 3)
- Full recovery @30 °C, 150 W/m² rear side illumination in under 3h (see Fig. 4)

Recovery in dark storage:

- Full recovery in dark storage at ambient T in a few weeks

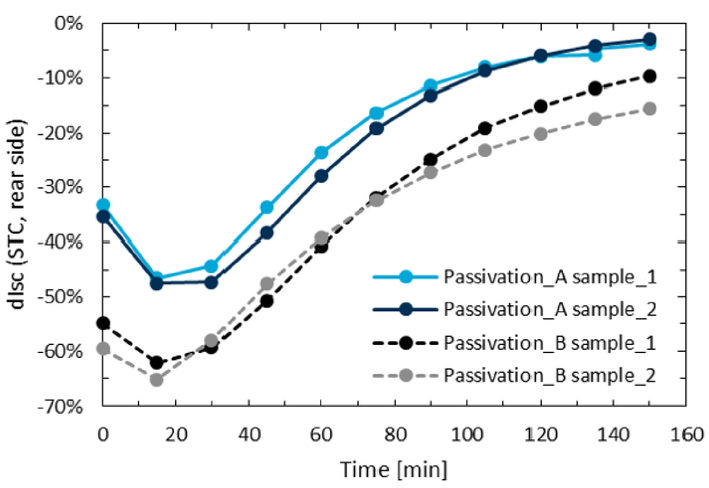

Fig. 4: Relative Isc recovery over time under rear side illumination (150W/m²) at 30°C module temperature for two different kinds of rear side passivation. Full recovery for passivation A occurs in150 min.

FIELD BEHAVIOR

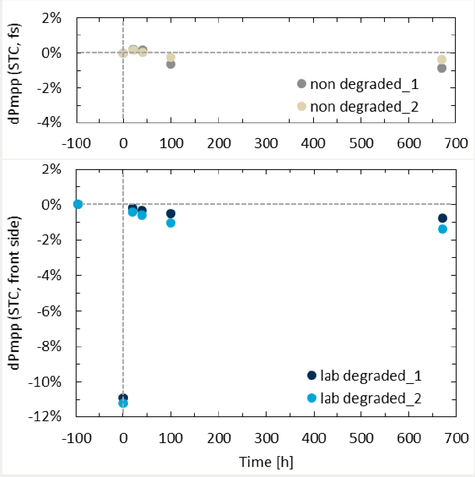

Fig. 5: Fast module power recovery of modules degraded in lab test and then installed outdoors (top) and stable performance of installed modules (bottom), both under 1500 V bias and with repeated artificial wetting.

Thalheim (Germany) test site:

- Modules-pre degraded in a lab PID test (method A) recover quickly under outdoor conditions, even with repeated artificial wetting (spray of water on module glass).
- Non pre-treated modules do not show degradation outdoor

PROPOSED TEST SEQUENCE

Add a final stabilization sequence after the PID stress and before the final power determination is done.

- **1 kWh of illumination at 50°C (+-10°C)** equivalent to standard stabilization procedure (conditions of MQT19 of IEC 61215) are sufficient to fully reverse the polarization artefact.

➔ CONCLUSION

- Bifacial PERC modules exhibit a reversible PID-p effect on the rear side in standard PID-s tests.
- This polarization artefact is reversible under illumination within very short time (minutes to hours)
- Under field conditions this degradation does not occur and modules previously degraded in lab tests recover fully under outdoor conditions.
- A final stabilization sequence (short light soaking) should be added to PID tests for bifacial modules in order to avoid this artefact and obtain field relevant results.

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[2] Wei LUO, Peter HACKE, et al. Progress in Photovoltaics Research and Application 26(1). 2018

Research Center for Photovoltaics

Corrosion underneath Front Electrodes of Crystalline Silicon Photovoltaic Cells Predominantly Contributes to Their Performance Degradation

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Background & Experimental Procedures

Background (1) (HAc = Acetic Acid)

Corrosion in Alumina Paste Layer (APL)

25 °C / 45% rh, 2 months | 25 °C / 85% rh, 240 h | 25 °C / 85% rh, 240 h with HAc Atmosphere

H. Xiong *et al.*, "Corrosion behavior of crystalline silicon solar cells," *Microelectron. Reliab.*, vol. 70, pp. 49–58, Mar. 2017.

Background (2) (HAc = Acetic Acid)

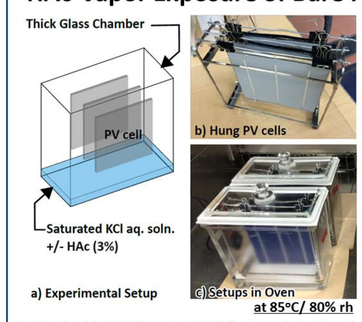
Proposed Corrosion Models

Front Side | Rear Side

H. Xiong *et al.*, "Corrosion behavior of crystalline silicon solar cells," *Microelectron. Reliab.*, vol. 70, pp. 49–58, Mar. 2017.

Experimental (1) (HAc = Acetic Acid)

HAc-Vapor Exposure of Bare PV Cells



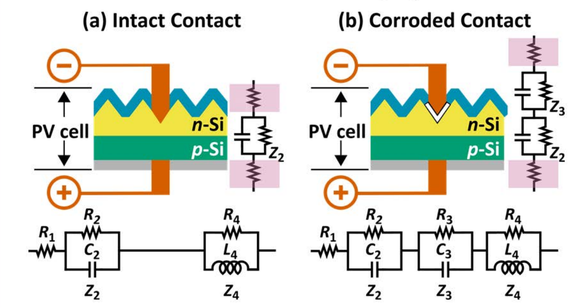
Whole planes of both surfaces in a testing PV cell are uniformly surrounded by the applied stressors (temperature, humidity, and HAc vapor).

→ Spatiotemporally harmonized power-loss and *R*s-elevation are supposed to be observed in the testing PV cell.

T. Tanahashi, N. Sakamoto, H. Shibata, and A. Masuda, "Localization and characterization of a degraded site in crystalline silicon photovoltaic cells exposed to acetic acid vapor," *IEEE J. Photovolt.*, vol. 8, no. 4, pp. 997–1004, Jul. 2018.

Experimental (2)

Localization of Series Resistance (R_1)



,with the respective AC equivalent circuits (under dark conditions) Squares colored in pink indicate the assumed locations of R_1.

Summary

To address the origin of the elevated series-resistance (R_S) that is a primary cause of corrosive degradation observed in field-aged photovoltaic (PV) modules*, we evaluated the electrical characteristics of PV cells corroded with acetic acid (HAc) vapor.

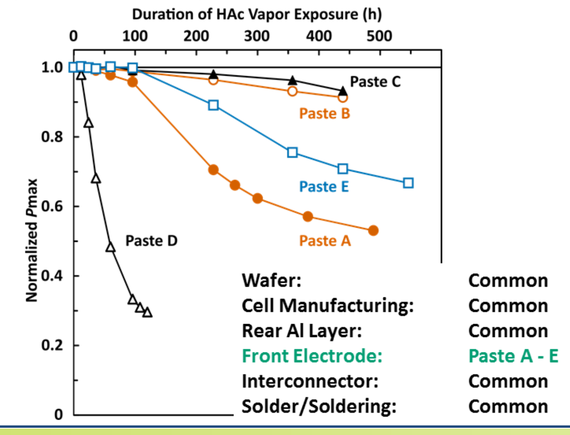
The origin in R_S-elevation during corrosion of PV cells is fixed underneath front electrodes, from the following observations.
(a) Evolution of EL-, R_S-, and visual-images during corrosion (**Panel 1 to 3**)
(b) Effects of resistances in the Al bulk and the interconnector-busbar interface on power-loss (**Panel 4 to 5**)
(c) Localization of R_1 ($\simeq R_S$) in a corroded PV cell with single comb grid-fingers (**Panel 6 to 9**)

Because we have reported that Z_3 (a novel AC-impedance component that emerges during corrosive degradation) is also localized underneath the front electrodes**, it can be concluded that performance degradation with corrosion is preferentially caused by the evolution of electrical characteristics at this interface, but not at anyplace within a PV cell.

*Tanahashi *et al.*, DOI: 10.1109/JPHOTOV.2019.2893442 **Tanahashi *et al.*, DOI: 10.1109/JPHOTOV.2018.2839259

A Convincing Demonstration

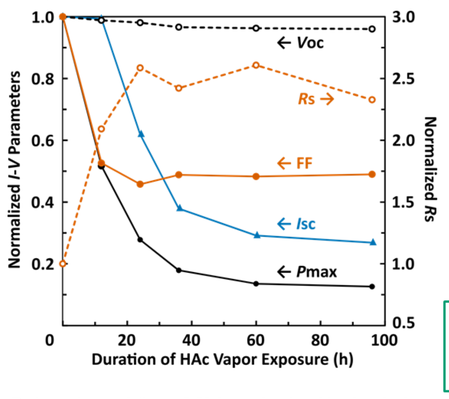
Degradation Profiles of PV Cells (with Different Compositions of Paste) Exposed to HAc Vapor at 85 °C / 80% rh



Results

Panel 1: Degradation Behavior

Degradation Profiles of a PV Cell Exposed to HAc Vapor



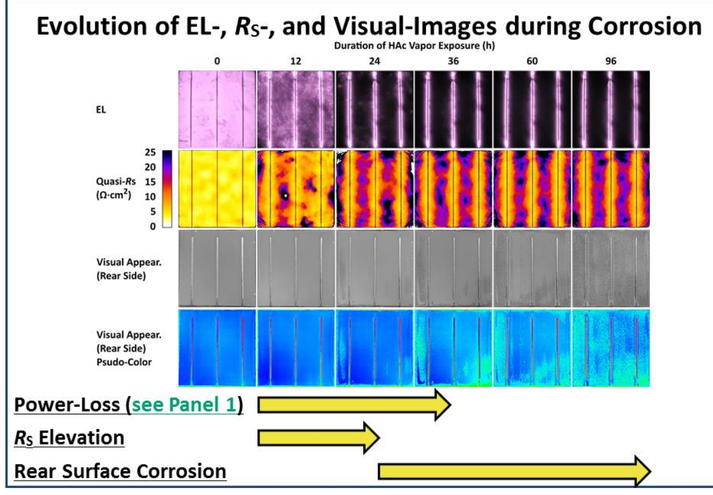
- Rapid power-loss correlated with FF-reduction.
- Decrease in FF synchronized to the increase in R_S.

Concurrently observed EL-, R_S-, and visual-images are indicated in Panel 2.

R_S is estimated from *I-V* data obtained in the dark.
Both vertical axes indicate *I-V* parameters normalized by their initial values.

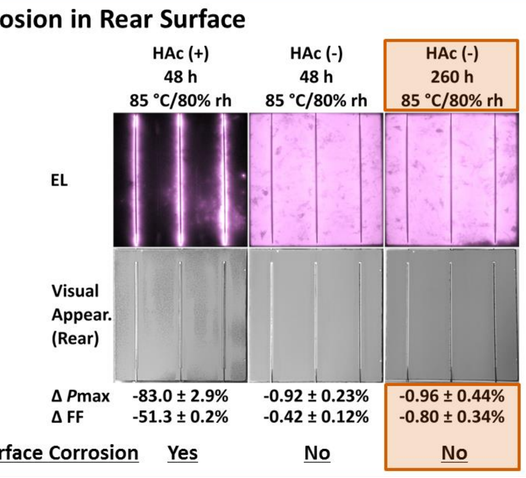
Panel 2: Degradation Behavior

Evolution of EL-, R_S-, and Visual-Images during Corrosion



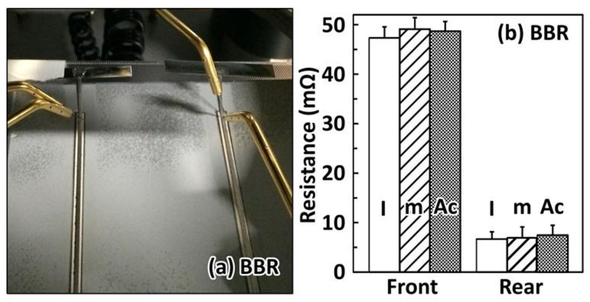
Panel 3: Degradation Behavior

Corrosion in Rear Surface



Panel 4: Bulk Resistance

Busbar - Busbar Resistance (BBR)



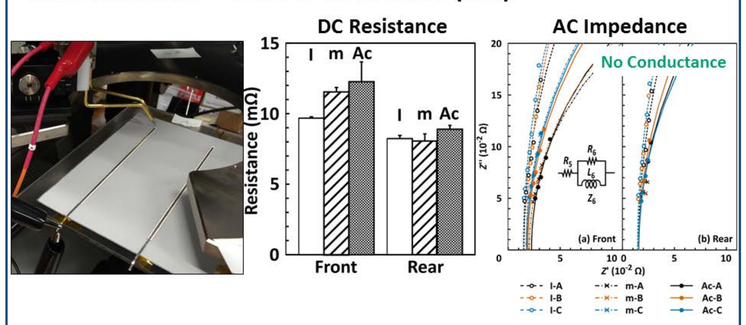
Bulk resistances of aluminum layer (with rear busbars) does not contribute to the power-loss in the corroded PV cells.

I: Intact PV Cell
m: PV Cell (without HAc Vapor)
Ac: PV Cell (with HAc Vapor)

m- and AC-PV cells were incubated at 85 °C/80% rh for 48 h.

Panel 5: Interface Resistance

Interconnector – Busbar Resistance (IBR)

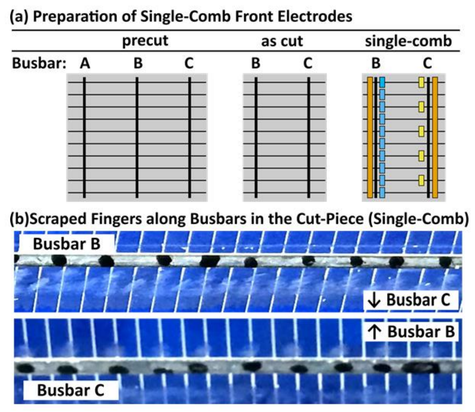


Obvious enhancement of the resistance at solder joint is not confirmed, even when PV cells were nearly completely degraded with HAc vapor.

I, m, and Ac: see Panel 4
A, B, and C in the right graph indicate the respective interconnector-busbar pairs.

Panel 6: Identification of R_1-Origin

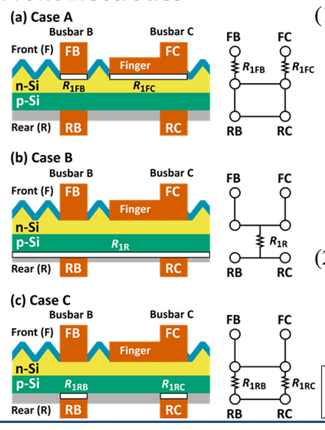
Preparation of a Cut Piece with Single-Comb Front Electrodes



Squares colored in orange, blue, and yellow indicate the scraped positions of the front electrodes.

Panel 7: Identification of R_1-Origin

Determination of R_1–Origin in a Cut Piece with Single-Comb Front Electrodes



(1) If R_1 associates with front electrodes (a), the respective extents of R_{1FB} and R_{1FC} are independently assessed by various contacts of the probes (Panel 8). When the summation of R_{1FB} and R_{1FC} agrees with R_1 determined by the FB-FC contact, we conclude that R_1 is associated with the front electrodes.

(2) In other cases (b and c), the extents of R_1 measured by various contacts are equivalent (Panel 8), and R_1 assessed by the FB-FC contact is nearly zero.

Figure Caption: Corroded site(s) is indicated as colorless box(es)

Panel 8: Identification of R_1-Origin

Assumed and Measured R_1 at Various Contacts

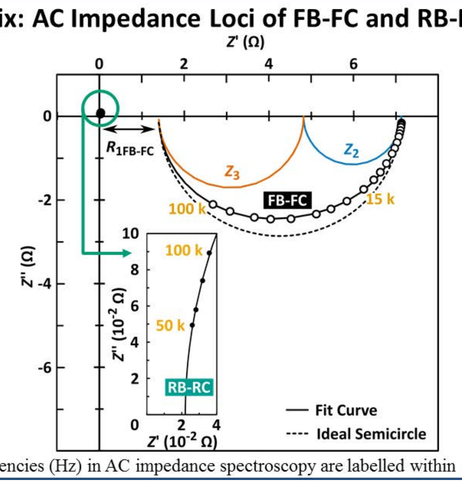
Contacted Terminals	Assumed R_1: Case A	Case B	Case C	R_1 (Ω): Meas.	Case A
FB-RB	R_{1FB}	R_{1R}	$R_{1RB\|RC}$ [a]	0.945	0.907 [b]
FB-RC	R_{1FB}	R_{1R}	$R_{1RB\|RC}$ [a]	0.868	
FC-RB	R_{1FC}	R_{1R}	$R_{1RB\|RC}$ [a]	0.724	0.734 [b]
FC-RC	R_{1FC}	R_{1R}	$R_{1RB\|RC}$ [a]	0.744	
FB-FC	$R_{1FB} + R_{1FC}$	≈ 0	≈ 0	1.404	1.641
RB-RC	≈ 0	≈ 0	≈ 0	0.022	0.022

[a] $R_{1RB\|RC}$ denotes the resistance in a parallel circuit with R_{1RB} and R_{1RC} [i.e., $R_{1RB\|RC} = (R_{1RB} \times R_{1RC}) / (R_{1RB} + R_{1RC})$].
[b] These values indicate the respective mean resistances in FB-RB/RC and FC-RB/RC contacts.

Actual data completely agree with those assumed in Case A.

Panel 9: Identification of R_1-Origin

Appendix: AC Impedance Loci of FB-FC and RB-RC Contacts



Frequencies (Hz) in AC impedance spectroscopy are labelled within this chart.

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This poster does not contain any proprietary or confidential information.

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

MODULE-LEVEL SOLUTIONS FOR DEGRADATION BY IONIZATION DAMAGE

Peter Hacke and David C. Miller
Stephanie Moffitt, Archana Sinha, Laura Schelhas

National Renewable Energy Laboratory
SLAC National Accelerator Laboratory

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

Degradation processes involving ion-related damage from UV radiation and/or high voltage of the encapsulation and cell/encapsulant interface will be characterized, mechanisms will be clarified, degradation models and rate equations will be developed, and the value proposition of various packaging-based solutions will be quantified.

Accomplishments

From the start of the project, October 1, 2018 we

- Obtained Si cell types with n^+ and p^+ front surfaces and with silicon oxide, nitride, and aluminum oxide passivation
- Set up UV exposure tools and prototyped fixturing design
- Purchased glass product for maximum UV-transmittance
- Performed literature review of module ionization degradation
- Baselined samples with Auger and X-ray photoelectron spectroscopy (XPS)

Outcomes and Impact

The properties of polymer packaging materials required to mitigate module power degradation will be identified. Material properties and performance models will be entered into the DuraMAT data hub. With this, we will inform the PV module value chain how degradation rates can be minimized for a 50-year module life along with the corresponding valuation of degradation & preventative packaging materials.

Motivation

- After years of improving module durability and the reduction of degradation rates toward a mean of 0.5 % to 0.6 %/y for crystalline silicon technology, there is much evidence that the degradation rates for many crystalline silicon modules are now increasing significantly. Contributing to this degradation are:
- Light stress ionization effects:
  - Trina solar published -4.5 %/y degradation rate, Singapore
  - DOE National Laboratory Regional Test Centers showed degradation of -1 % to -2%/y in newer crystalline silicon modules.
  - Jinko Solar published a 4 % to 7 % efficiency loss from 540 MJ/m^2 of UV-A light
  - Degradation during UV exposure of 1.8 GJ/m^2 showed a 15% relative power loss at ISFH in crystalline silicon solar cells, attributed to H^+
- Ionization caused by electrical bias originating from system voltage (e.g., +1000 V, +1500 V), which can drive ions and metallization through the encapsulation
  - Ion transport can affect the passivation of cells, leading to power loss of 5% to 40 % in p-PERC+ (bifacial) - NREL
  - Damage at cell back and up to 17 % loss due to damage at cell fronts in tests with n-PERT modules - NREL

In addition to power loss, delamination can occur due to cell surface reactions driven by light and bias. – AIST/NREL/SunPower

Enabling Mechanism (for UV)

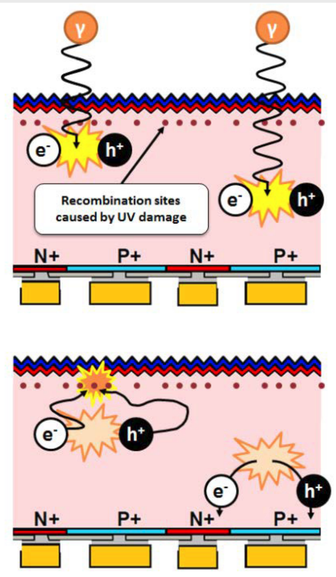
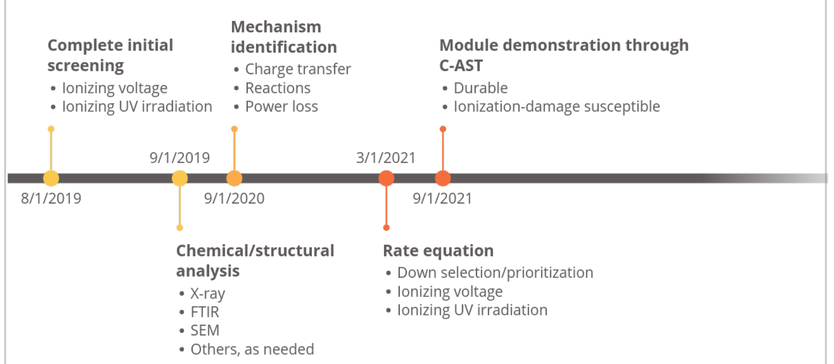


Figure: UV induced damage or charge accumulation at the AR/cell interface and cell sub-surface is suspected. From SunPower Corp.

Scope

- This work will serve to first quantify and characterize the effects of UV- and voltage-induced damage in various modern commercial cell types to identify samples of interest.
- We will then modify the degradation rate: (for UV) by varying the cut-off wavelength to reduce UV energy (controlled with base material type, choice of additives, or by glass/external optical filters); and (for voltage) by varying the module package resistivity (by reducing dangling bond population, choice of additives, initial ion concentration/purity, or type of base material).
- Materials-based characterization of the degradation processes including ion migration and encapsulation and cell/encapsulant interface chemistry will be performed to understand the degradation and verify its prevention.
- Using these approaches, the properties of polymer packaging materials required to mitigate module power degradation can be identified.
- Material properties and performance models will be entered into the DuraMAT data hub. With this, we will inform the PV module value chain how to minimize degradation rates for a 50-year module life and the corresponding valuation of degradation & preventative packaging materials .

Timeline

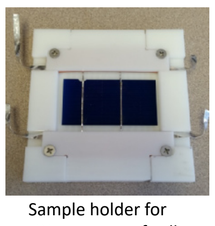


The goal of this work is to reduce the degradation rate through better understanding of ionization enabled degradation and show pathways to mitigation so that the value proposition of higher performing module encapsulants can be quantified.

Approach for UV Ionizing Degradation

This work will serve to first quantify and characterize the effects of UV and polarization damage in various modern commercial cell types using cells and mini-modules with susceptible to degradation.

1. Bare cell degradation – understand worst case effects. Select samples.



Sample holder for UV exposure of cell

UV exposure tool-SLAC

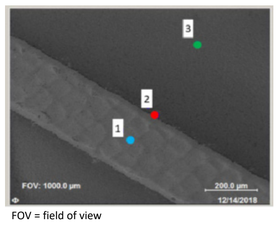
UV exposure tool-NREL

2. Evaluate degradation mechanisms for power loss
   - Chemical changes, including encapsulant and cell
   - Fixed and interface charge stages
   - Loss of hydrogen passivation
3. Evaluate materials to identify reactions
   - Auger, optional depth-profiling
   - XPS, optional depth-profiling
   - Laser-ablation mass spectroscopy (with DOW Chemical)
3. Clarify rate equations to aid module cost/benefit analysis

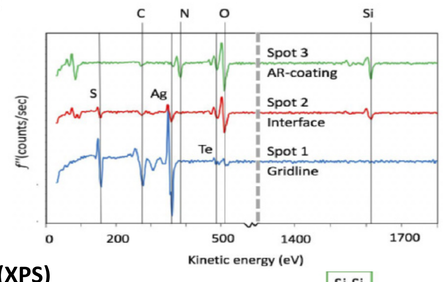
Characterization of Cell Specimens

Auger Spectroscopy

- Enables quantitative chemical analysis of surfaces
- Equipped with scanning electronic microscope (SEM) for precise sampling
- More sensitive to light elements

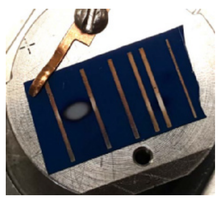


FOV = field of view

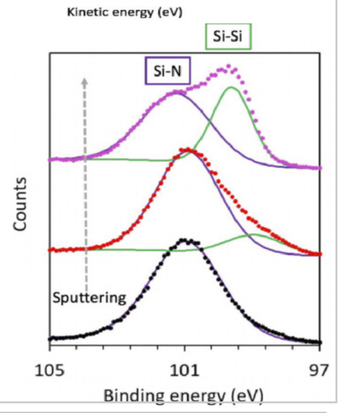


X-ray Photoelectron Spectroscopy (XPS)

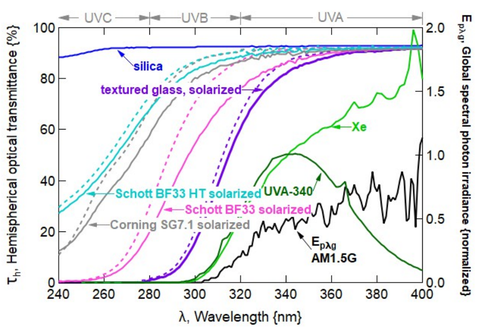
- Enables quantitative chemical analysis of surfaces
- Equipped with multiple sputtering sources to enable depth-dependent characterization
- More sensitive to heavy elements



Figures: Results shown for baseline characterization of unaged cell.



Optical Performance of Packaging Materials



- The transmittance of glass readily affects UV at the cell.
- Optical performance of glass can change from the solarization of trace impurities.
- We have verified & procured low-cost UV transmitting glass for MiMo specimen builds.

Figure: Performance (transmittance) of glass as-received (solid lines) and after (dashed lines) solarization, relative to common UV sources.

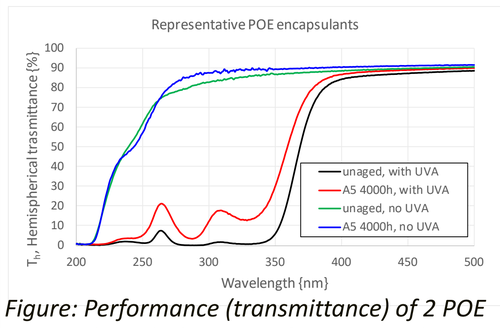
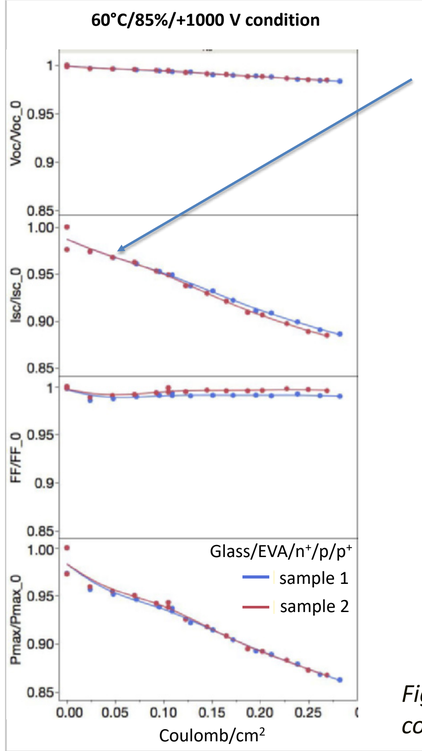


Figure: Performance (transmittance) of 2 POE encapsulants before and after UV weathering.

- The transmittance of the encapsulant readily affects UV at the cell.
- Transmittance may change from chromophore formation or the loss of additives.
- Industry partner will provide tailored encapsulant materials for specimen builds.

Approach – Voltage Ionization



Photocurrent loss associated with ionic charge transfer from cell through glass in c-Si modules under (+) system voltage stress applied to the cell in the module package. The arrow indicates photocurrent loss that is to be characterized and mitigated in this work by changes to the resistance of the encapsulant. This is **not** PID-shunting mode.

We will examine ionizing voltage degradation with respect to

- Encapsulant type/resistivity
- Cell technology

Figure: SunPower–NREL DOE Predicts2, corrosion project

DuraMAT Thrusts Engaged

The DuraMAT thrusts that will be applied include:

(1) Chemical and structural analysis of encapsulant and cell including: XPS, Auger, XAS, SAXS/WAXS, TOF-SIMS, FTIR, and SEM to examine the photo-electro-chemical degradation effects at interfaces and heterogeneous surface reactions.

(2) Predictive simulation through application of models developed in this work

(3) Outdoor testing, for materials studied, experimental modules, and reference modules

(4) Applied data analytics with the DataHub for data tools to model designing, testing, and manufacturing procedures that can be used to forecast performance and durability.

(5) Through industry outreach, we will test polymeric packaging materials (encapsulants, transparent frontsheets and backsheets) of various DuraMAT stakeholders, verifying the capability of those materials to provide durability against power degradation, i.e. the benefit associated with UV filtering and resistance to charge transfer in electric fields.

U.S. DEPARTMENT OF ENERGY
NREL NATIONAL RENEWABLE ENERGY LABORATORY
Sandia National Laboratories
BERKELEY LAB
SLAC NATIONAL ACCELERATOR LABORATORY

Cracked Up: how should we classify and respond to various electroluminescence defects in silicon PV modules?

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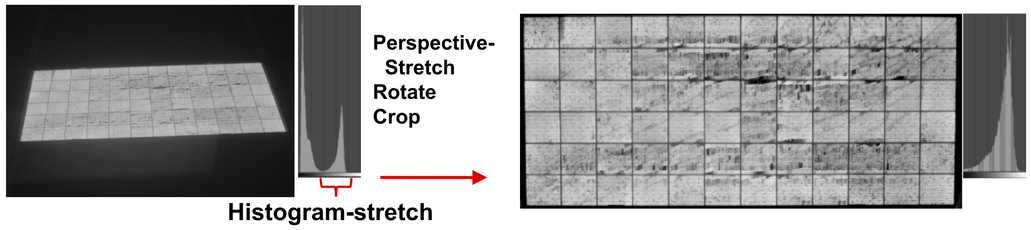
[1]BrightSpot Automation LLC, Westford, MA, USA; [2]Acuity Power Group, Lawrence, MA, USA;
[3]Florida Solar Energy Center, University of Central Florida, Cocoa FL, USA

1. Problems

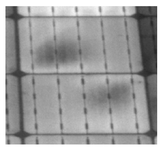
- Module degradation rates are strongly correlated to the number of cracked cells[1]
- IEC 61215 is lenient regarding cracked cells
  - The static load test creates cracks, but there is no subsequent cyclic loading to open up the cracks
  - Cold explosure[2] in the chamber tests creates tiny microcracks in many modules but there is no subsequent mechanical loading to propagate them into full cracks
- Few modules are tested for cracks in the field by electroluminescence (EL); just in factory
- No clear agreement on how to interpret EL images or how to react to cracked cells
- Without wider testing and consequences, module manufacturers have little incentive to improve designs and may not even be aware that they should
  - There is immense difference in the crack resistance of different module designs, but most module buyers are clueless

2. How enhance & interpret EL images?

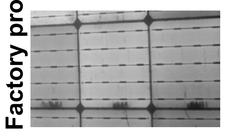
Enhance example



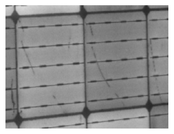
Factory problems



Blotches in repeating pattern - Si growth or cell processing contamination. Not cracks.

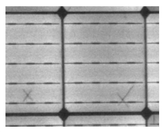


Repeating pattern: poor screen printing. Not cracks.

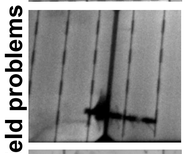


Curved and non-continuous lines on mono cells: Cell processing contamination. Not cracks. Many mono cracks are at 45º

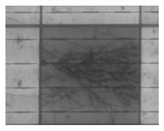
Field problems



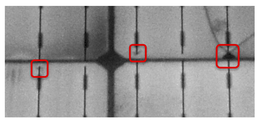
"X" cracks: Rear side point impact, likely post shipping, sometimes from cable connectors swinging against back



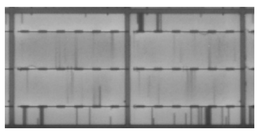
Line of "X" cracks: Rear side dragging impact, possibly from dragging a corner of another module across backsheet when unpacking pallet



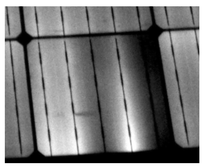
Dense dendritic crack pattern. Likely cracked at high load level with high release of energy. Shunting makes image dark. Worse low-light performance.



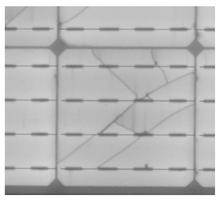
"Crow's feet" V cracks at wire tips: poor soldering



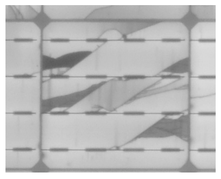
Dark finger regions consistently going up to busbars: Likely cracks in fingers but not in Si; poor metallization and/or tabbing process/design



Dark regions around 1 or more busbars: poor soldering or cracked wire

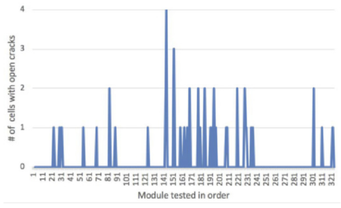


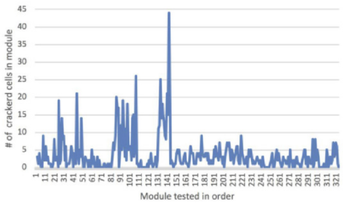
Closed cracks – no power loss. Yet.

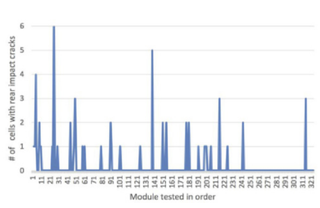


Open cracks – possible power loss and hot spots

3. How quantify EL images?



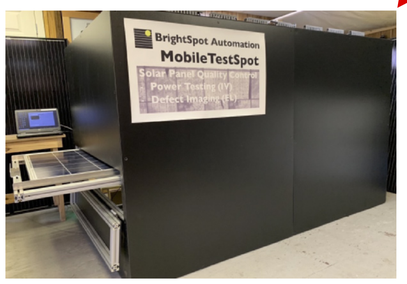




# of modules	322
# of modules with cracks	258
% of modules with cracks	80%
# of cracked cells	1147
% of cracked cells	4.9%

- Keep track of cracks in key categories: Closed, Open, Rear Impact
- Important to automate detection and quantifications

3. How and when test panels?



Systems	Throughput (modules/hr with 2 workers)	Pros	Cons
Tripod systems	20-60	Lowest cost Easy to transport	Focusing challenges Poor reproducibility
Trailer systems	40-120	Best quality images Reproducible conditions Can do IV and other tests Can test during daytime	More expensive Undesirable to de-mount modules Difficult to move far
Drone systems	>120	Fastest Best for difficult to access installations	Focusing challenges More expensive? Dangerous high-voltage power supplies to bias many modules at once

Who?	When?	Why?
Distributors	Sample incoming shipments	Ensure quality of modules Differentiate from competitors
EPCs/Installers	Sample incoming shipments Sample	Because investors or insurance companies require it Ensure quality of modules and work Differentiate from competitors
Independent Testing Services	Sample new installation and low-performing systems	Hired to verify system quality
O&M Groups	Test low performing strings or modules with hot cells from thermal imaging	Replace or "repair" high risk modules
Investors and insurance companies	At all stages through above groups	Maximize revenue and minimize risk Establish baselines in case of warranty claims

Parameter	Baseline	Crack Free
Degradation rate (%/year)	0.75	0.45
Service life (years)	25	30
LCOE % change from baseline	0.0%	**-7.8%**

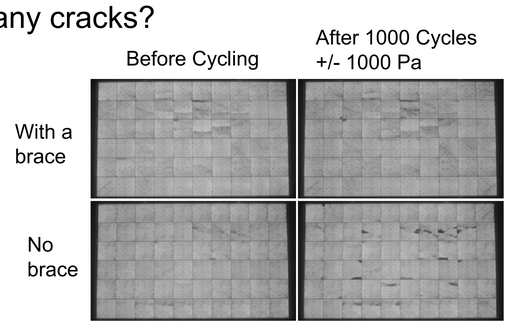
Improving the degradation rate or service lifetime has huge impact on LCOE (*NREL Comparative LCOE calculator*)

4. How to respond to EL images?

Testing after shipping:
- Why accept any cracks?
- How much higher $/W to demand replacement from module supplier of panels with any cracks?

Testing right after installation:
- Why accept any cracks?
- How much higher $/W to demand replacement from installer of panels with any cracks?

Testing of older systems:
- Is it acceptable to add a "band-aid" to badly designed or compromised modules?
- What damage can be ignored
- What damage requires further testing?
- What damage requires replacement?



Adding a brace can limit deflection vs load and prevent crack opening or even close opened cracks[3]

Criteria	No action	Thermal image and IV test within 2 years	Thermal image and IV test in place within 3 months	Replace Module
# of closed and rear impact cracks	3 or less	4-6	7-10	>10
# of open cracks	0	1	2-4	>4

Example of possible responses to cracks

Example of a brace that presses on back side

5. References

[1] S. Chattopadhyay et. al., "All-India Survey of Photovoltaic Module Reliability: 2016," IIT Bombay and NISE.
[2] M.W. Rowell, S.G. Daroczi, D.W.J. Harwood, and A.M. Gabor, " The Effect of Encapsulant Properties and Temperature Cycling on the Fracture Strength and Performance of Encapsulated Solar Cells," in WCPEC-7, 2018.
[3] A. M. Gabor, J. Lincoln, E. J. Schneller, H. Seigneur, R. Janoch, A. Anselmo, D. W. J. Harwood, M. W. Rowell, Compressive Stress Strategies for Reduction of Cracked Cell Related Degradation Rates in New Solar Panels and Power Recovery in Damaged Solar Panels," in WCPEC-7, 2018.

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Quantitative Electroluminescence Imaging of PV Modules: Low-Frequency Blur Removal

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SERIS Solar Energy Research Institute of Singapore

Introduction

- Even in a well-focused electroluminescence (EL) imaging setup, photon-scattering in lens or camera sensor can cause image blur. This work differentiates between high-frequent (HF) and low-frequent (LF) blur (Fig. 1a). HF blur causes smoothed gradients and therefore a reduction of the smallest resolvable object size (Fig. 1b,II). In contrast to this, LF blur shifts low-gradient changes, causing a higher background level towards the PV module center and a halo around the device (Fig. 1b,III).

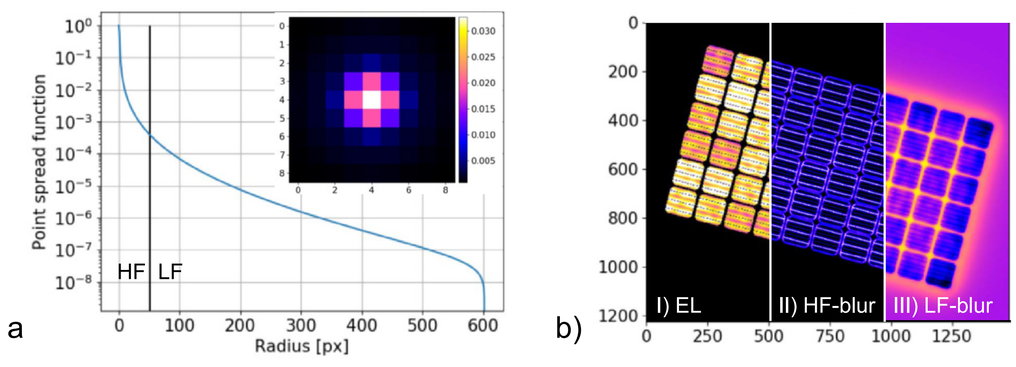

Figure 1: a: Point spread function (PSF) measured for SERIS EL imaging system; b: I: synthetic EL image; II: (I) blurred with PSF(HF); III: (I) blurred with PSF(HF+LF)-(II);

- This impairs certain types of quantitative analysis, such as cell intensity average and -standard deviation.
- EL images of a module manufacturer are corrected for dark current, vignetting, lens- and perspective distortion [2] (Fig. 2a). Nevertheless, the intensity contrast seems to decrease towards the module center (Fig. 2b).

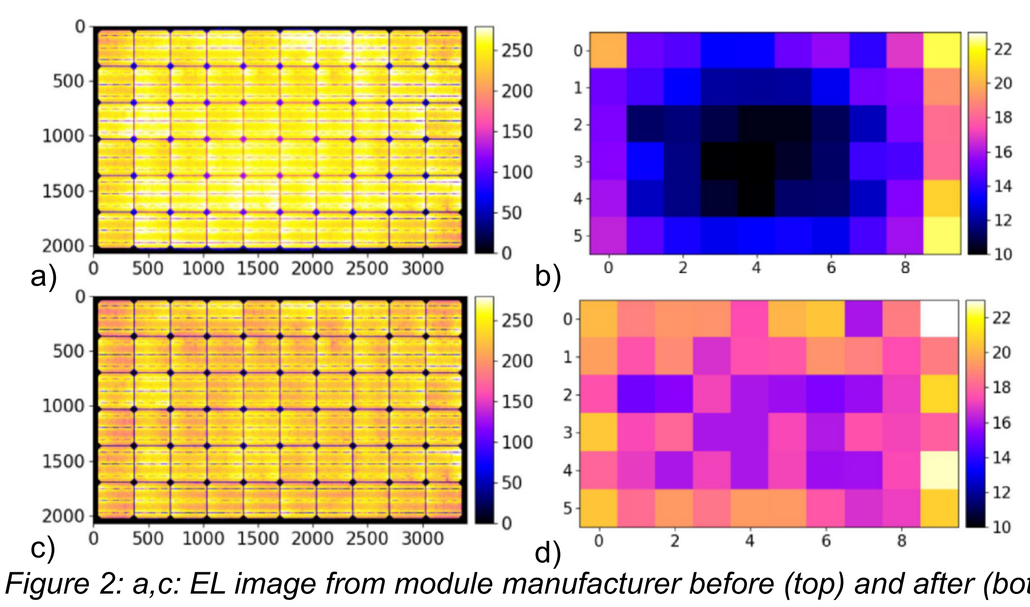

Figure 2: a,c: EL image from module manufacturer before (top) and after (bottom) proposed routine; b,d: corresponding standard deviation of cell intensities

Proposed routine

- This work presents a robust method for LF blur removal without the need of an additional calibration. It is based on localized background level estimation and contrast adjustment (Fig. 3). EL images corrected with this routine have a homogenous (zero) background level while keeping their upper EL signal level.
- LF blur removal is applicable on EL images of Si-based PV modules. It should be executed as last step of the image correction routine, proposed in [2].

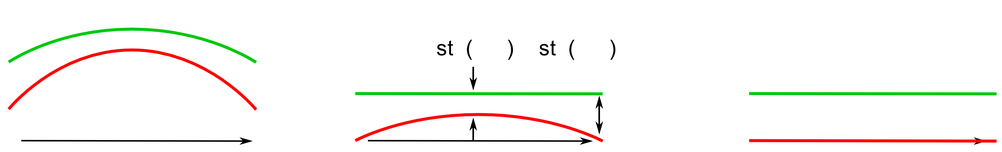

Figure 3: Shematic of upper EL signal and background (BG) level

- An intensity offset image (I_{off}) is removed from the EL image (I_{EL0}). Subsequent multiplication of an amplitude image (I_{amp}) ensures that the upper EL intensity level remains unchanged:

$$I_{ELc} = I_{amp} \cdot (I_{EL0} - I_{off}) \quad (1)$$

- To obtain the intensity offset, a region of interest (ROI) around the gap between four neighbouring cells is analyzed. The cumulative distribution function (CDF) of the image intensities inside the ROI at 1% is defined as intensity offset for that point. For a 60 cell module, 9x5 values can be obtained (Fig. 4a, inside green box). The same method cannot be applied for the edges of the module since the image intensities gradually fall to background level (~zero) . These areas (Fig. 4a, between red and green box) are set to the result of a 2D polynomial fit from all inner values. To obtain I_{off} , the result is up-sampled to I_{EL0} resolution using Lanczos interpolation (Fig. 4b).

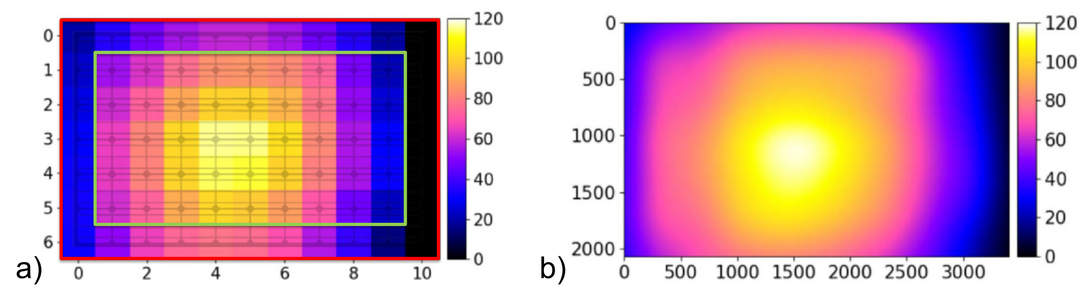

Figure 4: a: discrete intensity offset (gray mask: module position) b: I_{off} from up-sampled (a)

- The initial amplitude image (I_{amp0}, Fig. 5a) is obtained from the ratio of the input EL image to the intensity offset-corrected image:

$$I_{amp0} = \frac{I_{EL0}}{I_{EL0} - I_{off}} \quad (2)$$

- I_{amp0} is down-sampled to 1 px per cell (Fig. 5b). To retain the upper EL intensity level, the local minimum of I_{amp0} is used for every cell. The result (I_{amp}, Fig. 5c) is up-sampled in the same fashion as I_{off}.

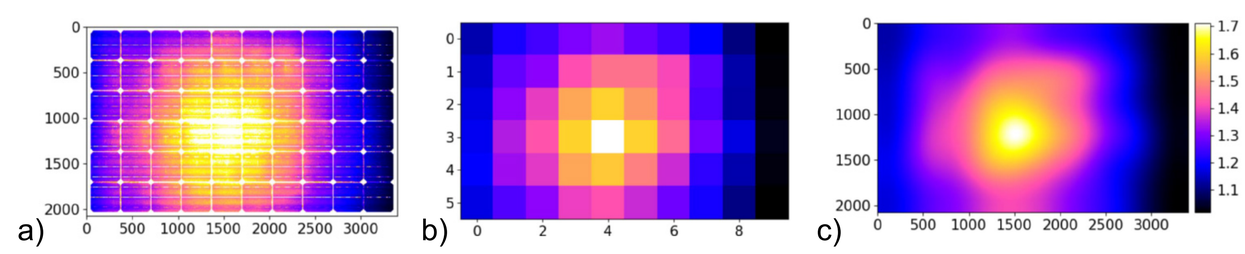

Figure 5: Steps to obtain the intensity amplitude image; a: I_{amp0}; b: cell-minimum of (a); c: (b) up-sampled using Lanczos interpolation

Impact

- Theoretically, a noise-free image can be fully deblurred (HF and LF) if the PSF is precisely known. In practise, LF-blur largely remains. The proposed method can be implemented without extra measurements and only minor computational effort. For 2x100 EL images of new mono and poly Si modules is was found to reduce the inhomogeneity of cell standard deviations 60% (mono) and 66% (poly).

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[2] K. G. Bedrich, “Quantitative Electroluminescence Measurement of PV Devices (Thesis),” Loughborough University, 2017.

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NUS National University of Singapore

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

Capability 1: Data Management & Analytics

Todd Karin[1], Robert White[2], Mike Deceglie[2], Birk Jones[3], Margaret Gordon[3], Laura Schelhas[4], Stephanie Moffitt[4], Anubhav Jain[1]

[1]Lawrence Berkeley National Lab, [2]National Renewable Energy Lab, [3]Sandia National Lab, [4]Stanford Linear Accelerator Center

DuraMAT Capabilities

1. **Data Management & Analytics, DuraMAT Data Hub**
2. **Predictive Simulation**
3. **Advanced Characterization & Forensics**
4. **Module Testing**
5. **Field Deployment**
6. **Techno-Economic Analysis**

Capability Goals

- Ensure DuraMat data infrastructure supports analytics tasks
- Provide data analytics, machine learning, and software support to PV researchers within collaborative projects
- Develop PV analysis software toolkits and predictive models to estimate performance and degradation
- Help researchers use and understand PV toolkits, e.g., through interactive web sites and visualizations

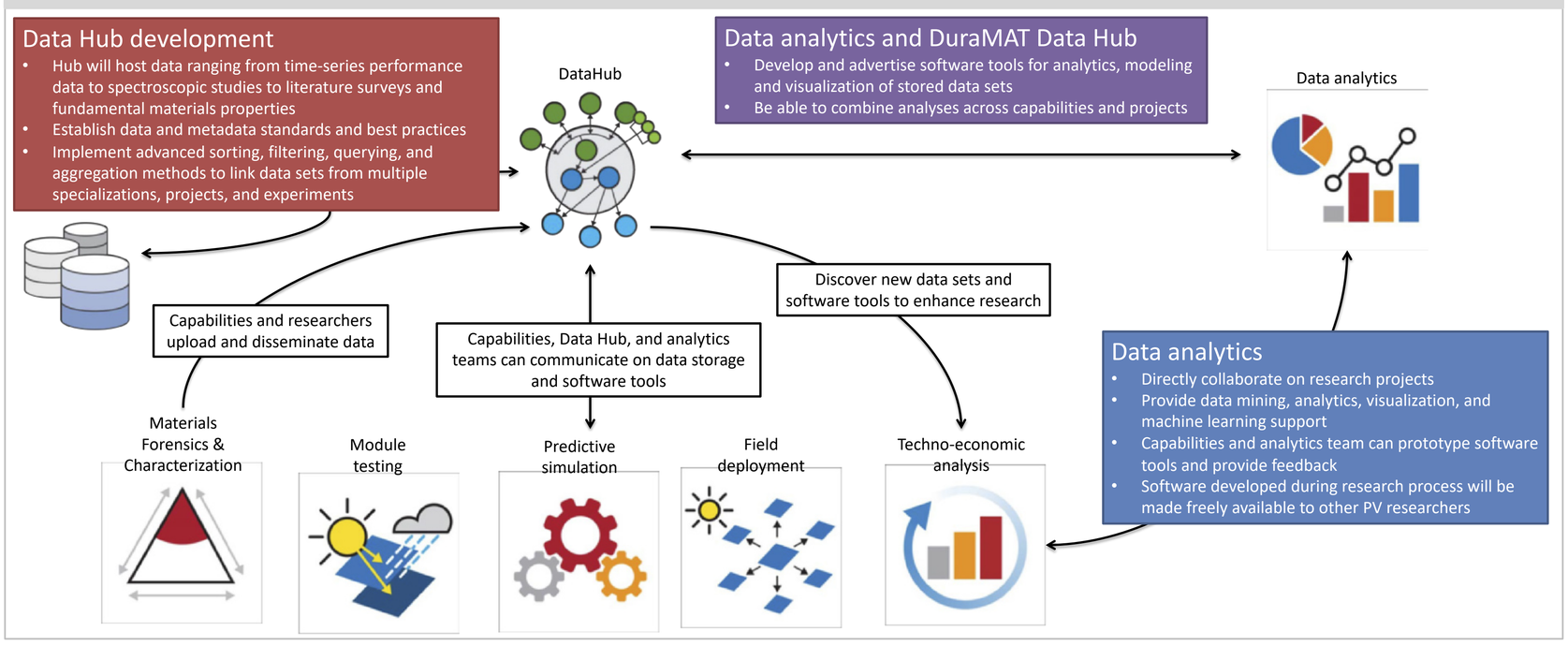
Accomplishments

- Formalizing data standards and best practices with other capabilities / collaborate on DuraMat Data Hub
- Developed clear sky classification software based on GHI
- Developing a PV degradation web dashboard
- In progress: PV climate zones, module string sizing tool, image analysis projects

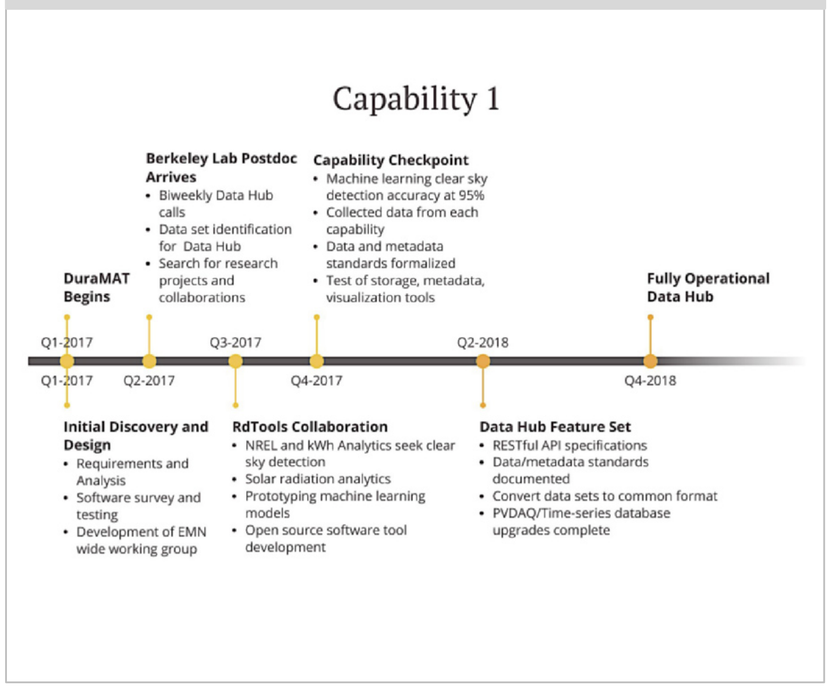
Outcomes and Impact

- Data Hub design complete, data sets collected from most capabilities
- New clear sky models may allow for site-agnostic classification of clear / cloudy days based on GHI measurements alone and with no tunable parameters
- Currently seeking collaborators with PV data in need of data analysis and machine learning

Capability Development



Timeline



Photovoltaic Climate Zones (PVCZ)

Climate affects photovoltaic (PV) degradation.

- Conventionally the Koppen-Geiger climate scheme is used without justification for comparing PV degradation by climate. This scheme classifies zones based on temperature and precipitation patterns relevant for plants.
- We use climate variables relevant for PV degradation: Arrhenius-weighted equivalent module temperature, mean temperature velocity, specific humidity, wind speed and UV insolation to create a climate zone scheme specific to PV degradation.

Outlook for PV climate zones

- Working with kWh Analytics to analyze >100,000 systems to find average degradation rates in each zone.
- Goal: project financing can use climate-specific degradation rates in economic calculations.
- Multiple ways to define climate zones:
  - Since equivalent temperature, temperature velocity and UV insolation are well correlated, can define zones using a rule-based approach incorporating module temperature and specific humidity.
  - Clustering algorithms such as K-Means or DBSCAN define zones using all variables.

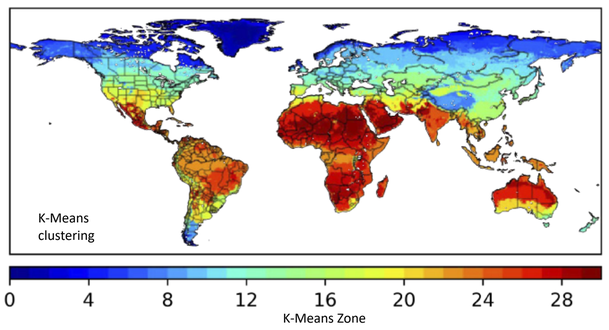
$$\exp\left(-\frac{E_a}{k_B T_{\mathrm{eq}}(E_a)}\right) = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} \exp\left(-\frac{E_a}{k_B T_m(t)}\right) dt$$

$$C = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} \left|\frac{dT_m}{dt}\right| dt.$$

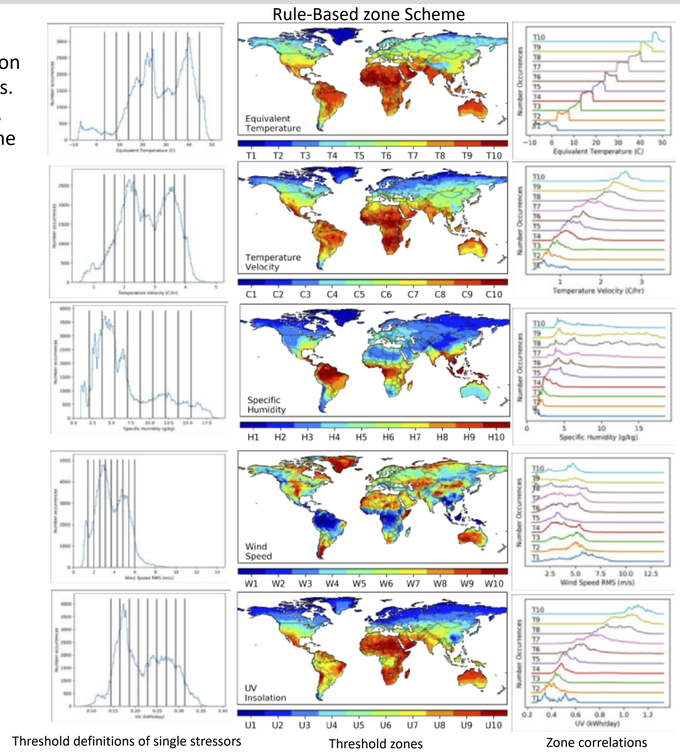
$$H = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} \mathrm{SH}(t)\,dt,$$

$$V^2 = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} v(t)^2\,dt$$

$$U = 0.06\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} \mathrm{GHI}\,dt$$



Climate data from GLDAS.
https://ldas.gsfc.nasa.gov/gldas/

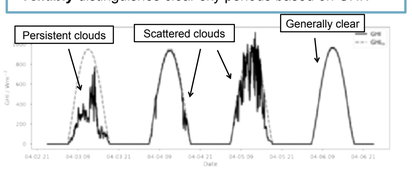


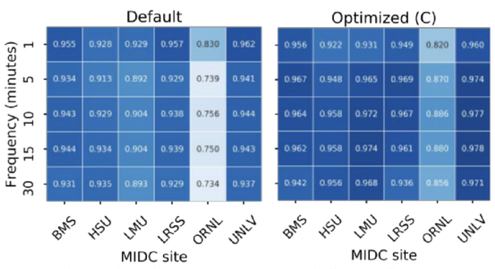
Clear sky detection

- Prior work ahs shown that filtering out cloudy periods is important to robustness of PV degradation analysis[1]
- Work by SNL researchers Reno and Hansen[2] provides detection implemented in PVLib
- We have improved upon the previous algorithm by automatically training parameters in the model to independent satellite-based data
- Our results demonstrate that a single algorithm can accurately detect clear sky periods across many different locations and data frequencies without user tuning

Can we design an algorithm that ***automatically*** and ***reliably*** distinguishes clear sky periods based on GHI?

Approach: use satellite data to modify a published clear sky detection technique[1]





Heatmaps plot $F_{0.5}$ scores, or classification accuracy, of clear sky algorithms, demonstrating significant improvement over the prior work especially at longer data intervals. (manuscript currently under review)

1. Jordan, D. C., Deline, C., Kurtz, S. R., Kimball, G. M. & Anderson, M. IEEE J. Photovoltaics 8, 525–531 (2018)
2. M. J. Reno and C. W. Hansen, Renew. Energy, vol. 90, pp. 520–531, 2016.

String Length (max Voc) Dashboard

Conventional string length calculations are conservative

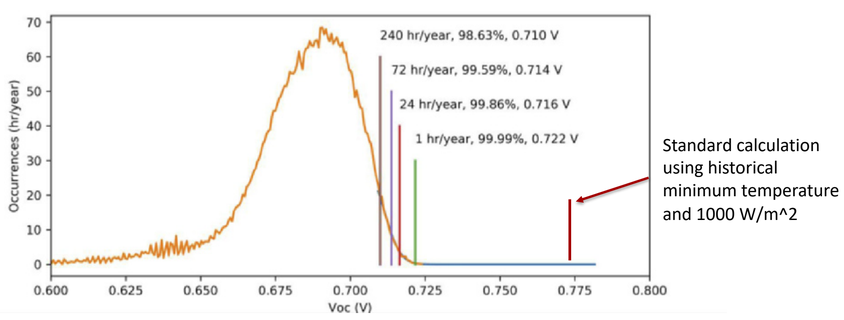
- Longer strings result in lower balance-of-systems costs
- To meet codes for low voltage, string voltage must be <1500 V.
- But there is no required standard method for calculating the maximum open circuit voltage (Voc), which depends on temperature and irradiance.
- Usual practice is to use minimum historical ambient temperature and 1000 W/m^2 for calculating maximum string Voc.
- But minimum historical temperature often occurs at night – when Voc is close to zero.
- This results in a very conservative string length limit, with has a negative impact on project economics

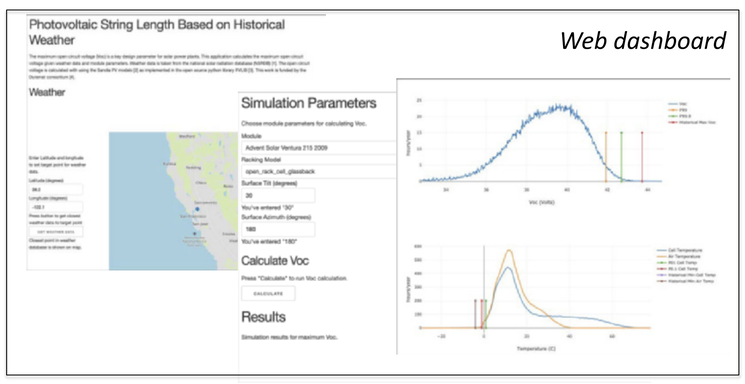
Need for standard method for calculating string length

- We are creating a new standard tool intended for reference in the National Electric Code.
- More precise calculation of string Voc results in the possibility of 1-2 more modules per string and a significant improvements in project economics, reducing LCOE
- Simple web dashboard uses Sandia models for cell temperature as a function of ambient temperature, irradiance and wind speed [1], weather data from the national solar radiation database (NSRDB) [2] and PVLib [3] to simulate Voc.

Discussion Points

- What is a reasonable threshold of hours per year or percentile for string voltage to exceed maximum.
- What is a reasonable safety factor?
- Contacts to NEC?





[1] D. King, W. Boyson, and J. Kratochvill, "Photovoltaic array performance model," *SAND2004-3535*, 2004.
[2] M. Sengupta, Y. Xie, A. Lopez, A. Habte, G. Maclaurin, and J. Shelby, "The national solar radiation data base (NSRDB)," *Renewable and Sustainable Energy Reviews*, vol. 89, pp. 51 – 60, 2018.
[3] W. F. Holmgren, C. W. Hansen, and M. A. Mikofski, "pvlib python: a python package for modeling solar energy systems," *Journal of Open Source Software*, vol. 3, no. 29, p. 884, 2018.

Future work

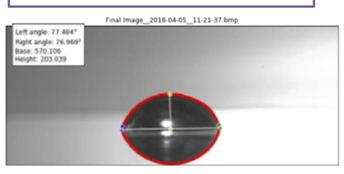
Future work

We have several other projects underway:

- Image analysis for evaluating contact angles of anti-soiling coatings
- Relating combined accelerating stress testing (C-AST) and field measurements
- Image analysis for crack detection in electroluminescence images
- Web tools for degradation analysis

We are open to further suggestions and discussion!

Top: web tools for degradation analysis
Bottom: Automated contact angle analysis for evaluating anti-soiling coatings



Interested in a data analytics project collaboration?

Contact us: ajain@lbl.gov

This work was funded as part of the Durable Modules Consortium (DuraMAT), an Energy Materials Network Consortium funded by the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, Solar Energy Technologies Office.

U.S. DEPARTMENT OF ENERGY
NREL NATIONAL RENEWABLE ENERGY LABORATORY
Sandia National Laboratories
BERKELEY LAB
SLAC NATIONAL ACCELERATOR LABORATORY

Characterization of Polyamide-Ionomer Based Backsheet After Highly Accelerated Stress Testing (HAST) and Acetic Acid Exposure

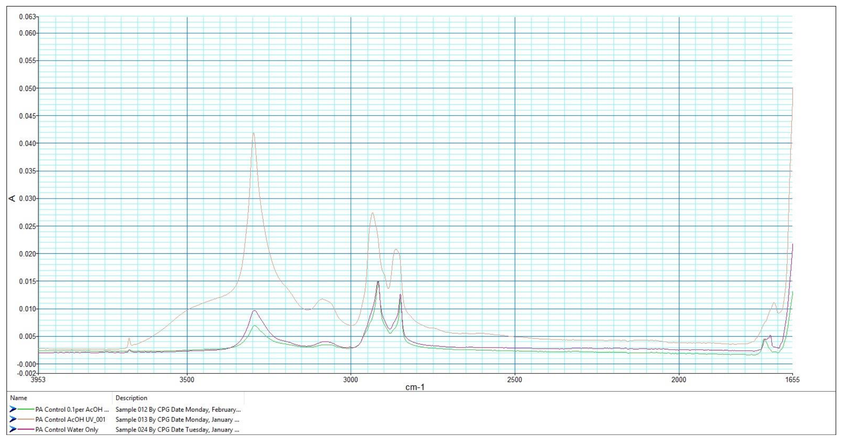
Dr. Christopher Thellen, Mr. Andreas Rothacker, Mr. David Santoleri, Mr. Peter Perez
Contact: Chris@Tomark-Worthen.com, www.Tomark-Worthen.com

Polyamide-Ionomer Alloy
Structural Layer
Moisture Barrier Layer
Structural Layer
Polyamide-Ionomer Alloy

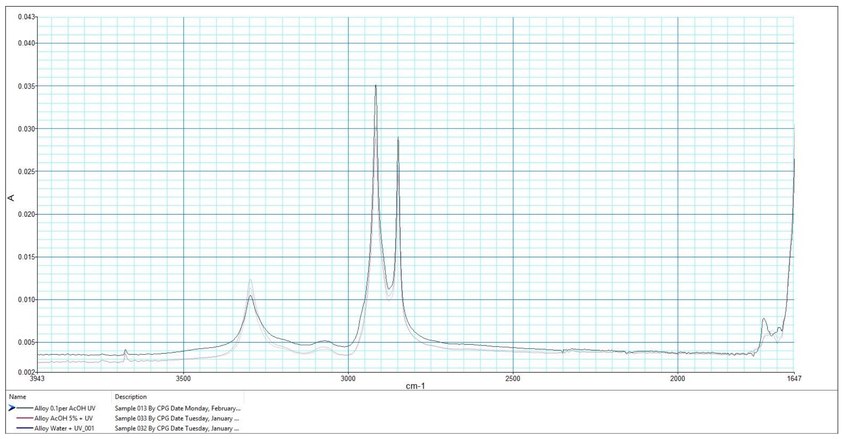
Multilayer Co-Extruded Backsheet with Polyamide Ionomer Alloy Skins

AcOH Exposures	
Time (Days)	10
Concentration (%)	0, 0.1, 5
Temperature (°C)	50

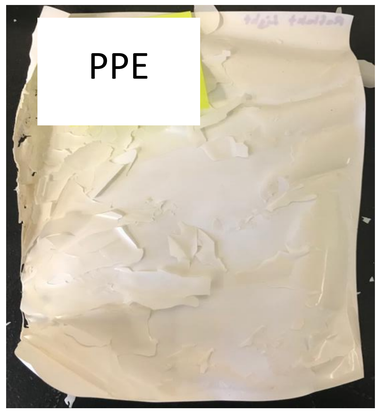
FTIR Scans of Polyamide 6 Exposure to Acetic Acid



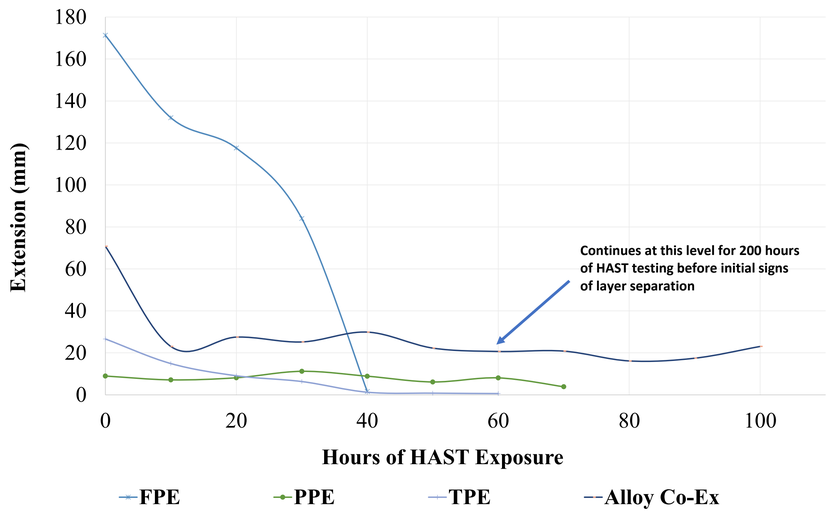
FTIR Scans of PA Alloy Exposure to Acetic Acid



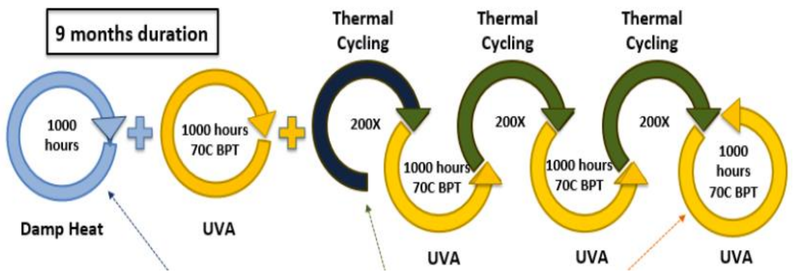
HAST Conditions	
Time (Hours)	100
Temperature (°C)	121
Humidity (%)	100
Pressure (bar)	2.1



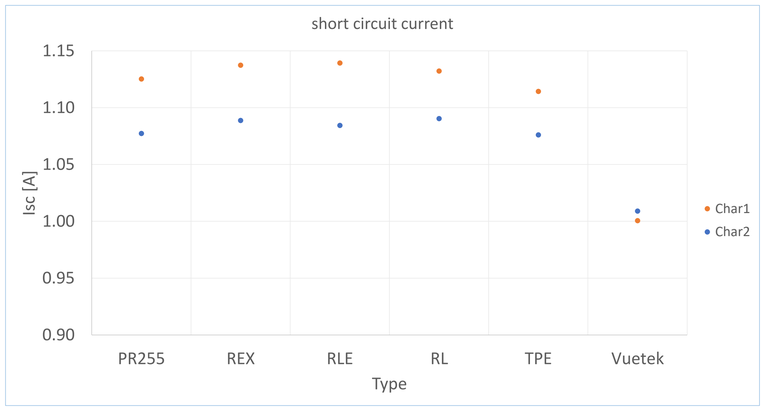
Elongation to Failure During HAST



Dupont's Module Accelerated Sequential Test (MAST 1)
(Currently Underway with Fraunhofer USA)



Initial MAST 1 Test Results on Mini Module Current after 1st Stage Damp Heat Cycle



Summary

- **HAST testing conducted at the University of Massachusetts Lowell indicated that, under the test conditions, only the co-extruded backsheet did not de-laminate during the test. This result confirms that layer to layer bonds achieved during this process are significantly stronger and more durable than the alternative adhesive-based bonds. The co-extruded alloy backsheet showed no signs of delamination until 200 hours of HAST testing was achieved.**
- **Acetic acid exposure at 0.1% and 5.0% concentration to a control Nylon 6 film resulted in increased carbonyl generation, indicated by elevated peaks at a wavelength of 1713cm^{-1} in FTIR scans. Carbonyl groups are typical bi-products of photo-oxidation. Carbonyl groups are present at a significantly lower extent in the testing of the alloy sheet. Work will be conducted to examine the effect of acid scavengers in the PV backsheet.**
- **A sequential test based on Dupont's Module Accelerated Sequential Test (MAST 1) has been initiated at Fraunhofer USA using the co-extruded alloy backsheet along with several laminated and co-extruded control backsheets. This test will evaluate both laminated coupons as well as mini-modules. Early power testing on mini-modules after 1000 hours of damp heat indicates no significant difference between the backsheet types.**

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TOMARK WORTHEN

Fraunhofer

Weathering Performance of Cable Ties for Solar Wire Management

Sophie Napoli[1], Bryan Douglas[1], Adam W. Hauser[1], Gregory S. O'Brien[1], Bryan Skarbek[2], Sumanth Lokanath[2]

[1]Arkema, Inc., 900 1st Ave., King of Prussia, PA 19406, USA
[2]First Solar Inc., 350 West Washington Street, Tempe, AZ 85281 USA

Introduction

Cable management is an important aspect of construction of safe and reliable power plants. Polymers are commonly utilized for cable management and this paper compares a few commonly used materials against a new material Kynar.

Choice of material is a critical consideration when the cost of replacing a failed cable tie is almost 10 times the initial cost of the wire tie in terms of labor and material costs alone.

In this paper we compare commonly used materials that are rated UV grade such as Nylon 6.6 and Nylon 12 and a new material Kynar® PVDF, with high lifetime potential (25+ years) utilizing a suite of durability tests for polymeric cable ties developed by First Solar.

Materials & Methods

Materials

- 8 inch long cables ties
- Kynar® PVDF ties from Nile Polymers
- Nylon ties from HellermannTyton

Methods

Chemical treatment before testing

Un-tied cable ties soaked in one chemical before weathering: Aqua-tex, Poly-tex, Chlor-tex, Ecco-tex, Milestone Herbicide, $ZnCl_2$.

Short Term Environmental Testing

Thermal Cycling :
200 cycles of 6 hours, from -40 °C to 90 °C with a ramp of 100°C/min

Damp Heat :
1000 hours of conditioning at 85 °C and 85% relative humidity

Humidity Freeze :
30 (for Kynar) or 10 (for Nylon) cycling between -40 °C and 85 °C with a relative humidity of 85%

Accelerated Indoor Weathering

Accelerated weathering performed in a Xenon Chamber: temperature of 65 °C, irradiance at 0.8 W/m² at 340 nm, 20% RH and water-spray for 18 min out of the 120 min cycle.

Mechanical Testing

Un-tied cable ties mechanically tested after every exposure.

Indoor Weathering

Accelerated Indoor Testing

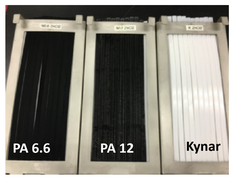
Equivalent in years (UV exposure in Arizona)	Hours in Xenon Arc	Dose (MJ/m²)
1	1300	3.7
3	3900	11.2
5	6500	18.7

Testing includes pristine and chemically treated ties with either :

- Aqua-Tex
- Milestone Herbicide
- Zinc Chloride

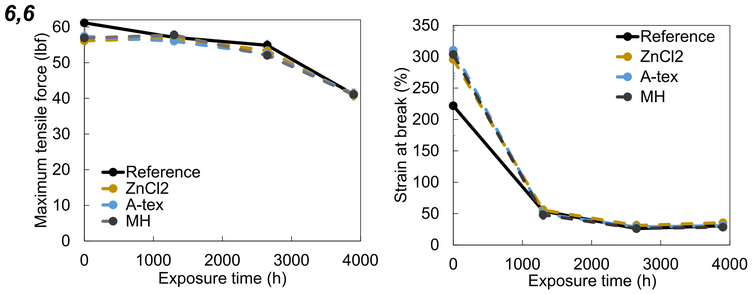
After 2600 hours in the chamber:

Nylon 12 ties: matte, brittle, surface cracking, gloss loss
Nylon 6.6 ties: matte and dull surface, gloss loss



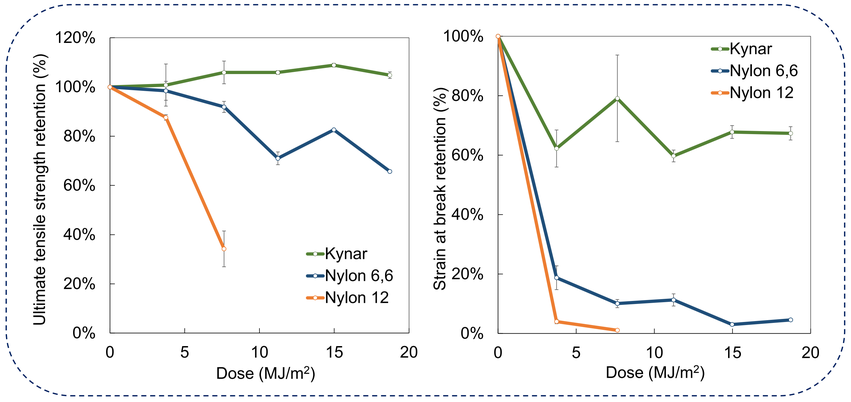
→ **Effect of chemical treatment before weathering:**

Nylon 6,6



- In all materials, mechanical property retention was unaffected by the pre-soaking of chemicals
- $ZnCl_2$ causes stress cracking in Nylon 6,6, but does not appear to have a significant effect in the unstrained state

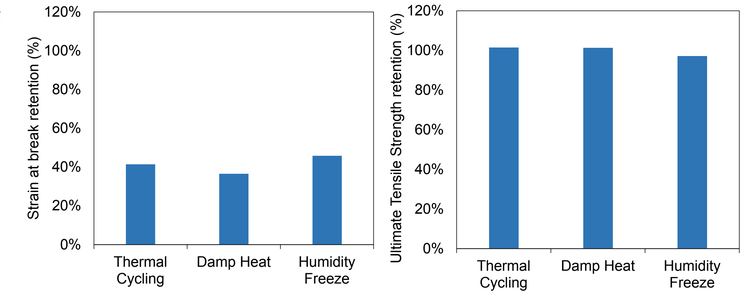
→ **Strain at break and Ultimate Tensile Strength Retention:**



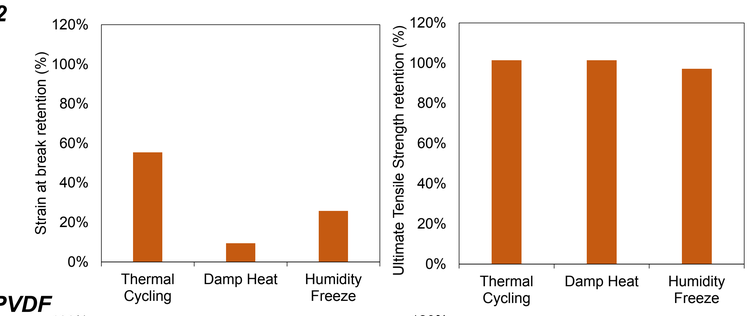
- **Nylon 12:** stopped after 2600 hours due to intensive brittleness and cracking. Failure of the material after an equivalent of two years of exposure.
- **Nylon 6.6:** good tensile strength retention, still > 40lbs. but an elongation dropped at 5% of its original value.
- **Kynar® PVDF**: little impact of weathering. Maximum tensile load still > 50 lbs. Initial drop of strain at break due to a small increase in crystallinity.

Short Term Environmental Testing

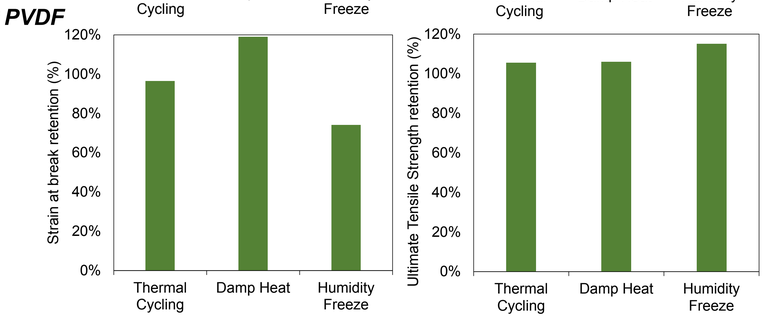
Nylon 6,6



Nylon 12



Kynar® PVDF



- Significant decrease of strain at break for Nylon 6.6 and Nylon 12
- Water can plasticize and cause mechanical property loss in Nylon
- Kynar® PVDF cable ties are not significantly impacted

Outdoor Weathering

- Failure of Nylon 6.6 cables ties after 1 year of service in southwest US desert climate.
- Failure analysis revealed the presence of corrosive ingredients at or near line artifacts which caused stress corrosion cracking.

- In May 2017, installation of 8000 Kynar® PVDF cables ties in various positions and mechanical stress levels, monitored every 6 months.
  → After 1 and ½ year: no Kynar® PVDF failure reported

Conclusion

- Early field failures most likely caused by mechanical strain and chemical exposure that leads to stress cracking
- Poor UV resistance of Nylon 6.6 and Nylon 12 despite being UV grades.
- Excellent durability of Kynar® PVDF, compared to Nylon 6.6 and 12.

- **Arkema:** Robert Lowrie Tel.: 610-205-7408 Email: Robert.lowrie@arkema.com
- **Nile Polymers:** https://nilepolymers.com/
- **First Solar:** http://www.firstsolar.com/

Sandia National Laboratories

PV Lifetime Project: Measuring PV Module Performance Degradation: 2019 Indoor Flash Testing Results

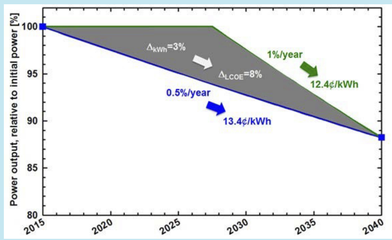
Joshua S. Stein[1], Charles Robinson[1], Bruce King[1], Chris Deline[2], Steve Rummel[2], and Bill Sekulic[2]

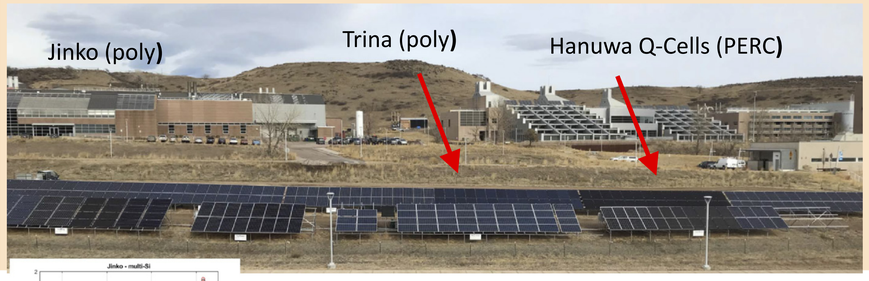
[1]Sandia National Laboratories, Albuquerque, NM, USA;
[2]National Renewable Energy Laboratory, Golden, CO, USA

Introduction

Abstract — Photovoltaic (PV) module and system performance degradation is being measured by periodic flash testing of fielded PV modules at three sites. As of early 2019, new results from modules fielded in New Mexico and Colorado are available. These data indicate that module degradation varies significantly between module types and can also vary between modules of the same model. In addition, degradation rates for some module types appear to vary over time. Great care is made to control for stability and repeatability in the measurements over time, but there is still a +/-0.5% uncertainty in flash test stability.

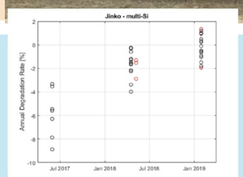
Due to the typically slow pace of PV module degradation in operation, often less than 1% per year [1], as well as variations in the operating and test conditions, any resulting differences in degradation rate are difficult both to measure and compare.

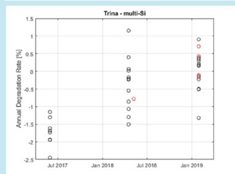




Modules Under Test

Site	Manufacturer	Model	Technology	# of modules	Installation Date
NM	Trina Solar	TSM-PD05.08 260W	poly-Si	56	Jun-16
NM	Jinko Solar	JKM260P-60 260 W	poly-Si	56	Jun-16
NM	SolarWorld	SW 245W Mono	mono-Si	21	2013
NM	Canadian Solar	CS6K-270P 270W	poly-Si	48	Oct-17
NM	Canadian Solar	CS6K-275M 275W	mono-Si	48	Oct-17
NM	Hanuwa Q-Cells	Q.Plus BFR-G4.1 280W	poly-Si PERC	48	Oct-17
NM	Hanuwa Q-Cells	Q.Peak BLK G4.1 290W	mono-Si PERC	48	Oct-17
NM	Panasonic	N325SA16 325W	HIT Mono	48	May-18
NM	LG	LG320N1K-A5 320W	N-type Si	48	May-18
CO	Trina Solar	TSM-PD05.08 255W	poly-Si	28	Sep-16
CO	Trina Solar	TSM-PD05.08 260W	poly-Si	28	Sep-16
CO	Jinko Solar	JKM260P-60 260W & 265W	poly-Si	56	Sep-16
CO	Hanuwa Q-Cells	Q.Plus BFR-G4.1 280W	poly-Si PERC	28	Oct-17
CO	Hanuwa Q-Cells	Q.Peak BLK G4.1 290W	mono-Si PERC	28	Oct-17
CO	Canadian Solar	CS6K-300MS 300W	mono-Si PERC	28	Jun-18
CO	Panasonic	N325SA16 325W	HIT Mono	30	Jun-18
CO	LG	LG320N1K-A5 320W	N-type Si	28	Jun-18
			Total	675 modules	

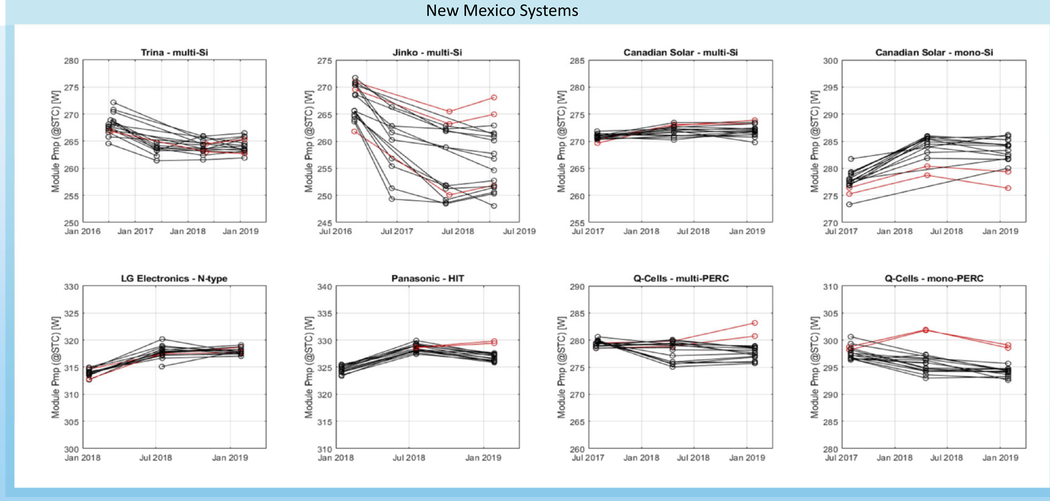




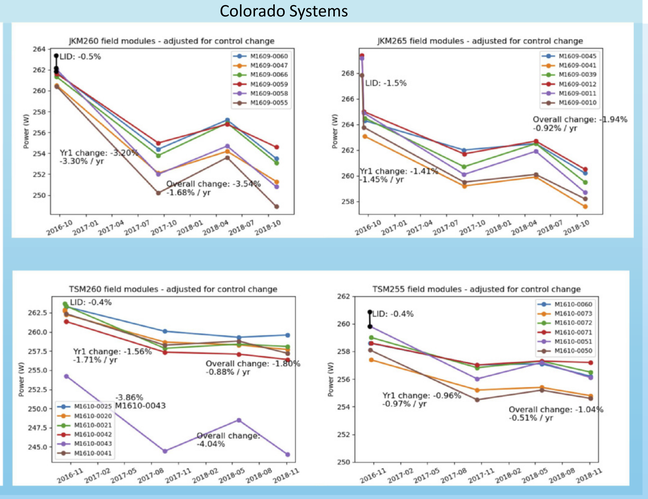
Flash Test Results

Flash test results are shown in the figures below. Trina and Jinko modules have been in the field almost three years and show decreasing rates of degradation over time. Panasonic, Canadian Solar, and LG Electronics modules appear to be improving over time in the first year and then stabilizing or degrading slightly later. One result is clear, degradation rates appear to be changing over time. Within the next year we will get more results from Colorado and can see if we similar patterns on their systems.

New Mexico Systems

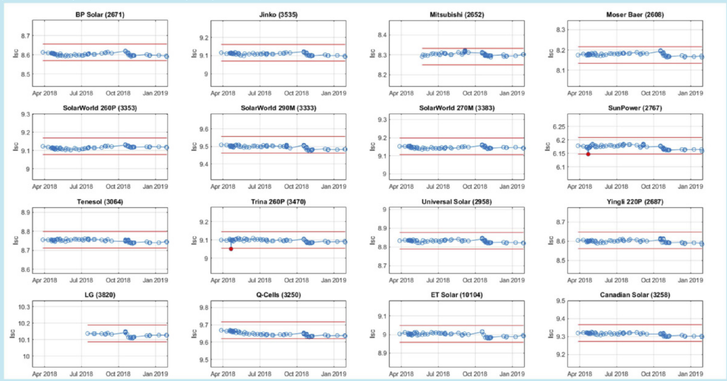


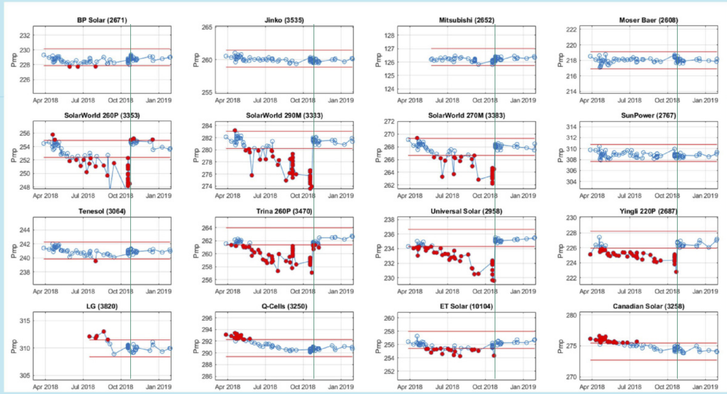
Colorado Systems



Flasher Stability

The stability of the flash simulators at each lab was monitored by regularly measuring control modules that are stored indoors. We noted that some of these modules showed progressive degradation and variability of Pmp (and RVoc). We attributed this to increasing series resistance from connector fatigue. We replaced all connectors with gold-plated multi-contact connectors and this problem disappeared (vertical lines in Pmp plot). We found that we can maintain approximately +/- 0.5% stability in power (red lines).





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[3] J. Lindroos, Y. Boulfrad, M. Yli-Koski, H. Savin, "Preventing light-induced degradation in mylticrystalline silicon", Journal of Applied Physics **115**, 2014
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[5] F. Kersten et al., "A New mc-Si Degradation Effect called LeTID" IEEE Photovoltaic Specialists Conference, 2015
[6] K. Ramspeck, S. Zimmermann, H. Nagel, A. Metz, Y. Gassenbauer, B. Birkmann, A. Seidl, "Light induced degradation of rear passivated mc-Si solar cells", 27th EU-PVSEC, 2012

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Using an Environmental Wind Tunnel for PV and CSP Applications

Dirk Goossens, ESAT ELECTA KU Leuven & EnergyVille

The KU Leuven / EnergyVille wind tunnel

The KU Leuven / EnergyVille wind tunnel has been specially designed to study wind and dust dynamics and provides solutions to understand and mitigate soiling problems in various environments and climates. It is used to study soiling on PV modules and CSP setups and to investigate the effect of wind on PV power production. The tunnel has 2 available test channels, each equipped with special light sources suitable for photovoltaic measurements.

Advantages of wind tunnel approach:

- Environmental parameter control
- Repeatability and reproducibility
- Subprocesses can be studied separately

Creation of natural soiling patterns

Sedimentation chambers mimic dust deposition under no-wind conditions, which is rather uncommon at outdoor stations. In the KU Leuven / EnergyVille wind tunnel a fully controlled sediment supply system creates natural dust deposition and dust accumulation patterns under any desired wind condition.

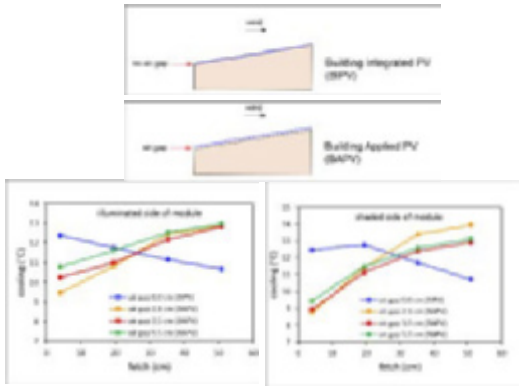
Measurements on scale models

Photovoltaic collector

CSP collector

Soiling is studied under controlled conditions in the wind tunnel. Results are compared to dust accumulation on full-scale constructions.

Cooling of roof-installed PV modules

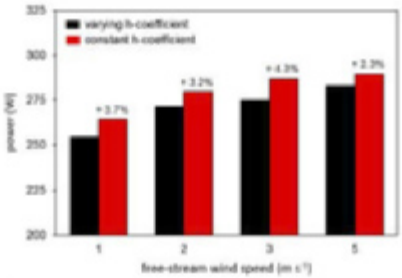


The cooling of PV modules can be studied for various PV and building configurations. In the example shown in the graphs above the BAPV patterns differed strongly from the BIPV pattern.

Measurements on full-scale modules

Wind, cooling, heat transport, and electrical performance are studied on full-scale PV modules in the wind tunnel.

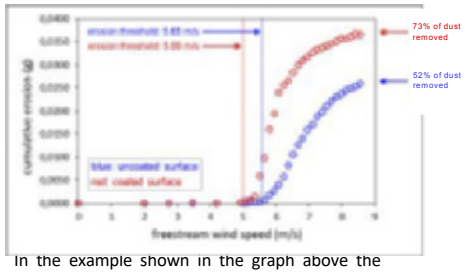
Correcting PV module power output



Energy prediction models often assume that temperature patterns over PV modules are uniform, which is seldom the case. This may lead to incorrect predictions. In the graph above, the total power output of a tested PV module is shown for a uniform heat transfer coefficient over the module (red bars) and a realistic distribution of the heat transfer coefficient based on wind tunnel experiments (black bars). Differences up to 4.3% occurred.

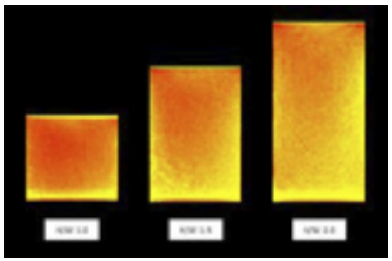
Testing of anti-soiling coatings

Anti-soiling coatings and anti-reflective coatings are tested in the wind tunnel to determine their efficiency and their effect on power production.



In the example shown in the graph above the coating tested promoted the removal of the dust layer on the glass

Soiling of BIPV building façades



PV panels on buildings will become dirty over time. Wind tunnel measurements can predict the areas on the building that are most vulnerable to soiling.

Can we help?

We can test your instruments, products, and protocols under harsh (windy and/or dusty) conditions. For more information, contact us:

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johan.driesen@esat.kuleuven.be

Using numerical simulations to understand BO-LID and LeTID

Brett Hallam and Moonyong Kim

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Introduction

- Currently, there is confusion over BO-LID and LeTID, and the impact of testing conditions on the defect systems.
- Investigate:
  - Light induced degradation with BO-LID and/or LeTID at different temperatures.
  - The impact of damp heat testing and module encapsulation on BO passivation stability

Demonstrate the impact of BO-LID and LeTID on c-Si using numerical simulations

Numerical modeling

- A numerical model is developed in MATLAB using an ODE solver and a 3-state model with equations (1) – (4) for both BO and LeTID.
- Incorporate impact of BO and LeTID on injection-level-dependent lifetimes.
- Include established temperature- and injection level dependent reaction rates of degradation and regeneration for both BO-LID and LeTID (Table I).

$$\frac{dN_A}{dt} = k_{BA}N_B - k_{AB}N_A \quad (1)$$

$$\frac{dN_B}{dt} = k_{AB}N_A + k_{CB}N_C - k_{BC}N_B - k_{BA}N_B \quad (2)$$

$$\frac{dN_C}{dt} = k_{BC}N_B - k_{CB}N_C \quad (3)$$

$$k_{ij} = v_{ij}(\Delta n)\, exp\left(-\frac{E_{a,ij}}{k_B T}\right) \quad (4)$$

Table I: Reaction rates of the BO-LID and LeTID defect systems. (*)normalised to 1 sun. (**) assumed to have same attempt frequency and 0.1 eV higher activation energy than that for LeTID degradation.

Reaction	Attempt frequency for 1-sun OC (/s)	Dependence on carrier injection	Activation energy (eV)	Notes
BO-LID degradation (AB)	4×10^{3}	Constant (>0.01 suns)	0.475	Bothe *et al.*
BO-LID regeneration* (BC)	4.63×10^{9}	Linear	0.98	Wilking *et al.*
BO-LID annihilation (BA)	1×10^{13}	Constant	1.32	Bothe *et al.*
BO-LID destabilization (CB)	5×10^{9}	Constant	1.25	Wilking *et al.*
LeTID degradation (AB)	9.37×10^{8}	Linear	0.94	Bredemeier *et al.*
LeTID regeneration** (BC)	9.37×10^{8}	Linear	1.04	Estimated

Results and Discussion

- At 75°C, commonly used to investigate LeTID, if samples have no prior BO regeneration process, with and without BO-LID and LeTID can result in a different extent of degradation (see Fig. 1).

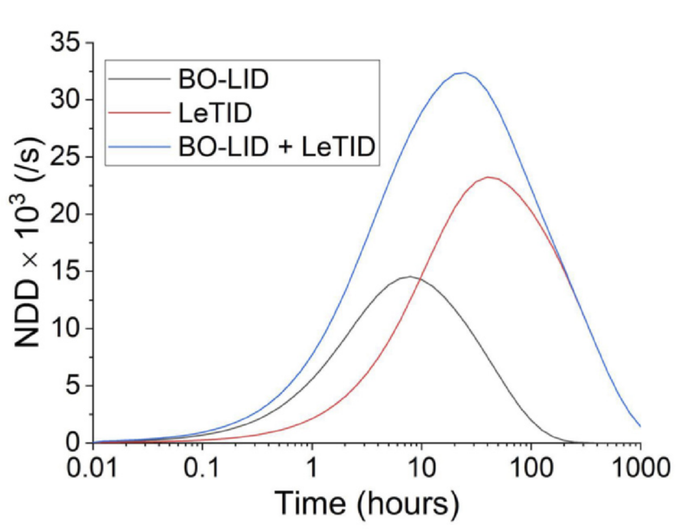


Figure 1: Simulations at 75°C highlighting evolution of BO-LID, LeTID and BO-LID+LeTID.

- Comparing IEC testing condition to standard LeTID testing conditions, they can lead to different amount of BO-LID and LeTID formation (Fig. 1b) if the testing is done for a fixed time (100 hours) compare to the maximum degradation time (t_{max}).

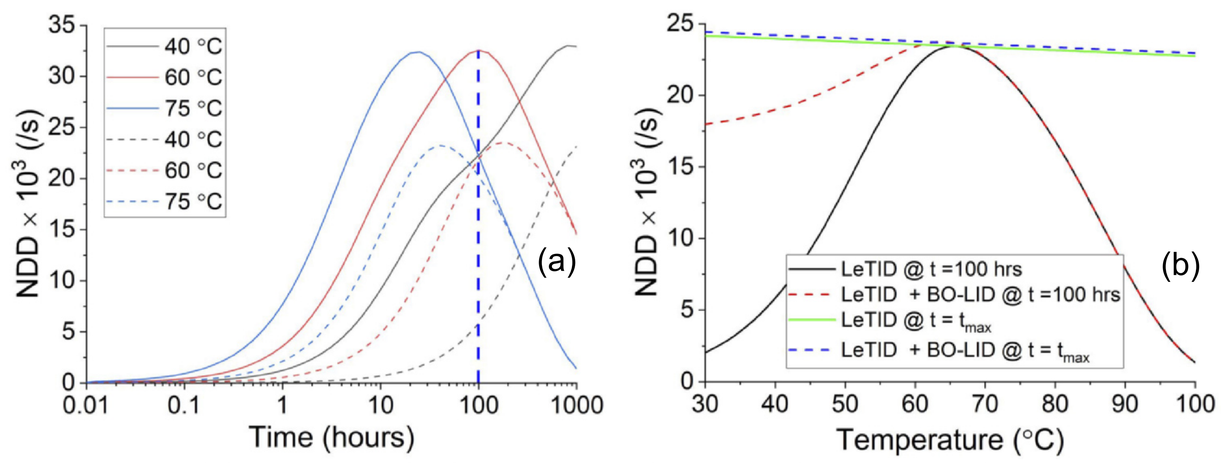


Figure 2: (a) evolution of BO-LID+LeTID (solid lines) and LeTID (dash lines) at different temperatures (b) NDD with LeTID or BO-LID + LeTID when t= 100 hours or t_{max} at different temperatures.

- Different bulk quality alone can change the injection level at given intensity, so reaction rates can be accelerated under same operating condition

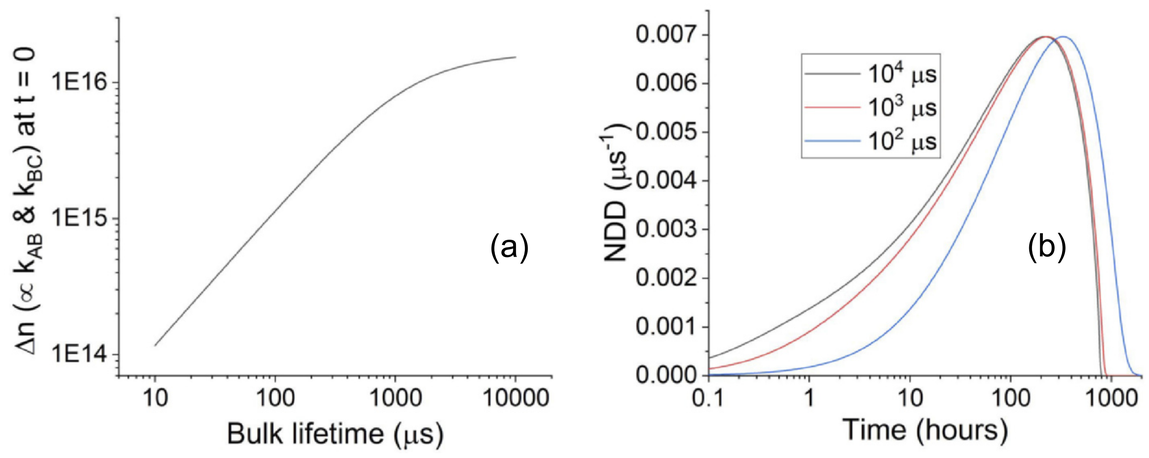


Figure 3: (a) bulk Lifetime with J0 = 10 fA/cm2 vs. injection level at 1 sun & t= 0 (b) NDD of LeTID vs. time with different bulk lifetimes (10^2 – 10^4 µs)

- For BO regenerated cells, damp heat testing is only expected to destabilise <5%, and for the typical module encapsulation process only 1% of passivated defects should destabilise.

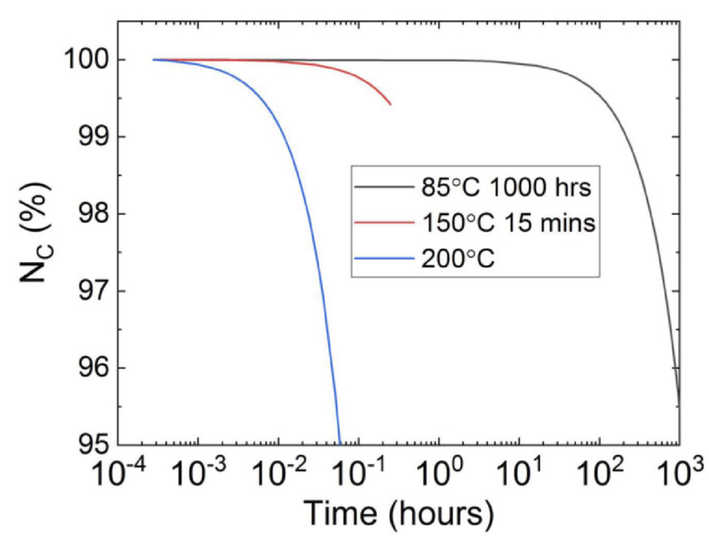


Figure 4: Fraction of NC over time, which shows destabilization due to damp heat testing, (85 °C for 1000 hours), module encapsulation process (150 °C for 15 mins) and 200 °C annealing

Conclusions

- The presence of B-O and LeTID can lead to confusing results.
- Different testing conditions can lead to different conclusions
- Changing wafer quality, changes the injection at a given illumination intensity and can affect reaction rates.
- Thermal treatment can destabilize the B-O regeneration, which can increase the LID.

This work is supported by the Australian Government through the Australian Renewable Energy Agency (ARENA) and the Australian Center for Advanced Photovoltaics (ACAP). Responsibility for the views, information or advice expressed herein is not accepted by the Australian Government.

The bad practice bible: surefire ways to get poor results when power rating PV modules

Harrison Wilterdink, Ronald Sinton, Cassidy Sainsbury, Wes Dobson, Justin Dinger
Sinton Instruments, USA

MOTIVATION

When it comes to power rating PV modules for STC output, the PV industry has decades of experience to draw upon for informing best practices

But what bad practices still thrive due to historical precedent, technical confusion, or just plain misunderstanding?—examples below almost all boil down to bad statistics

GET INVOLVED—START A DISCUSSION!

What's missing from the list? What did I get wrong?

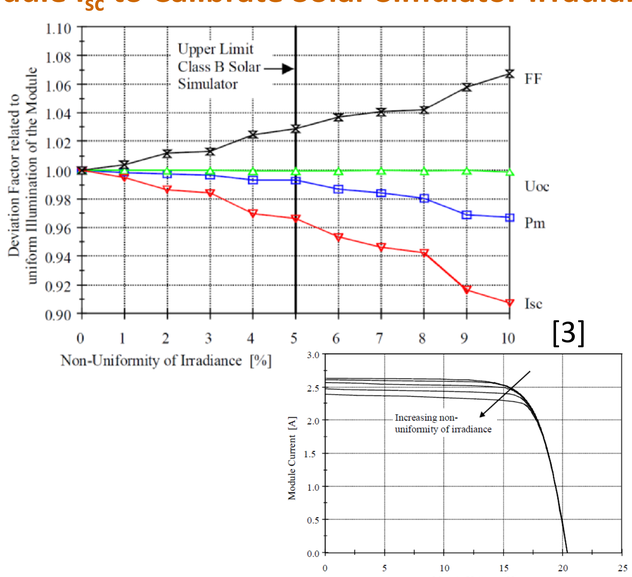
What bad practices exist in your part of the industry that should be retired?

BAD PRACTICE #1: Using Reference Module I_{sc} to Calibrate Solar Simulator Irradiance

Why is it bad?

I_{sc} is not a module property; it is determined by one cell (lowest-current cell in the highest-current string)

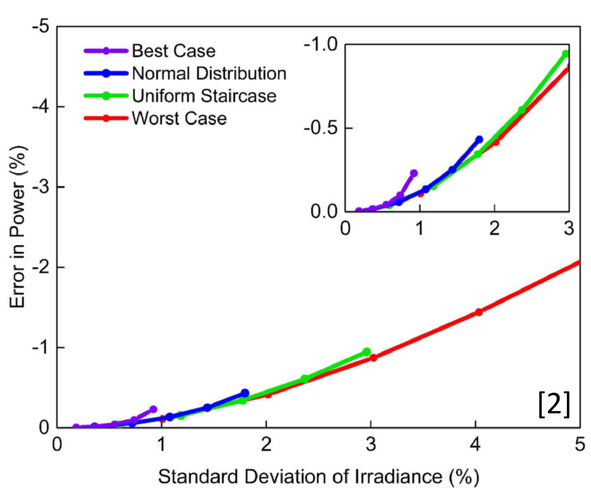
The most commercially relevant I-V parameter, P_{MAX}, is left "floating" [1] due to spatially non-uniform irradiance



[3]

Why is it still practiced?

Usefulness *outdoors* (insensitive to temperature, electrical connection)



[2]

Better practices:

Using reference module P_{MAX} to calibrate solar simulator irradiance

P_{MAX} has better statistics than I_{sc}

- It is the weighted average of the power produced by each cell, rather than the current of just one cell
- Sensitive to temperature and electrical connection, which can be monitored

BAD PRACTICE #2: Using a Single Reference Device to Ensure Traceability of I-V Measurement Results

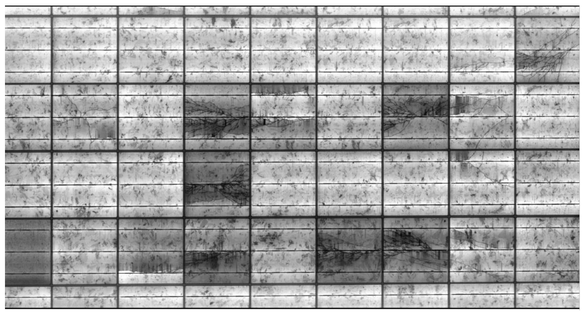
Why is it bad?

Reliance on a single reference device which may not be stable over time

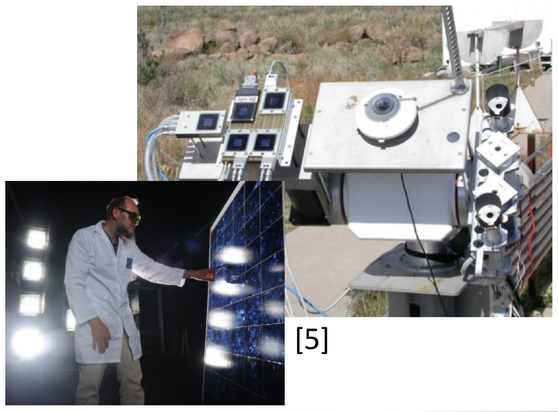
Why is it still practiced?

High cost of generating & maintaining calibration modules

Preference for "favorite" devices with the longest measurement history



[4]



[5]

Better practices:

Using multiple reference devices rotated through different production lines

Regularly adopting new references as technology advances

- Still balancing important historical reference devices

BAD PRACTICE #3: Quantifying Variation using *Range* (Maximum Minus Minimum)

Why is it bad?

Range depends on only two data points (possibly the outliers!), giving no information on the distribution between these extremes

Range does not converge with increased sampling

- Sometimes mistaken as irreproducibility

Why is it still practiced?

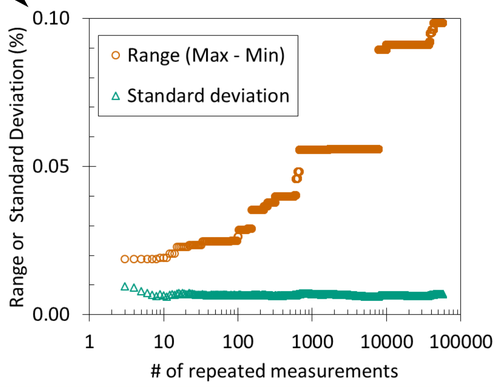
Quick-and-dirty way to estimate effect sizes

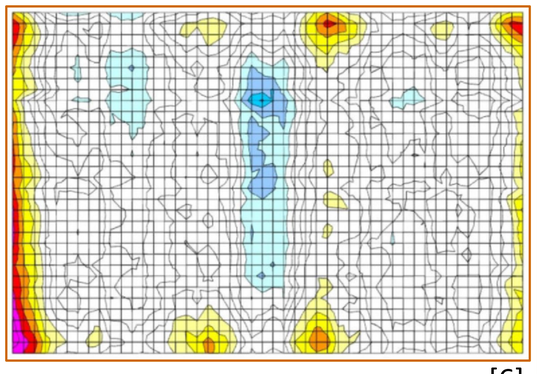
Taught extensively in statistical process control (SPC)

Example—solar simulator non-uniformity of irradiance

$$\text{Non-uniformity} \equiv \frac{G_{max}-G_{min}}{G_{max}+G_{min}}$$

Spread in repeated I_{sc} measurements: range vs. standard deviation

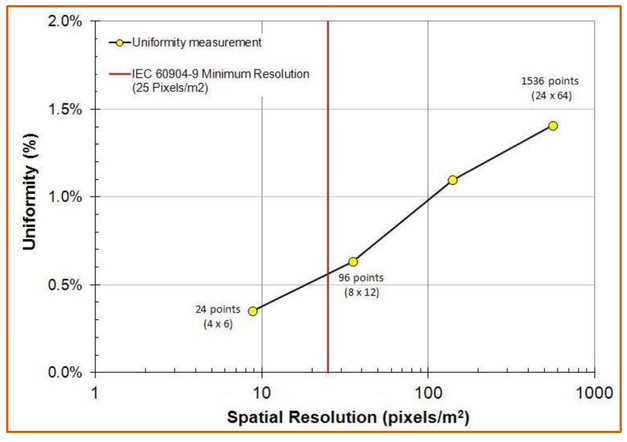




[6]

Better practices:

Using more robust statistical metrics (e.g., standard deviation!) that converge as you take more data



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Comparative Studies of the Effects of Soiling of PV Modules and Systems in Tropical and Subtropical Climate Zones in Brasil

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PVReliability.org
Confiabilidade de Sistemas Fotovoltaicos

Activities and Objectives

The project **mission** is to enhance ongoing research in solar-technology reliability, linking worldwide efforts with those important for the now-growing solar investments in the Brasil markets. The **objectives** of this poster focus on 4 areas that are current project priorities[1]:

(1) *Provide information on our methodologies and measurement systems (soiling monitoring stations, particulate analyses (microscopies), systems).*
(2) *Provide our soiling monitoring results (e.g., soiling and rates; IEC 61724-1) for Tropical and Subtropical Brasil climate-zones. Report initial results for comparative systems approaches to investigate these parameters.*
(3) *Compare the results (rates and conditions), describe differences in soiling mechanics based on location, summarize possible environmental effects and illustrate extent of non-uniform soiling conditions.*
(4) *Discuss and compare observed spectral and temperature effects to evaluate and compare technology (Si versus CdTe) performance.*

The project aims to understand, compare, and link the fundamental properties of the module soiling process with observed macroscale electrical and optical characteristics of these PV devices.

Climate Zones, Monitoring Sites, and Stations

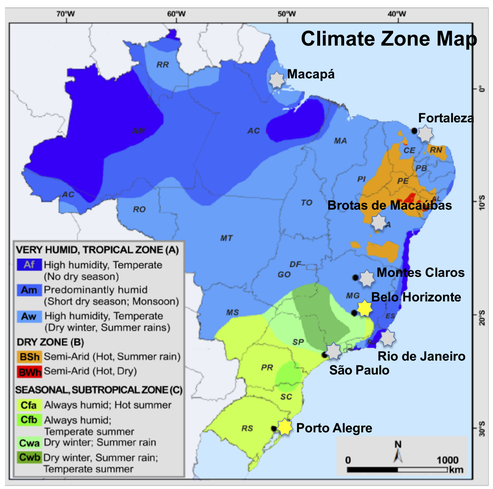


Figure 1. Climate zones[1], based upon Köppen-Geiger *[Meteorologische Zeitschrift **15**, 259-263 (2006)]*, showing chosen dust-monitoring locations [☼] for these studies and additional collaborating monitoring sites [☼] (based upon climate-zone coverage and priority PV-installation locations).

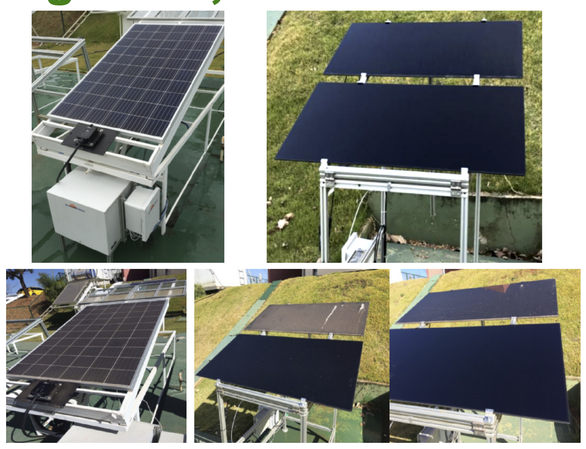


Figure. 2. Crystalline-silicon (c-Si) *(left)* and thin-film (CdTe) *(right)* monitoring stations)–Belo Horizonte, Minas Gerais (MG), Brasil. Capability to acquire I_{sc}, P_{max}, & entire I-V characteristic; remote radio transmission of data, and each location has dedicated meteorological station *(temperature, humidity, wind, rain)*. Lower portion shows modules after exposure to local soiling condtions (~7-days for Si and upper CdTe, and 15-days for lower CdTe). The cleaning effect of rain is represented on the right lower photos for CdTe.

Soiling Accumulation: Module Comparison

Equal Accumulation . . .

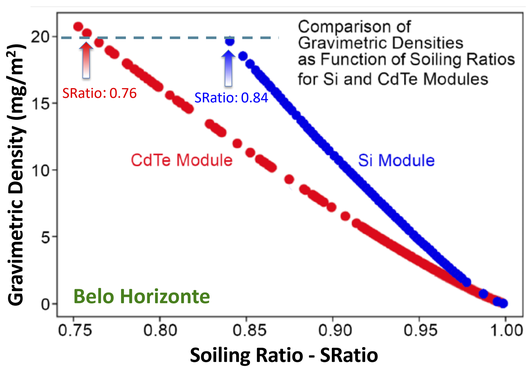
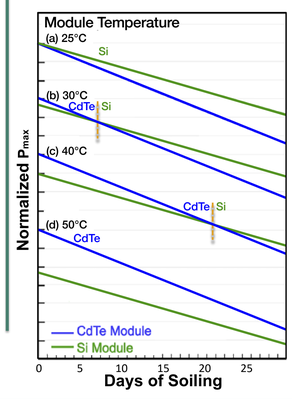


Figure 3. Comparisons of gravimetric densities based upon SRatio data (Belo Horizonte), using modeling by Coello and Boyle[1] (*IEEE JPV, "Simple model for predicting time series soiling of PV panels," 2019*) to calculate the parameters. The data are corrected for the critical region 300 nm to 600 nm. Data indicate the same "thickness" accumulated on each module surface. Example: *For corresponding SRatios from Fig. 5, gravimetric thicknesses are indicated by arrows.*

Soiling *versus* Temperature: Controverted Factors

Soiling spectral effects: Si better reponse than CdTe
Module temperature effects: CdTe better than Si
With these two competing parameters, which *wins*?

- **Literature:** Spectral effects[3,4] of dust (300-nm to 600-nm sensitivity) are documented and always indicate better Si over CdTe (bandgap) performance data because T is always normalized.
- **Modeling** using both these factors identify T-soiling ranges in which each technology is the *performance choice.*



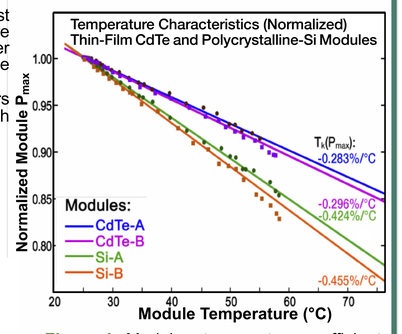


Figure 4. Module temperature-coefficient determinations for CdTe & Si modules used in these studies. The two lines for each module type represent the best and worst temperature responses from module sets.

Figure 5. Modeling of P_{max} with combined temperature and soiling accumulation (spectral effects) *[Si: 0.14%/day; CdTe: 0.20%/day, from analysis in Fig. 6]*, in Belo Horizonte.

Soiling Ratios and Rates

The soiling ratios are quantified using **short-circuit data ($SRatio_{I_{sc}}$)** & **power data ($SRatio_{P_m}$)** measured the clean- and soiled-modules for the thin-film and on the soiled module and the automatically-cleaned reference cell for the c-Si. These can be used to identify the whether the soiling is uniform or non-uniform and provide information on differences between technologies and Tropical & Subtropical climate zones[1,6].

Monitoring Stations

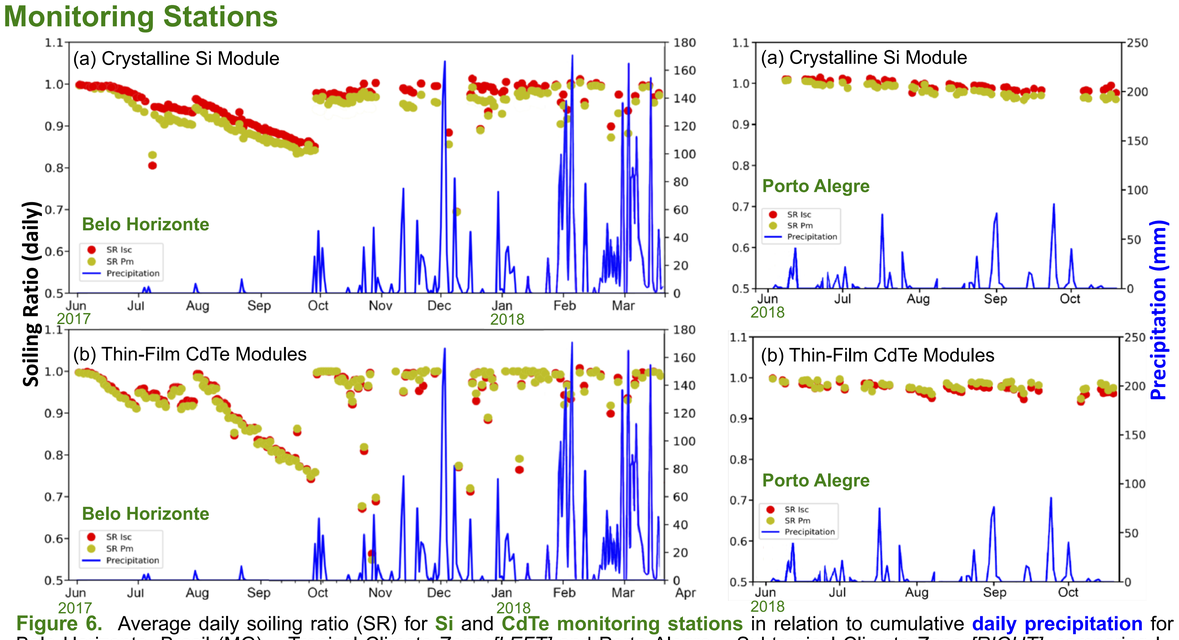
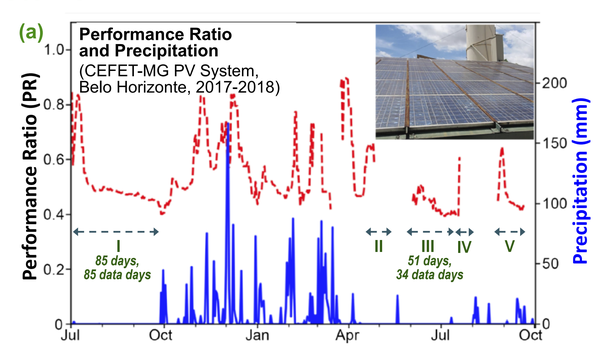


Figure 6. Average daily soiling ratio (SR) for **Si** and **CdTe monitoring stations** in relation to cumulative **daily precipitation** for Belo Horizonte, Brasil (MG) – Tropical Climate Zone *[LEFT]* and Porto Alegre – Subtropical Climate Zone *[RIGHT]*, comparing I_{sc} and P_{max} measurements. Results indicate non-uniform accumulation of soiling material (in this case, primarily along edges/frames) for Si. The thin-film CdTe data show good I_{sc} and P_{max} alignment for these frameless modules.

The soiling ratios from the monitoring stations were used to determine the soiling rates (Table 1). In each case, d(SR)/d(t) for thin-film CdTe is higher than that for Si module due to spectral effects[3-5] (same soiling layer accumulation; characteristic that "dust" absorbs more at in the 300-600-nm wavelength range). The analysis shows equal surface gravimetric densities (Fig. 2).

Energy production data of a PV system in Belo Horizonte was used to determine the soiling based upon the NREL methodology[7] (Figs. 7 and 8). This method considers the change in energy production from the PV systems associated with the accumulation of soiling during the dry season, where SRate is obtained through the estimation of the slope of the characteristic using the Theil-Sen estimator. The higher soiling rate for the system is attributed to a measured difference in the dust composition. The system is located adjacent to a heavily-trafficked highway and had considerable carbon content. *[The measured electrical parameters are normalized to the solar radiation (1000 W/m²) & the temperature (25°C). Representative data are presented for the 2-climate conditions in Brasil.]*

Systems



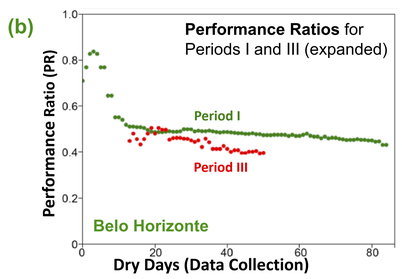


Figure 7. (a) Daily Performance Ratio (PR) [IEC 61724] for the CEFET-MG 3.24-kW system (140 p-Si modules) located in Belo Horizonte-MG over the period July 2017 though September 2018. Four-dry periods were identified, but only Periods I and III had sufficient data recorded for the analysis. **(b)** Specific PR data collected for Periods I and III.

Soiling Rates: Comparison and Summary

Table 1. Daily soiling rates from monitoring stations and system analysis. System rate is slightly higher due to compositional difference (vehicle emissions) in the accumulated particles.

	Technology	Porto Alegre* Monitoring Station	Belo Horizonte Monitoring Station	Belo Horizonte System
Daily Soiling Rate (%/day)	Si Modules	-0.043	-0.14	-0.18
	CdTe Modules	-0.045	-0.20	---

* *Initial results only: Need extended dry season*

Summary and Observations

- Monitoring shows differences I_{sc} and P_{max} results, directly associated with degree of non-uniformity of soiling accumulation (Importance of monitoring P_{max} for locations with large non-uniformities).
- Differences in Tropical and Subtropical Zones (initial indications from SRatio and SRate).
  (a) SRate higher north to south (related to climate conditions). *In general, SRates are low to moderate.*
  (b) Soiling components (composition) and origin differ from Tropical to Subtropical Zones.
- System analysis: Methodolgy[7] used to determine soiling rates for system in Belo Horizonte, showing slightly higher soiling losses due to compositional factors.
- Spectral differences, with effects on thin-film CdTe (higher bandgap) more pronounced–higher d(SR)/d(time)–with same soiling levels (sensitivity 300-nm to 600-nm wavelength range of solar spectrum).
- Controverted Factors: Soiling (spectral effects) and Temperature. Relative regions of dominance of each have been identified.

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CAPES

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This poster contains no sensitive or proprietary information.

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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

A Unified Constitutive Model for the Degradation of Electrically Conductive Adhesives (ECA)

Martin Springer and Nick Bosco
National Renewable Energy Laboratory, CO, USA

DuraMAT Capabilities

1. **Data Management & Analytics, DuraMAT Data Hub**
2. **Predictive Simulation**
3. **Advanced Characterization & Forensics**
4. **Module Testing**
5. **Field Deployment**
6. **Techno-Economic Analysis**

Capability Goals

- Predict degradation and failure of ECA PV module interconnects.
- Develop a physical model that connects mechanical and electrical behavior of ECA with a damage metric that captures the associated degradation processes.
- Create the materials characterization and modeling workflow.
- This work partners and contributes to Predictive Simulation, Advanced Characterization and Module Testing.

Outcomes and Impact

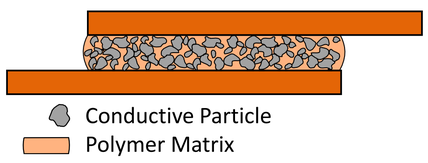
- Established framework for ECA characterization and modeling.
- De-risk new ECA's as PV module interconnect materials.
- Optimize the reliability of ECA interconnected modules.
- Define appropriate qualification standards for ECA modules.
- Provide an ECA service life prediction.

Motivation

Electrically Conductive Adhesive (ECA)

- ECA's are material compounds consisting of conductive particles and a polymer matrix

Schematic of an ECA



Some features of ECA's compared to solder

- Lower thermal stresses
- Adhesion to diverse substrates
- Smaller feature size
- Fast cure
- Removes Pb from interconnections
- "Easy-to-use" application processes

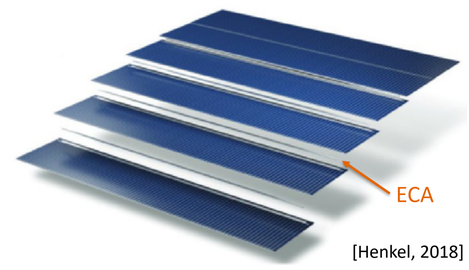
Current State

- ECA's are incorporated into PV modules as new interconnects replacing metallic solders
  - Cell Interconnect Ribbon Bonding
  - Interconnection of Shingled Solar Modules

Problem

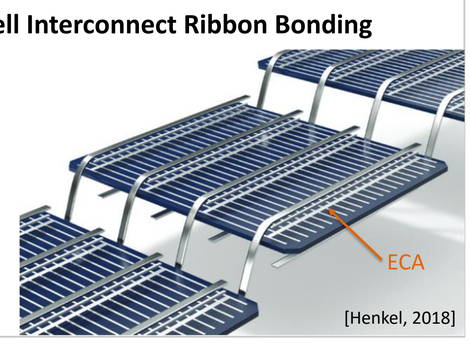
- Significant material change from metallic solders to ECA's
- Durability of ECA modulus is still assessed by accelerated tests developed for solders
- Reliability test results may not represent the long-term performance of ECA modules

Shingled Solar Modules



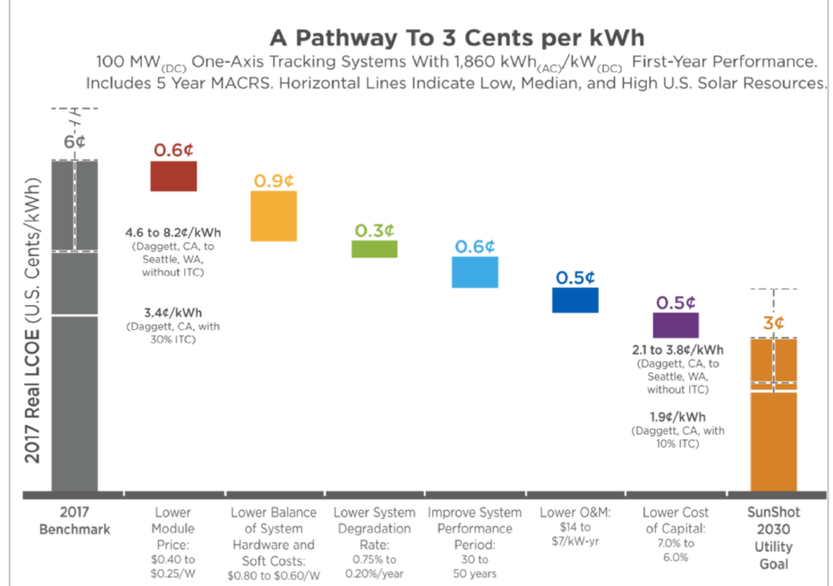
[Henkel, 2018]

Cell Interconnect Ribbon Bonding



[Henkel, 2018]

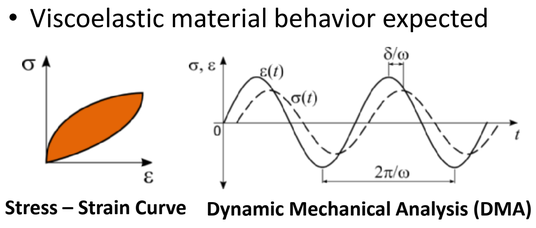
Cost Drivers



Materials Characterization & Constitutive Modeling

Linear Viscoelasticity

- ECA matrix = polymer material
- Viscoelastic material behavior expected



Stress – Strain Curve Dynamic Mechanical Analysis (DMA)

- Material parameters obtained from DMA
  - Storage modulus $E' = \frac{\sigma_0}{\varepsilon_0}\cos\delta$
  - Loss modulus $E'' = \frac{\sigma_0}{\varepsilon_0}\sin\delta$

ECA test specimens for DMA

- ECA beam for tensile & bending tests

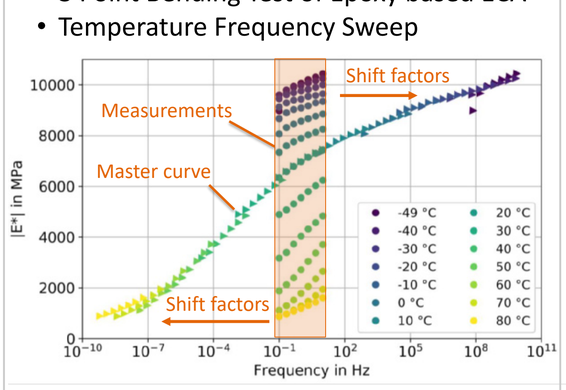
(30mm x 3mm x 1mm)

- Copper/ECA compound for shear testing

(18mm x 5mm x 5mm)

DMA Measurement Results

- 3 Point Bending Test of Epoxy based ECA
- Temperature Frequency Sweep



Master curve generation

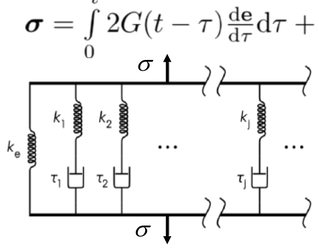
- Time Temperature Superposition
- Curve fitting with Prony series

$$G(t) = G_0\left[\alpha_\infty^G + \sum_{i=1}^{n_G}\alpha_i^G \exp\left(-\frac{t}{\tau_i^G}\right)\right]$$

G_0 ... relaxation moduli at t=0 α_i^G ... relative moduli
n_G ... number of Prony terms τ_i^G ... relaxation time

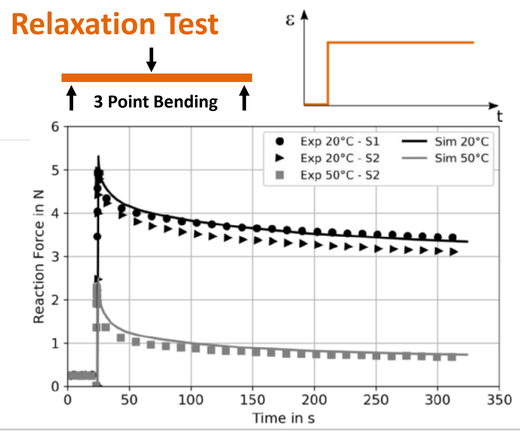
Generalized Maxwell Model

$$\boldsymbol{\sigma} = \int_0^t 2G(t-\tau)\frac{d\mathbf{e}}{d\tau}d\tau + \mathbf{I}\int_0^t K(t-\tau)\frac{d\Delta}{d\tau}d\tau$$

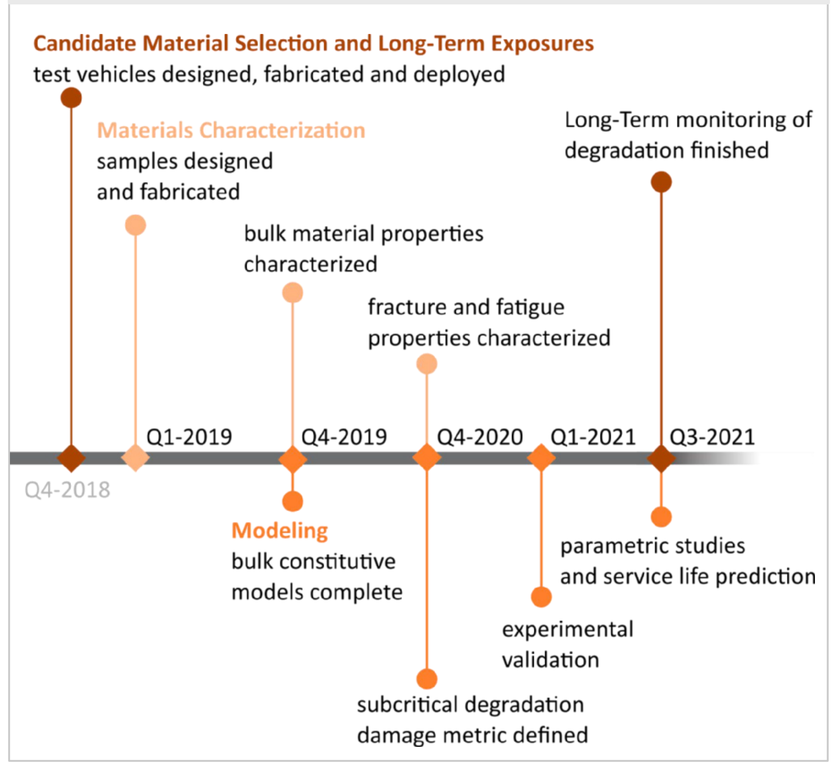


$\boldsymbol{\sigma}$ ... Cauchy stress tensor
$\mathbf{e}$ ... dev. strain tensor
Δ ... volumetric strain
τ ... past time
$\mathbf{I}$ ... identity tensor

Relaxation Test



Timeline

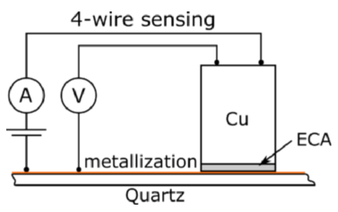


Identification of Damage Mechanisms

Thermal Cycling Test Vehicle

- Test vehicle designed to cause ECA degradation
- Degradation is monitored and damage mechanisms & damage driving forces are identified

Schematic



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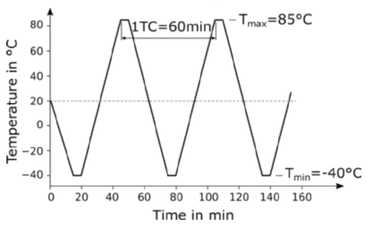
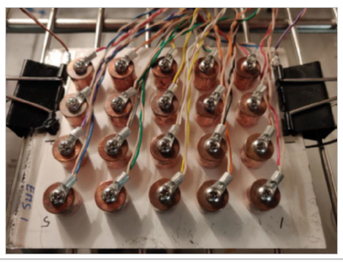
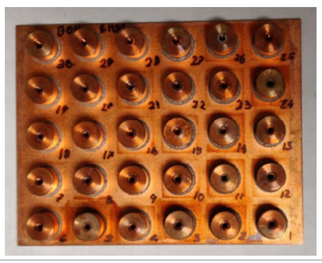


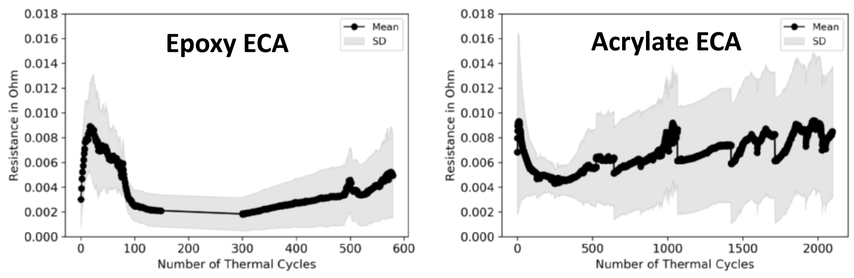
Test Vehicle - Quartz



Test Vehicle - DBC

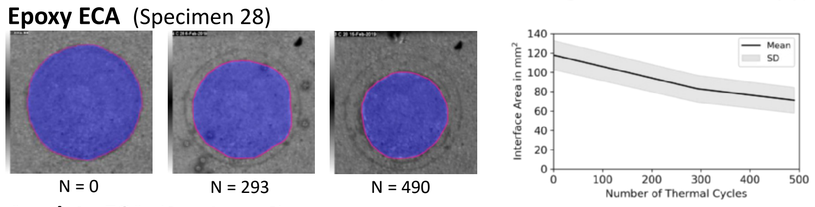


Measurement of resistance

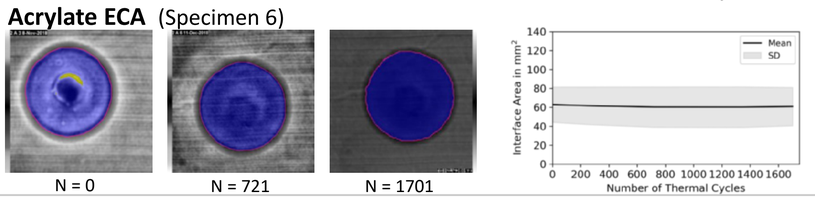


Evolution of interface area (Confocal Scanning Acoustic Microscopy)

Epoxy ECA (Specimen 28)

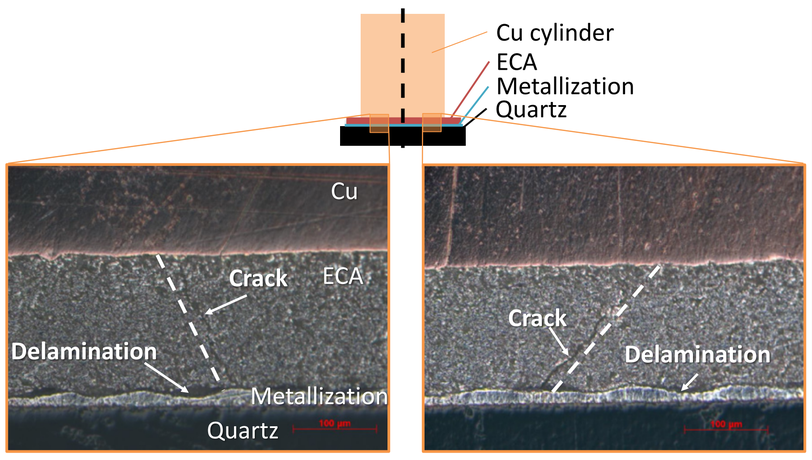


Acrylate ECA (Specimen 6)



Light Microscopy

- Cross Section through Cu Cylinder
- Acrylate ECA after 1651 thermal cycles



- ECA cracks through interface thickness (axisymmetric)
- Delamination between ECA and Ag metallization
- Deformation of the metallization film

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 as part of the Durable Modules Consortium (DuraMAT), an Energy Materials Network Consortium funded by the 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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Photovoltaic Reliability Workshop, NREL
Golden, CO, USA
2019-02-26 to 2019-02-28
NREL/PO-5K00-73383

European Commission's EcoDesign Preparatory Study Status

Tony Sample*[1], Ewan Dunlop[1], Nigel Taylor[1], Elena Salis[1], Ana Gracia[1], Nicholas Dodd[2], Nieves Espinosa[2]

[1]European Commission, Joint Research Centre (JRC), Ispra (VA), Italy.

[2]European Commission, Joint Research Centre (JRC), Seville, Spain.

In October 2017, DG GROW of the European Commission started a preparatory study on potential sustainable product policy instruments for solar photovoltaic modules, inverters and systems. Potential instruments include Ecodesign, Energy Label and EU Ecolabel regulations, as well as Green Public Procurement (GPP). Several public consultations will take place during the study, which is expected to be completed in 2019.

Introduction

The DG GROW of the European Commission asked the JRC to develop a preparatory study in order to assess, by a techno-economic and environmental analysis, the feasibility of applying Ecodesign, Energy labelling, Ecolabel and Green Public Procurement to PV products grouped in three main categories: PV modules, power conversion equipment and PV systems.

Due to the overarching approach used for the first time in this preparatory study, its development is guided and coordinated by DG GROW with active involvement of other two Directorates General of the European Commission, DG ENER and DG ENV, due to aspects of the study that fall under their direct competence.

JRC B.5 role

For the JRC, Unit B.5 "*Circular Economy & Industrial Leadership*" is leading the preparatory study considering all the aspects relevant to the four above-mentioned European policy tools.

JRC C.2 (ESTI) role

The JRC Unit C.2 "*Energy Efficiency and Renewables*", through its European Solar Test Installation (ESTI), is supporting JRC.B.5 with its scientific knowledge and technical competence on PV devices, their calibration and testing, built on the experience accumulated in the last 40 years of its operation.

Transitional Methods

Analysis of existing standards and proposal of transitional methods

Standardization levels considered

Harmonised standards ("European standard" that has been adopted on the basis of a request made by the European Commission)

CEN-CENELEC (EN)

International Electrotechnical Commission (IEC)

International Organization for Standardization (ISO)

..... where certain aspects essential to the implementation of Ecodesign, Ecolabel, Energy Label & GPP are not covered by existing standards, the Commission may choose to specify transitional methods, that are implemented as regulations until suitable standards are adopted.

Inverter performance: Proposed functional unit:

"1 kWh of AC power output from a reference photovoltaic system (incorporating the efficiency of a specific inverter) under predefined climatic and installation conditions as defined for a typical year and for a service life of 10 years".

Photovoltaic System Energy Yield: Proposed PV system functional unit:

"1 kWh of AC power output supplied under fixed climatic and installation conditions as defined for a typical year (with reference to IEC 61853-4) and for a service life of 30 years".

Proposed methodology – input data

- PV array size and module performance characteristics (IEC 61853)
- DC energy yield (EYDC) of 1 kWp PV array over a year (kWh/year)
- 3 reference climatic datasets

Tropical humid
Subtropical arid
Subtropical coastal
Temperate coastal
Temperate continental
High elevation (above 3000m)

- Power Conditioning Equipment - Inverter
  - EN 50530. European efficiency, η_{EUR}
- PV system losses (default values or system specific values)
  - Cables losses
  - Diodes and connectors
  - Mismatch
  - ...

η_{system_loss}

Losses	Typical (%)	Range (%)
DC cabling	2	1 - 3
Connectors	0.5	0.3 - 1
Mismatch	2	1.5 - 3

Proposed methodology – calculation

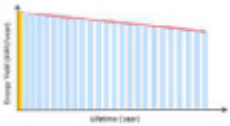
- Estimation of the AC energy yield, *System* $EY_{AC_year\ 0}$

$$System\ EY_{AC_year\ 0} = \eta_{EUR} \times (1 - \eta_{system_loss}) \times EY_{DC}$$

For every reference climate

- Lifetime AC energy yield for each reference climate

$$System\ EY_{AC_lifetime} = System\ EY_{AC\ year\ 0} \cdot T_{lifetime} \cdot \left(1 - \tau_{deg} \cdot \frac{T_{lifetime}}{2}\right)$$



$T_{lifetime}$: 30 years

τ_{deg}: degradation rate

Degradation of Inverters (prescribed values)

- Degradation rate: 0 %/year (no degradation)
- Failure rate: 10% per year

Degradation of PV Systems (prescribed values)

- Wafer-based c-Si: 0.7% per year (linear)
- Thin-film and heterojunction: 1% per year (linear)

Or

Product-specific values - requirements for acceptance:

- Robust data from the measurement of field-deployed systems and made available (upon request) to the market surveillance authorities, covering all reference climatic profiles, with data from at least:
  - 5 consecutive years
  - 2 separate geographical locations in each climatic profile
  - 2 mounting options
- Assigned value shall be the average of the collected values

Anyone who is interested in the consultation process can find additional information on the website;

http://susproc.jrc.ec.europa.eu/solar_photovoltaics/index.html

Or by sending an email to the following address

JRC-B5-PHOTOVOLTAICS@ec.europa.eu

*Tel: +39 0332 789062, e-mail: tony.sample@ec.europa.eu

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Joint Research Centre

CdTe Matched Filtered c-Si Ref Cell

February 2019

ATONOMETRICS

Introduction

- Spectrally matched PV reference devices can improve correlation to system output
- Especially for thin-film PV such as CdTe where spectral mismatch to broadband thermopile pyranometers and unfiltered Si reference cells can be significant
- We evaluate a CdTe spectrally matched filtered c-Si PV reference cell designed by Atonometrics
- The cell filter minimizes the relative impact of typical variations in solar spectrum due to atmospheric precipitable water vapor (PWV), which is the most significant factor affecting CdTe spectral mismatch

Reference Cell Design

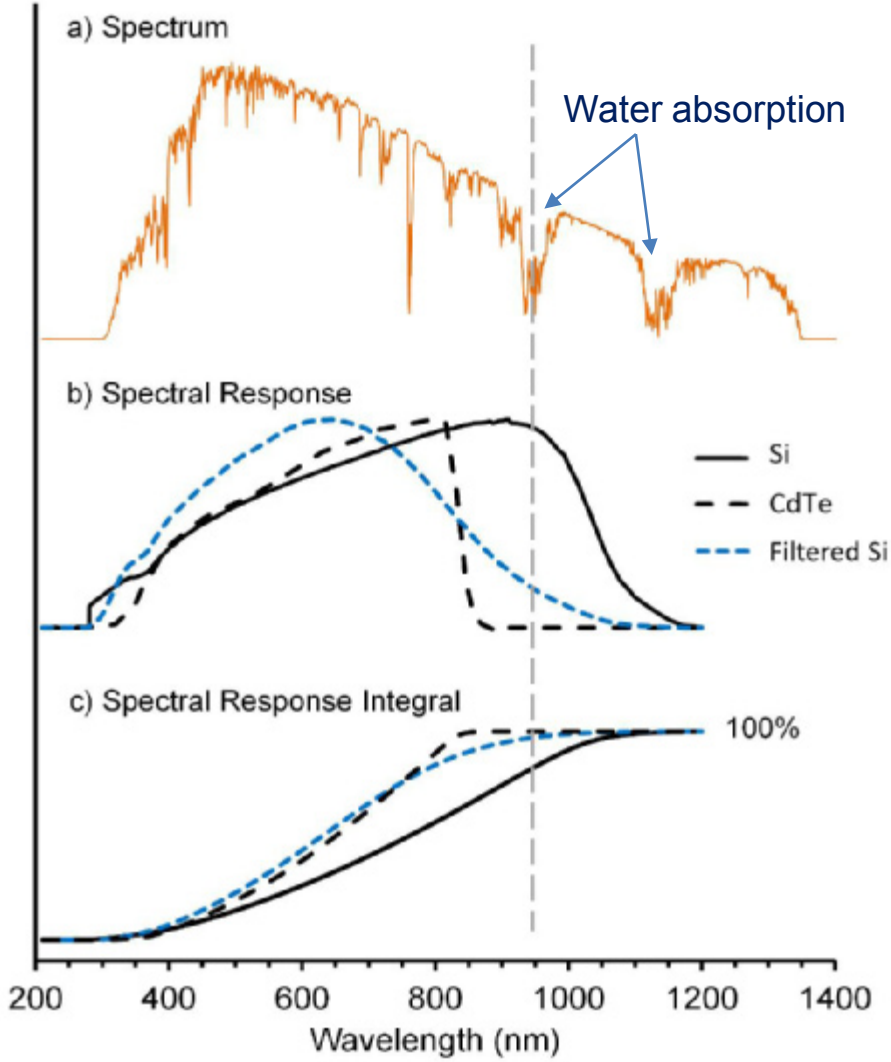
Mono c-Si cell

Filter glass for CdTe match

Internal temperature compensation using RTD contact back of encapsulated cell

ATONOMETRICS

Filter Concept – Block Water Absorption Region



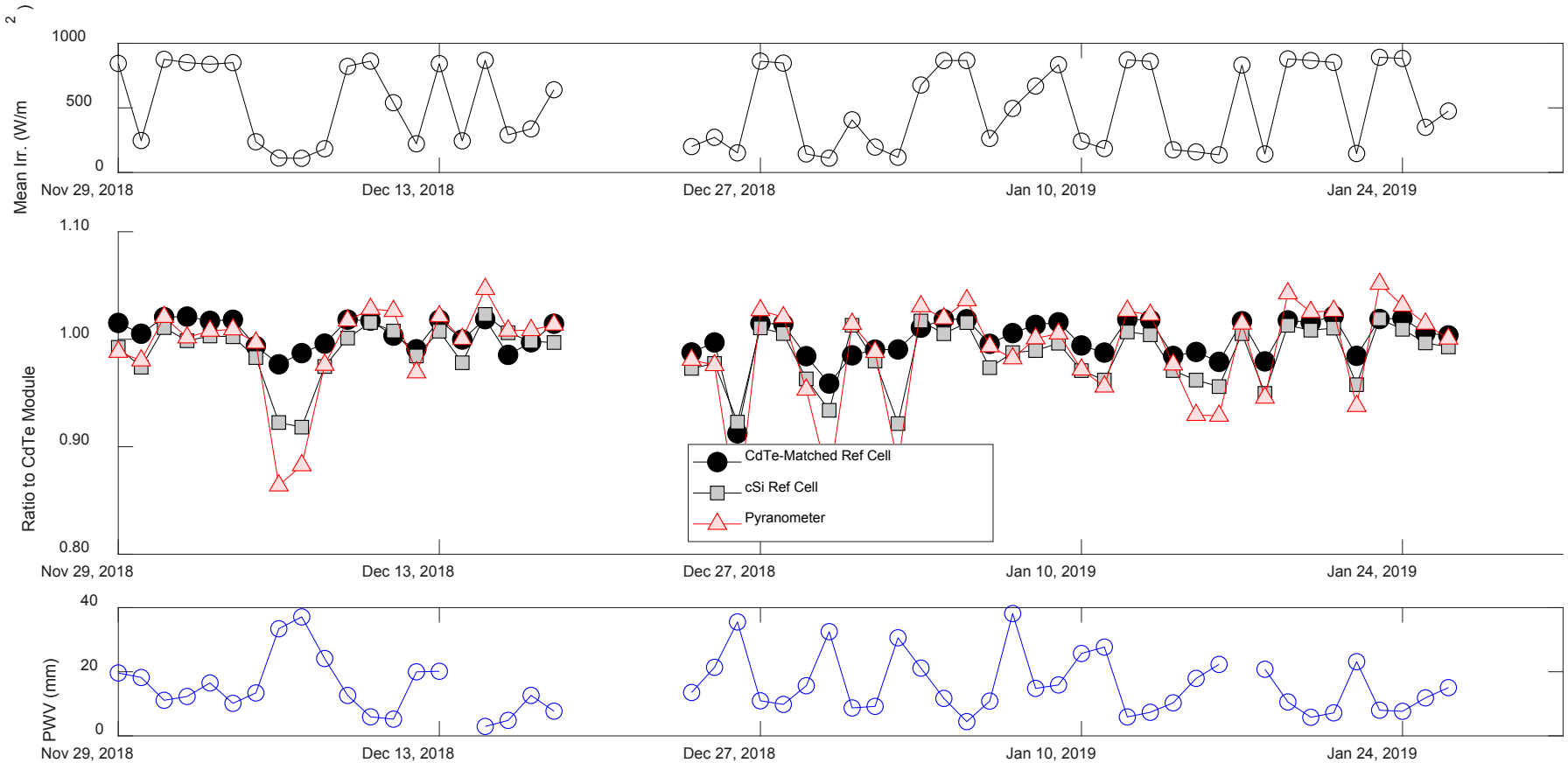
ATONOMETRICS

Experiment

- Deployed 4 sensors near Austin:
  - CdTe module, measured in short circuit
  - C-Si reference cell
  - Thermopile pyranometer
  - CdTe matched filtered c-Si reference cell
- Collect precipitable water vapor (PWV) data from Suominet station 20 miles away, in central Austin
- Use data stream to calibrate all sensors to match when conditions ~near STC, including PWV near 14.2 mm
- Plot ratios of integrated daily irradiance for noon +/- 2 hours

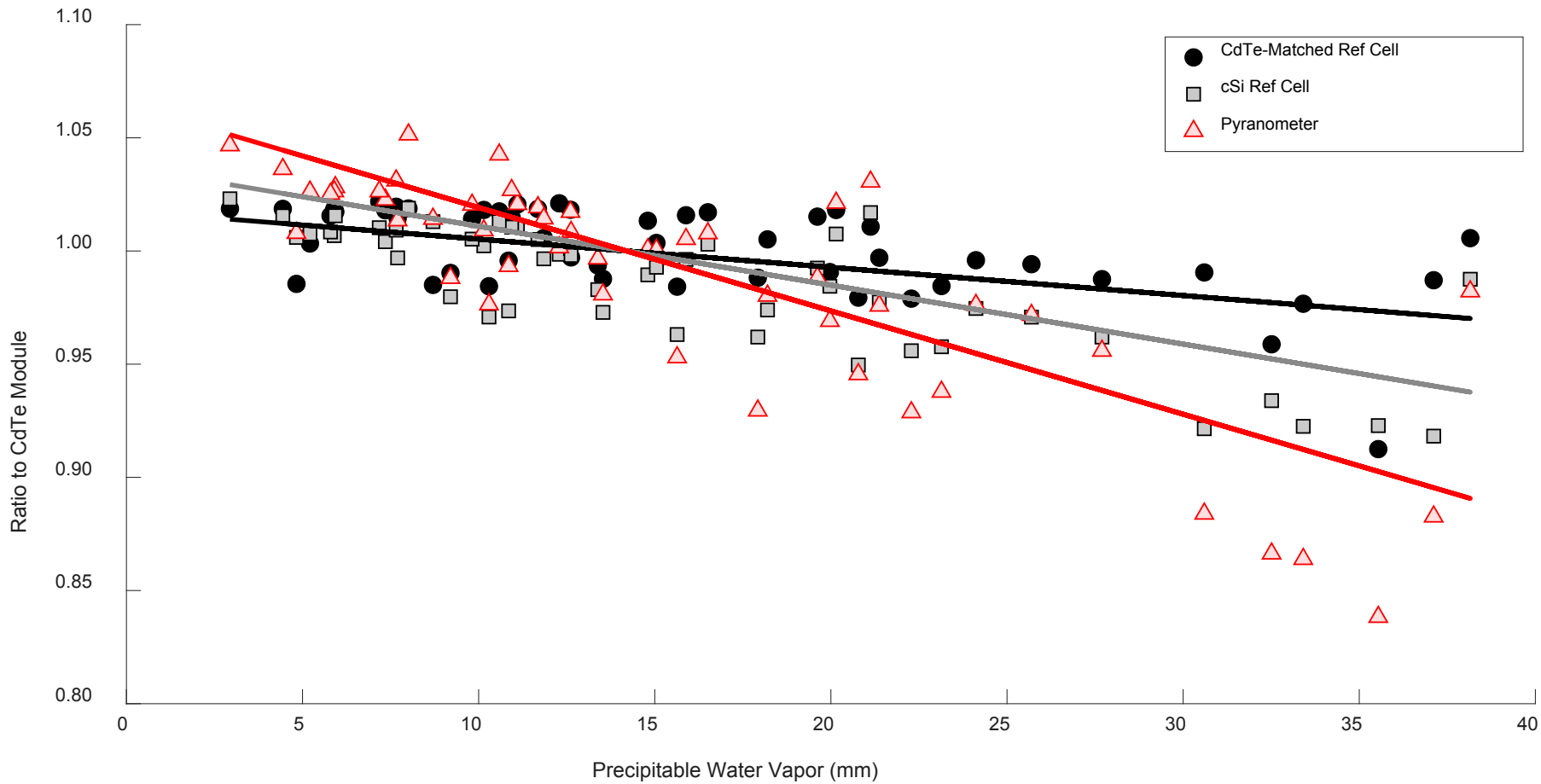
ATONOMETRICS

Results



ATONOMETRICS

Correlation



ATONOMETRICS

Conclusions

- CdTe matched filtered c-Si reference cell shows good match to CdTe module
- Only minimal mismatch versus PWV
- Filtered reference cell may be advantageous for monitoring CdTe power plants

ATONOMETRICS

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

Development of Low-Cost, Crack-Tolerant Metallization Using Screen Printing

Omar K. Abudayyeh[1], Andre Chavez[1,2], John Chavez[1], Sang M Han[1,2], Francesco Zimbardi[3], Brian Rounsaville[3], Vijaykumar Upadhyaya[3], Ajeet Rohatgi[3], Byron McDanold[4], Timothy Silverman[4], and Nick Bosco[4]

[1]Osazda Energy; [2]University of New Mexico; [3]Georgia Institute of Technology; and [4]National Renewable Energy Laboratory

DuraMAT Capabilities

1. Data Management & Analytics, DuraMAT Data Hub
2. Predictive Simulation
3. Advanced Characterization & Forensics
4. Module Testing
5. Field Deployment
6. Techno-Economic Analysis

Industry Goals

- Produce screen-printable silver paste with crack-tolerance to substrate fractures.
- Incorporate low-cost, multi-walled carbon nanotubes for electromechanical reinforcement.
- Develop capability to electrically bridge cracks forming in PV cells for increased lifetime.
- Reduce LCOE by lowering cell degradation rate.

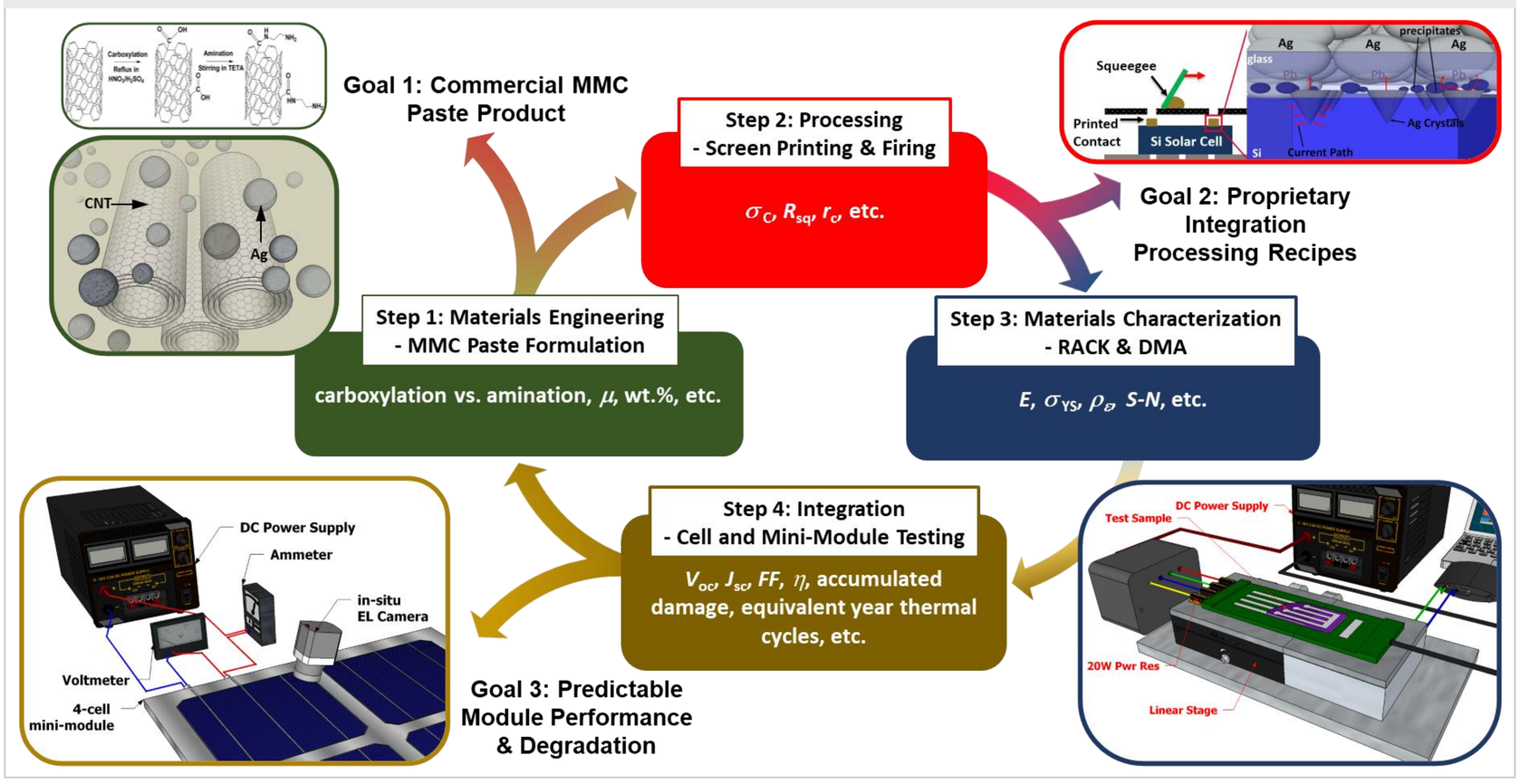
Accomplishments

- Demonstrated crack-bridging for commercial space solar cells.
- Translate the technology to silver paste used on terrestrial PV.
- Target terrestrial Si PV market > $25B for economic impact.
- Reduce module degradation for increased lifetime.
- Accomplished mini-module stress testing w/thermal cycling.

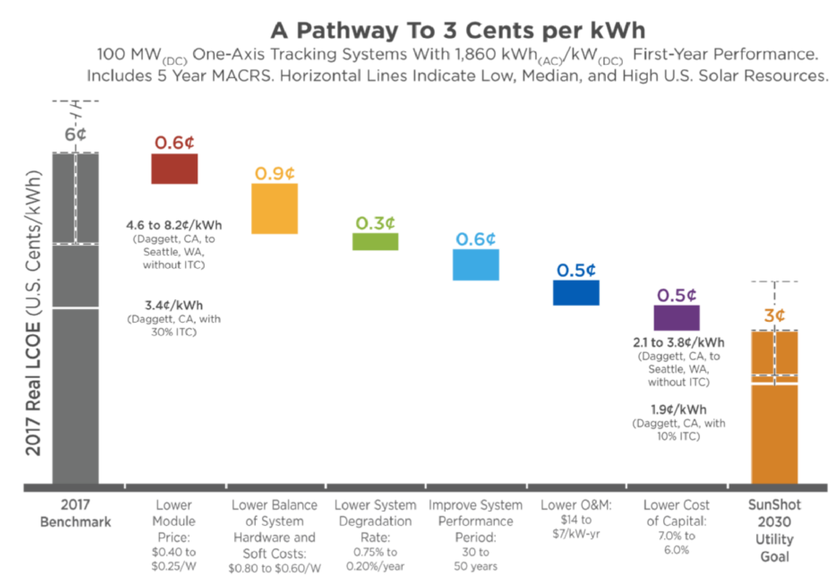
Outcomes and Impact

- Demonstrate increased module reliability against stress-induced cell fractures.
- Make specialized silver paste products available for integration on commercial Si PV modules.
- Target future partnerships with silver paste and module manufacturing companies.
- Provide new materials and integration solutions for Si PV.

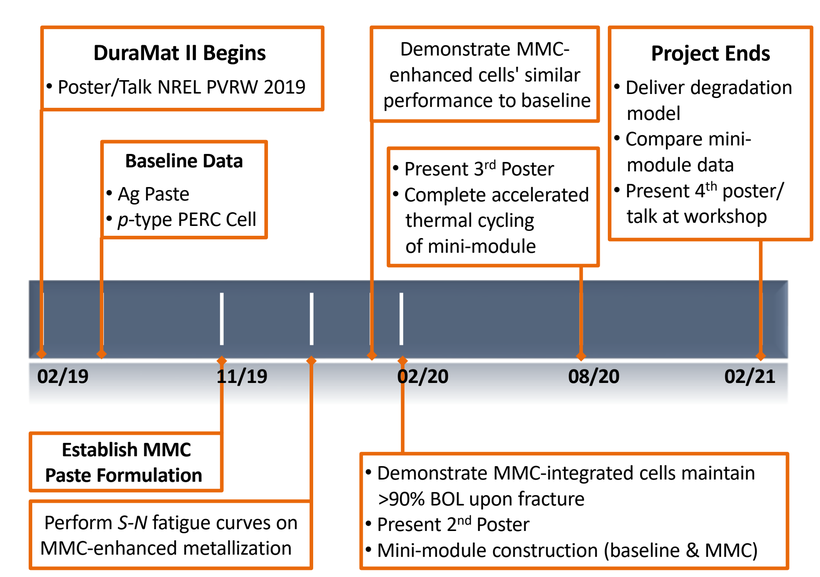
Capability Development



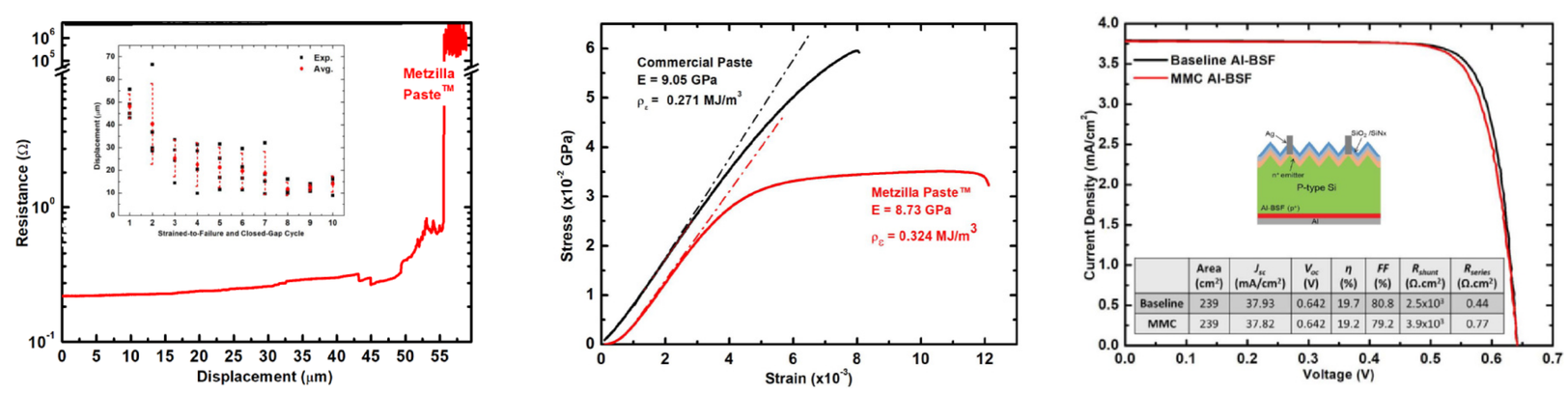
Cost Drivers



Project Timeline



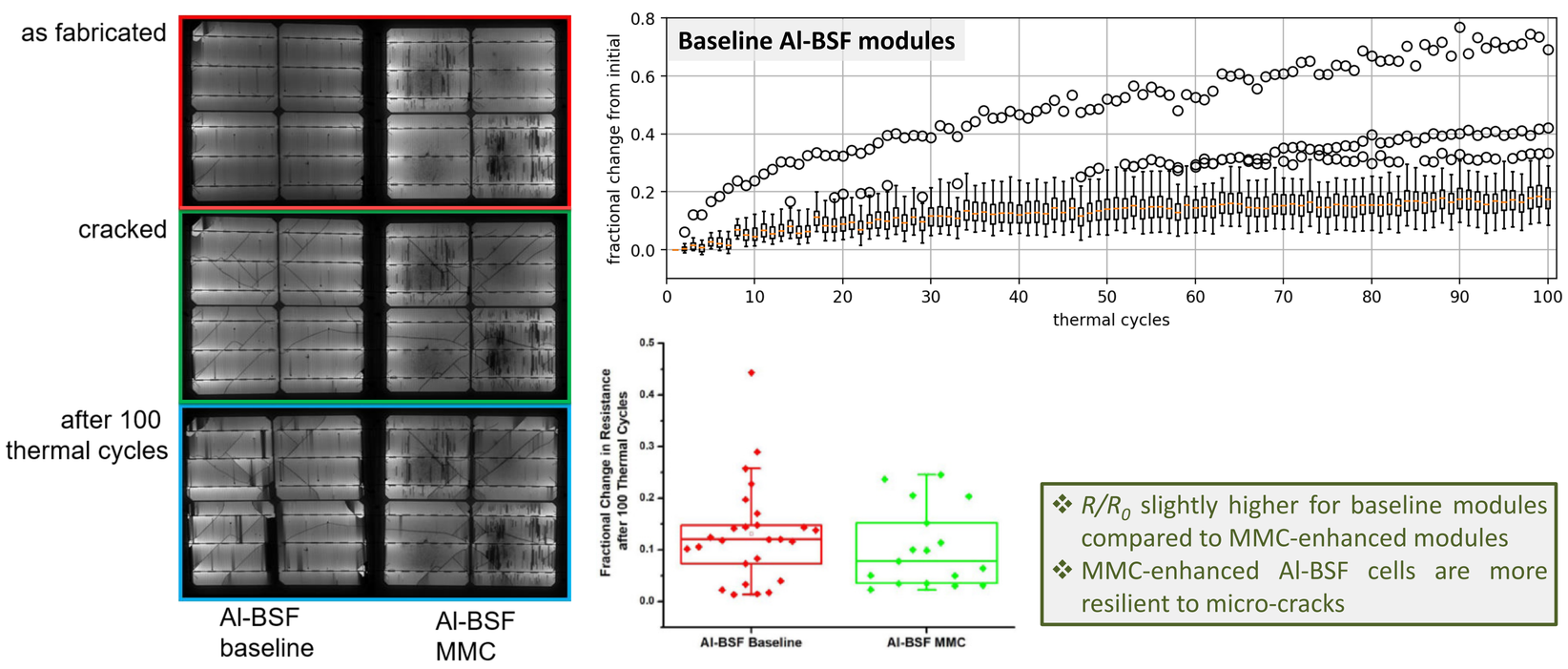
Materials Characterization



	Area (cm²)	J_{sc} (mA/cm²)	V_{oc} (V)	η (%)	FF (%)	R_{shunt} (Ω.cm²)	R_{series} (Ω.cm²)
Baseline	239	37.93	0.642	19.7	80.8	2.5x10³	0.44
MMC	239	37.82	0.642	19.2	79.2	3.9x10³	0.77

- Gap bridging capability up to 50 µm with proper CNT loading
- Self-healing properties after multiple strained-to-failure and closed-gap cycles
- Increased ductility with CNT incorporation (16% increase in modulus of toughness)
- Little to no impact on cell performance upon Metzilla Paste™ integration on commercial Al-BSF cells

Mini-Module Characterization



- R/R_0 slightly higher for baseline modules compared to MMC-enhanced modules
- MMC-enhanced Al-BSF cells are more resilient to micro-cracks

Summary

Durability by deliberate design; Perfecting a process that is engineered to last

Osazda Energy LLC provides materials engineering solutions to improve solar cell and solar module reliability. Our specialized metal matrix composites have been proven to electrically bridge stress-induced cracks that appear in solar cells over time; the composites also self-heal to regain electrical continuity. This MMC technology will potentially extend the lifetime of solar panels while increasing the bankability of utility-scale photovoltaic projects. This has substantial financial implications in making the price of solar electricity as low as the price of fossil-fuel-generated electricity.

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Reducing Power Degradation in c-Si Modules by using PIB Edge Seal

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D2 solar

RESEARCH QUESTION

Can use of a PIB edge seal cemented joint delay degradation of crystalline silicon PV modules with EVA encapsulant?

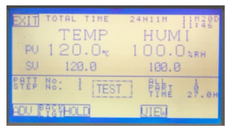
If so, module manufacturers could continue use of a field proven product line without the expense and handling issues of non-EVA encapsulants.

INVESTIGATIVE APPROACH

- Compare Glass-Glass monocrystalline silicon modules using EVA encapsulant with and without PIB edge seal capable of acting as a cemented joint
- Expose to a high temperature, high moisture environment to accelerate the study
- Track arrival of moisture in the EVA using Cobalt Chloride indicator paper that changes color at 8% RH
- Measure IV curves
- Take Electroluminescence (EL) Images

EXPOSURE & ACCELERATION FACTOR

HAST Highly Accelerated Stress Test 120C/ 100% RH



HIRAYAMA HASTEST PC-422R7 chamber

		g/m^3 water vapor
Damp Heat	85°C 85% RH	241
HAST	120°C 100% RH	1122
Cobalt chloride indicator changes color	120°C 8% RH	90

10x factor HAST vs Damp Heat in Glass-Backsheet modules (EVA – mono c-Si)[1]

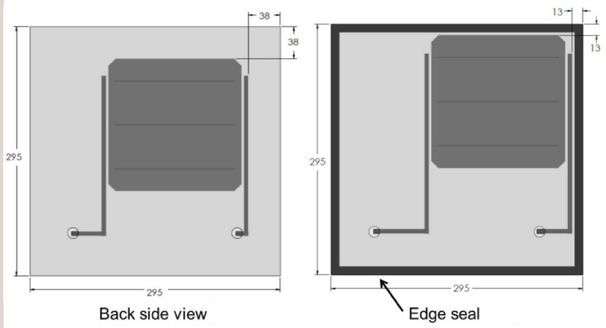
5x factor HAST vs Damp Heat for Power loss and 10x factor for discoloration[2]

Previous HAST studies GBS vs GG with standard mono c-Si EVA[1]
GBS = 100 hours to reach 5% change in Pmax
GG = 400 hours to reach 5% change in Pmax
Current study
GG = 600 hours to decline more than 5% in Pmax

LAYOUT

Placement mimics corner cell in a full size 1500V module to meet Distance Through Insulation requirements

Standard | Cemented Joint



BILL OF MATERIALS

Cell
p-type mono 3 busbar c-Si solar cell
EE6D3C Ever Energy PV

Encapsulant:
2 pieces 0.45 mm EVA
F806P Hangzhou First PV

Edge Seal:
Thermoplastic PIB sealant
SET LP03 8 mm x 1.7 mm Quanex

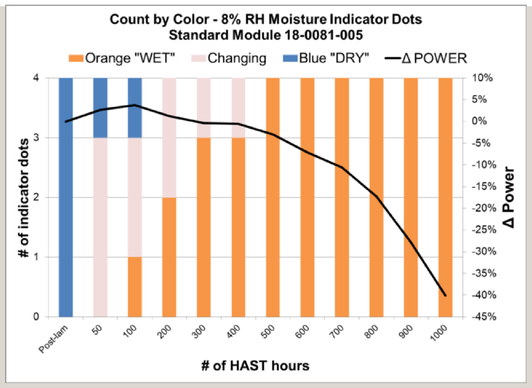
Indicators:
Cobalt Chloride paper
8% RH humidity indicator cards
MS26507-1 Clariant International

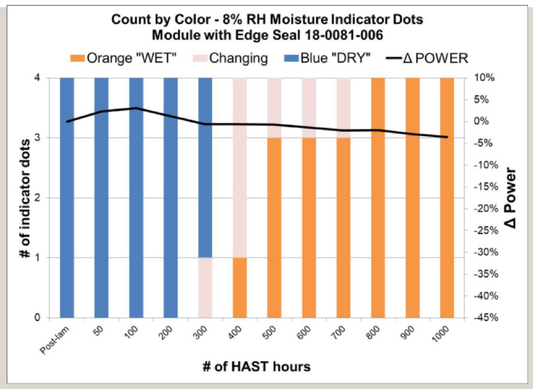
ACKNOWLEDGEMENTS

Special thanks to Duncan Harwood (D2Solar) and Mihail Bora (LLNL) for assistance and insight in testing

RESULTS: MOISTURE INGRESS

The PV industry has significant concern that tests with excessive moisture are unrealistic to field exposures.[5] By using indicators for tracking time to detect a low, but measurable moisture content, the time for moisture to enter the active area and begin the degradation process has been documented. Power loss begins soon after Cobalt Chloride indicator changes color at a low moisture level. At a minimum, using edge seal should double the time before the initiation of moisture induced degradation modes.

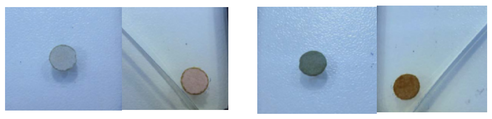


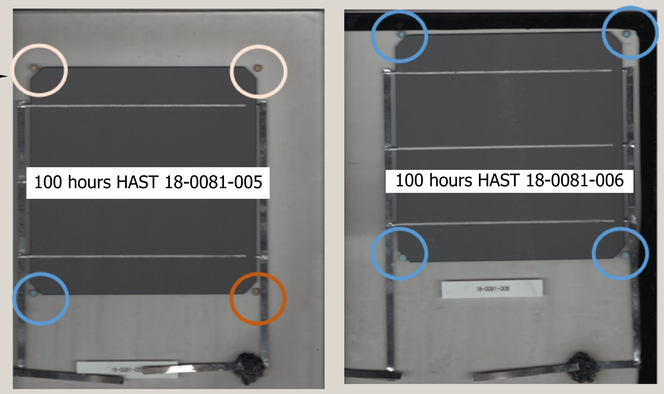


Plots of moisture ingress vs Time were based on Visual monitoring of dot color of actual modules, not based on photos.

At 120°C in EVA environment, Cobalt Chloride indicators turn orange rather than pink. Moisture still triggers a color change.

Against Glass Dry dot | Against Glass Humid dot | Through EVA Dry dot | Through EVA Humid dot

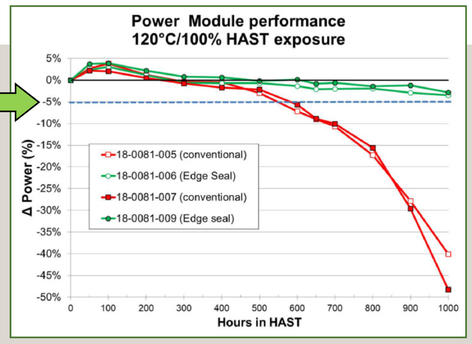




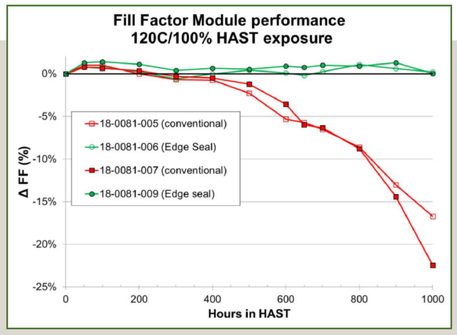
RESULTS: POWER AND FILL FACTOR

Power is the dollars & cents of PV modules. Modules with edge seal produced significantly more power.

P/F criteria

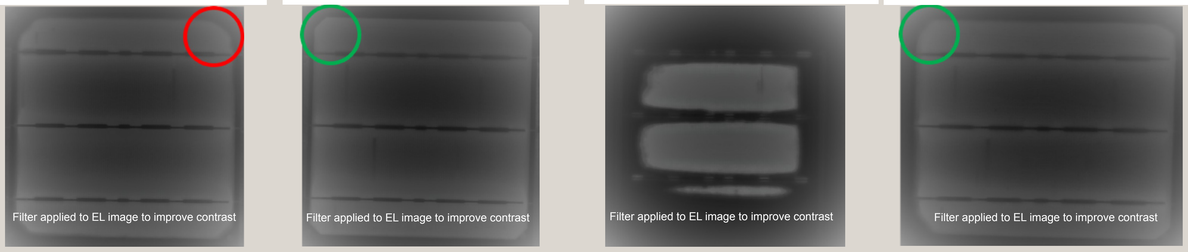


Modules with Edge Seal maintained a steady Fill Factor throughout the study.



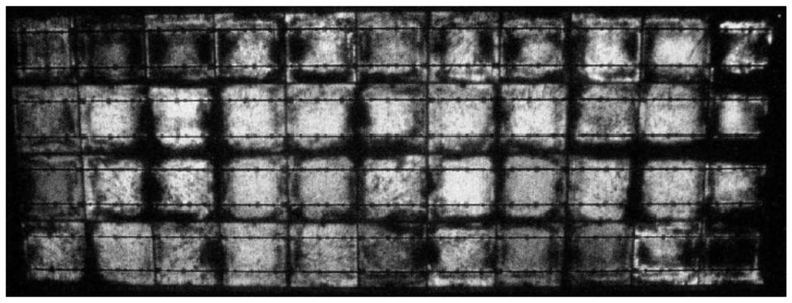
ELECTROLUMINESCENCE

500 hours HAST 18-0081-005 | 500 hours HAST 18-0081-006 | 1000 hours HAST 18-0081-005 | 1000 hours HAST 18-0081-009



At 1000 hours, the modules with Edge Seal have similar shading in EL to the conventional module at 500 hours.

Between 500 and 1000 hours, the conventional modules in this study behave similar in EL & P_{max} decline to those reported by Tanahashi[2] for 30 year old outdoor modules. Edge seal is likely to delay this degradation and potentially produce more power at 30 years than conventional modules.



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[2] T. Tanahashi *et. al.*, "Acceleration of Degradation by HAST and air-HAST in cSi PV Modules" SAYURIPV 2016 (Tsukuba, JP) and in *Jap. J. of App. Phys.*, **55** (2): 22302 2016
[3] P. Hacke, "PVQAT Task Group 3, PID and Combined Stress Testing", Proceedings of NREL PVRW 2018
[4] M. Köntges, *et. al. Review of Failures of Photovoltaic Modules.* IEA, 2014
[5] J. Wohlgemuth & M. Kempe, "Equating Damp Heat Testing with Field Failures of PV Modules", 2013 IEEE 39th Photovoltaic Specialists Conference (PVSC)

ESTABLISHED LINKS

The degradation of EVA has been well documented. Below is from the 2018 report of PVQAT TG3[3]: Interaction of stress factors (showing only the Modes where Humidity is a factor) . However, if desiccated edge seal eliminates the Humidity stress factor, the timing and mechanism for each failure mode may change.

Mode	Relevant Stress Factors	Relevant Stress Factors (if Humidity in module is blocked by edge seal)
PID	System Voltage High temperature **Humidity** Light Stress history Bias (Voc vs. Vmp) Injected carriers	System Voltage High temperature Light Stress history Bias (Voc vs. Vmp) Injected carriers
Solder fatigue failure	High temperature Temperature cycling Mechanical stress **Humidity (w/EVA and solder flux acidity)**	High temperature Temperature cycling Mechanical stress
Ag grid finger delamination	High temperature **Humidity (w/EVA acidity)** ? Temperature cycling ? Mechanical stress	High temperature ? Temperature cycling ? Mechanical stress

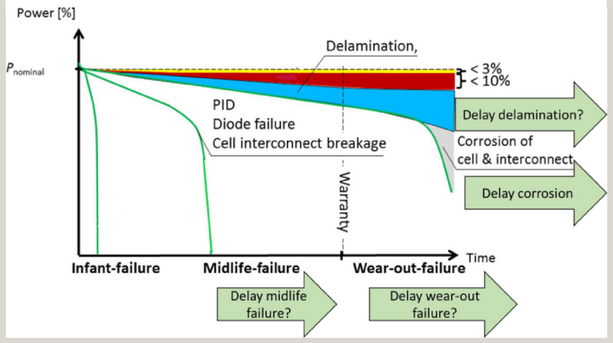
FUTURE QUESTIONS

Proposed theory is that blocking moisture delays the documented degradation mode of acetate ion generation in EVA as well as corrosion of components due to moisture alone.

Will midlife failures be delayed? Will wear-out failure be delayed?

By delaying these degradation mechanisms, will the addition of a desiccated edge seal create c-Si modules that are both more reliable and more durable?

TASK13 IEA-PVPS T13-01:2014 report Fig. 3.1[4]
Modified to include only modes that moisture may contribute to failure



CEMENTED JOINT

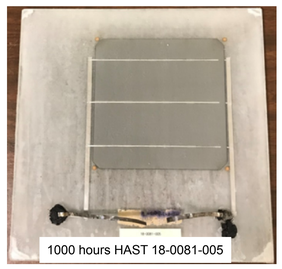
Additional Benefits: Changing the cell placement in a 60 or 72 cell 1500V module from 38 mm to 13 mm can reduce module area by over 4% resulting in multiple benefits in addition to sustained power output:

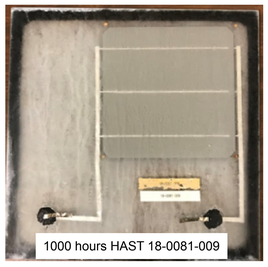
- Higher aperture efficiency
- Cost offset by reduction in area of glass and encapsulant
- Lower module weight

CONCLUSIONS

These results justify further study of the contribution of desiccated edge seal to a reduction in failure mechanisms associated with EVA that may result in longer c-Si module life.

Maintaining Power output after 1000 hours in HAST shows that desiccated PIB edge seal is still bonded and can withstand extremely harsh environments. Specialty applications that require moisture hardened modules, such as floating solar, may see the most immediate benefit.





Incorporation of edge seal will make adoption of perovskite tandem silicon cells easier to implement when tandem cells are commercially available.

Photovoltaic End-of-Life Management

Cara Libby – *Electric Power Research Institute, clibby@epri.com*
Stephanie Shaw – *Electric Power Research Institute, sshaw@epri.com*

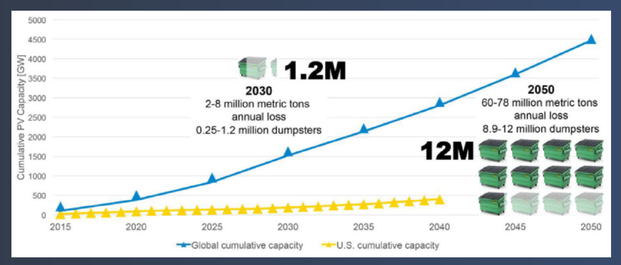
ELECTRIC POWER RESEARCH INSTITUTE

ABSTRACT

While global PV module waste volumes are currently small—at least 43,500 metric tons per year in 2016—they are steadily increasing, with over 1.7 million metric tons expected by 2030. In the U.S. market, PV plant end-of-life (EOL) costs are highly uncertain due to limited experience and lack of a mature PV module collection and recycling infrastructure. With examples of economically and technically feasible module take-back and recycling models implemented in the European Union and elsewhere, there is growing U.S. interest in understanding best practices for EOL module collection, reuse, recycling, and disposal. This poster provides a snapshot of the present situation in the U.S around PV module EOL management. It outlines currently available EOL options for PV plants and modules, as well as technologies adopted in mature PV markets such as Europe, where recycling is already mandatory. Key factors that may influence asset management decisions and module recycling and disposal practices include module composition and construction, policy and regulation, emerging recycling technologies, environmental impact, and economics.

PROJECTED PV MODULE WASTE VOLUME GROWTH

In the U.S., 170,000 to 1 million metric tons, or 25,000 to 150,000 dumpsters is expected by 2030. Those numbers are expected to grow roughly 10-fold by 2050.



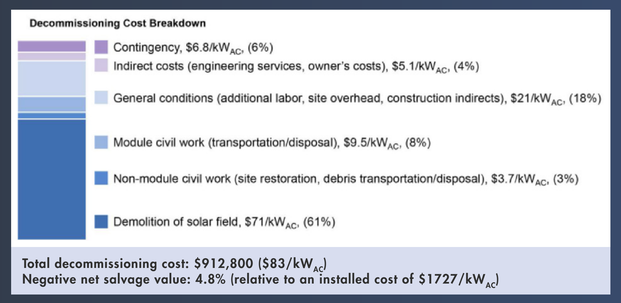
PV PLANT DECOMMISSIONING

Reasons for decommissioning may include end of project life, contract term, or property lease; economic viability, or safety concerns. Owners of older or underperforming PV plants can conduct field inspections and analyze historical and ongoing operational and weather data to assess performance and evaluate the options of selective module replacement, repowering, and decommissioning after careful consideration of safety and the latest codes and standards.

EPRI Decommissioning Cost Estimation

Conceptual 11 MWAC plant, assuming:

- Modules (38,680 total) are landfilled
- Steel and copper are recycled
- Actual costs will vary depending on contractual obligations, site restoration requirements, solid waste regulations, cost of module recycling or disposal options, and salvage value of materials.

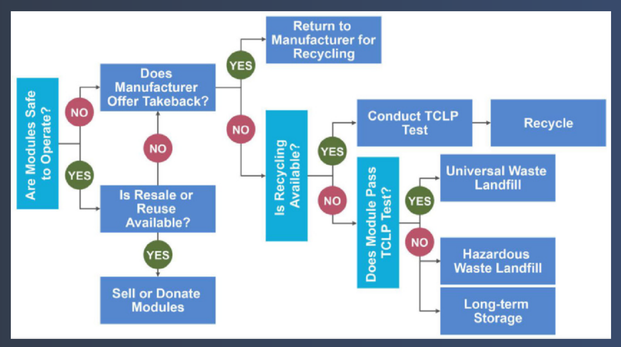


U.S. REGULATORY REQUIREMENTS FOR PV EOL

- No federal regulatory framework for PV recycling in U.S.
  - Resource Conservation and Recovery Act (RCRA) regulates disposal of hazardous and non-hazardous waste
  - PV modules are classified as hazardous if they exceed lead limits under Environmental Protection Agency (EPA) Toxicity Characteristic Leaching Procedure (TCLP) test method 1311
- California and Washington passed legislation to implement module management programs

DECISION TREE FOR EOL PV MODULES IN U.S.

- **Manufacturer Responsibility:** Determine if take-back is available, and if not ask for recommended EOL practice.
- **Reuse:** Explore secondary markets for taking advantage of remaining useful module output
- **Recycling:** Evaluate costs for transport and third-party processing of modules to recover raw materials and dispose of residuals
- **Landfill Disposal:** Examine module characteristics, applicable requirements, disposal costs and methods, and environmental considerations
- **Storage:** Consider storage in shipping containers to await emergence of better options

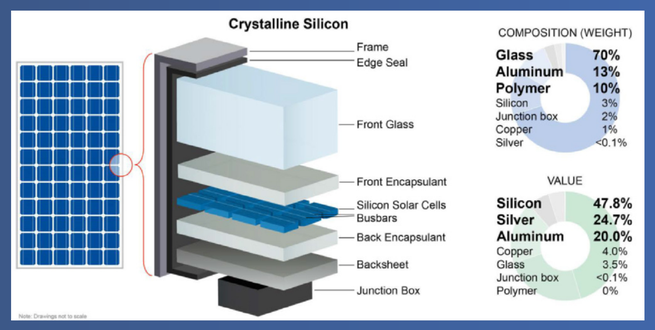


CURRENT BARRIERS TO COST-EFFECTIVE PV RECYCLING IN U.S.

- Modules are not designed for recycling
- Current low waste volumes do not justify dedicated recycling facilities
- Existing glass and metal recycling lines are not optimized for PV modules
- Valuable materials, such as silver and silicon, are often not fully recovered
- Achieving higher material recovery may increase energy consumption or require significant chemical processing

EFFECTS OF MODULE COMPOSITION OR CONSTRUCTION

- PV modules are constructed to withstand >25 years of outdoor exposure
  - Frame and junction box typically can be removed cleanly
  - Encapsulant and edge seals make complete materials separation difficult
- Residuals may include polymer film and metal foil materials that are often incinerated for energy recovery



RECYCLING TECHNOLOGIES

- **Today:** conventional glass and metal recyclers process modules in discrete batches on a periodic basis with varying output yield and quality
- **Tomorrow:** mechanical, optical, chemical, and thermal processes and technologies will separate modules into constituent parts, boosting materials recovery—particularly silver and solar-grade silicon—and purity, while reducing cost, achieving low energy consumption, and minimizing volume and risk of residual materials

Stage 1: Frame Removal – Automating frame removal can reduce labor and keep modules intact to improve materials separation in subsequent stages of the recycling process

Stage 2: Delamination and Separation – Avoiding glass breakage increases the recovery value of glass and silicon. Proposed processes:

- Hot knife (300°C) drives apart glass and semiconductor layers
- High-temperature decomposition (400-600°C) incinerates encapsulant
- Low-temperature laser treatment process softens encapsulant
- Suction cups under vacuum separate glass-glass modules after laser treatment
- Spinning steel brush abrades semiconductor from glass after delamination via one of the above processes

Stage 3: Metal Extraction and Purification – Leaching, filtration, melting, electrowinning, and electrolysis are some of the promising methods being explored specifically to improve the yield and quality of recovered metals

U.S. MODULE EOL ECONOMICS

Recovery of high-value materials expected to increase:

- IRENA and IEA-PVPS base case 2030: ~$5/module
- European consortium CABRISS: 13.4 euros/module (approximately $15.50/module)
- Arizona State University: $54/module

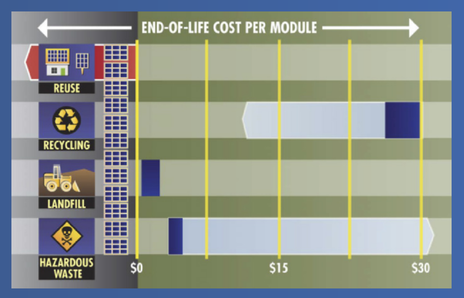
PV recycling economics are expected to improve as waste volumes grow and dedicated processes are employed, but there are several uncertainties

- Evolving module compositions, i.e., manufacturers reduce valuable materials
- Fluctuating resale prices of recoverable materials
- Increasingly stringent material purity requirements

Project Size	Number of Modules		Weight, US Tons (Metric Tons)		Number of Dumpsters (40 CY, 30.6 m³)		Number of Containers (100 CY, 76.5 m³)	
	250 W	350 W	250 W	350 W	250 W	350 W	250 W	350 W
10 kW	40	29	0.82 (0.74)	0.59 (0.53)	-	-	-	-
1 MW	4,000	2,858	82 (74)	59 (53)	11	8	4	3
10 MW	40,000	28,572	820 (744)	586 (531)	110	78	44	31
50 MW	200,000	142,858	4,100 (3,719)	2,929 (2,657)	549	392	220	157

* Module weight: 18.6 kg (41 lb)
** 30% void fraction (modules fill only 70% of volume)

- **Reuse:** Reused modules sold or donated into secondary markets can generate revenue or a tax savings
- **Recycling:** Anecdotal information shared by U.S. PV plant owners indicates a bulk rate on the order of $25 to $30 per module for c-Si modules. Pricing effects due to shipping distance, module condition, type, and composition—both high-value materials and toxic content—are uncertain.
- **Landfill:** Disposal costs at Subtitle D landfills vary significantly by region and are expected to increase over the next several years. Tipping fee quotes varied from $26/ton to $89/ton.
- **Hazardous Waste:** Subtitle C facilities quoted tipping fees of $175/ton and up for accepting, treating, and landfilling bulk EOL modules designated as hazardous waste. Prices may increase dramatically for small disposal volumes and modules that require multi-stage treatment due to high levels of lead and other RCRA contaminants.



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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

Characterizing Adhesives and Edge Seals for Roll To Roll Photovoltaics Packaging

Michael Sulkis[1] ,Samuel Graham[1], Jinho Hah[1], Jack Moon[1], C. P. Wong[1], Suresh Sitaraman[1], Matthew Reese[2], Sean Garner[3], Scott Jones[4], Doojin Vak[5]

[1]Georgia Institute of Technology, [2]National Renewable Energy Laboratory; [3]Corning, Inc., [4]3M, Inc., [5]CSIRO-Monash; Australia

Introduction

Manufacturing flexible, thin-film photovoltaics at scale has the potential to make solar electricity price-competitive with conventional electricity generation. However, the sensitivity of these PVs to environmental conditions has created the need to develop encapsulation and edge-seal materials that can adequately protect these devices while being compatible with high-throughput, roll-to-roll manufacturing processes. Therefore, the goal of this work is to understand the long-term performance of commercial adhesives and barriers for flexible PV cells. Additionally, modified adhesives and encapsulants will be made at Georgia Tech for comparison to commercially available options.

Materials for Packaging

Barrier Materials:

Source: Corning

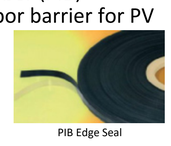
Corning Willow Glass

Source: 3M

3M Ultra Barrier

Adhesive/Encapsulant Material Classes:

- Polyisobutylene Rubber (PIB)
  - Established vapor barrier for PV
  - Flexible
  - Opaque
  - ADCO PVS101



PIB Edge Seal

- Polydimethylsiloxane (PDMS)
  - Highly modifiable
  - Flexible
  - Transparent
  - Qsil 216

Source: tgsolar

- Ethylene Vinyl Acetate (EVA)
  - Most common PV encapsulant
  - Transparent
  - UV stability issues
  - Moisture reaction

EVA Encapsulant

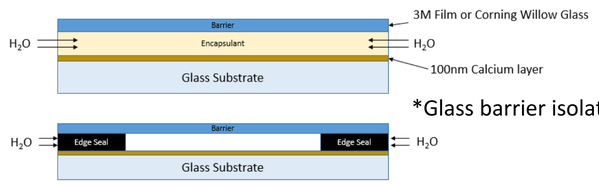
- Ionomer and Polyolefin
  - No acetic acid
  - UV stable
  - Strong adhesion

Ionomer Encapsulant

- Proprietary Adhesives
  - UV curable barrier adhesive

Calcium Testing and Mechanical Testing

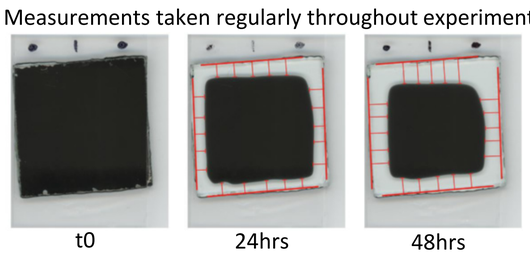
Calcium Test Specimens



*Glass barrier isolates side permeation

Measurements taken regularly throughout experiment

Epson Photo Scanner



t0 24hrs 48hrs

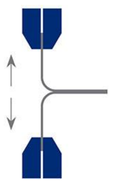
Degradation distance from average of 16 measurements (4 per side)

Mechanical Test Specimens

Peel Testing

- More compatible with flexible materials
- High-throughput

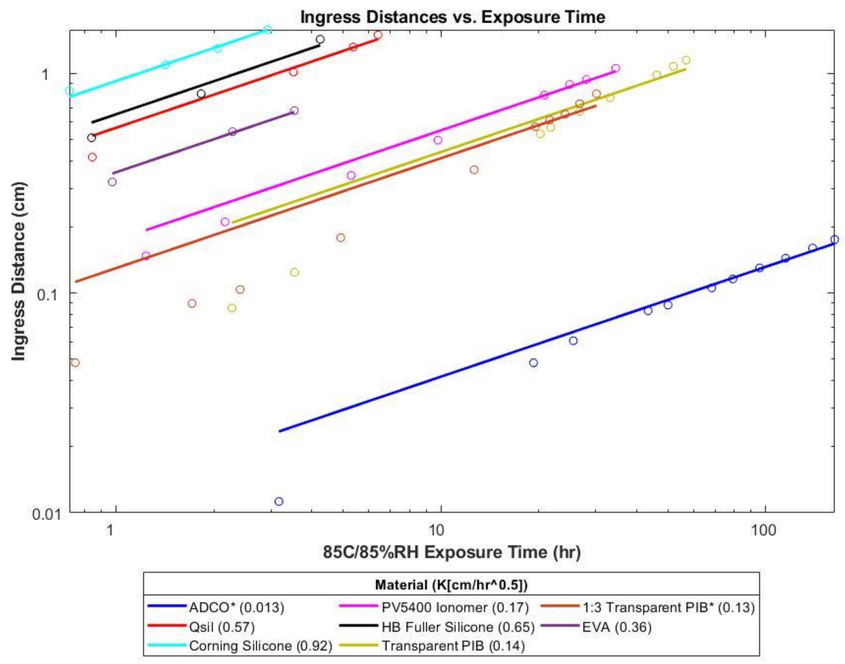
Testresources.net



Mecmesin.com

Optical Calcium Testing Results

Calcium Corrosion Testing for Permeation Through Adhesive:



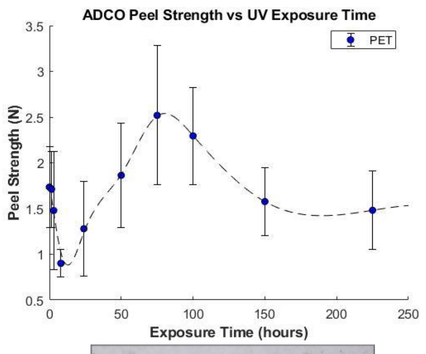
$$Ca(s) + 2H_2O(g) \rightarrow Ca(OH)_2(aq) + H_2(g)$$

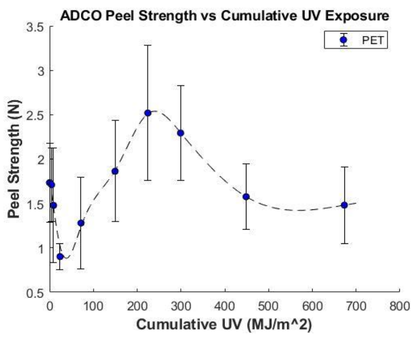
Environmental chamber

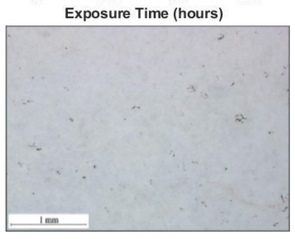
Samples

- K values determined from best fits to $X = K\sqrt{t}$
  - Holds for Fickian and non-Fickian materials
- Transparent PIB is a formulation developed at GT

Mechanical Testing

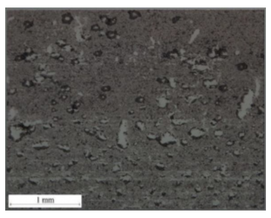




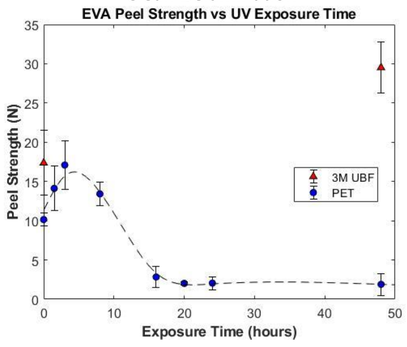


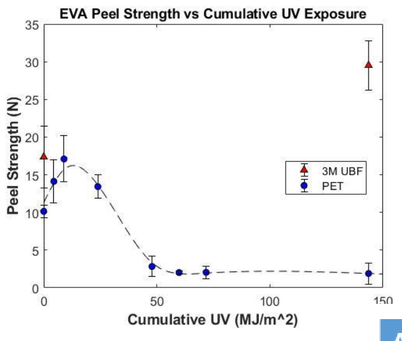
Clean Delamination

UV →



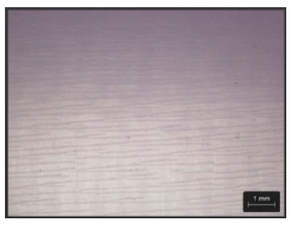
Residue on UV side





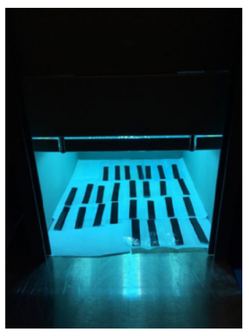
Delamination with cavitation

UV →

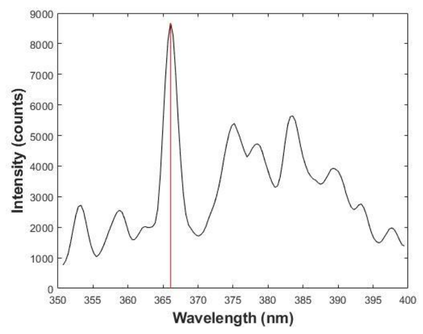


Delamination with no cavitation

UV Aging of Peel Samples



365nm Lamp @ 831 W/m²



EVA

ADCO PIB

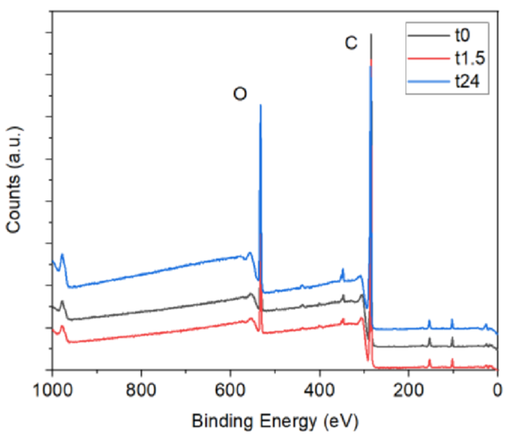
Inorganic Adhesion Layers

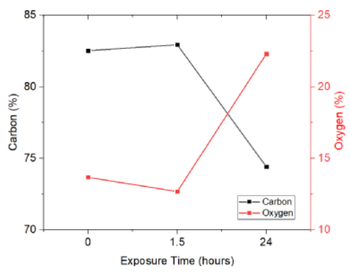
Adhesive	Substrate	Peel Strength (N)
PV5400 Ionomer	PET	0.21 ± 0.02
Qsil (PDMS)	PET	0.22 ± 0.03
PV5400 Ionomer	ITO/PET	0.54 ± 0.07
Qsil (PDMS)	ITO/PET	0.46 ± 0.02

Surface Characterization

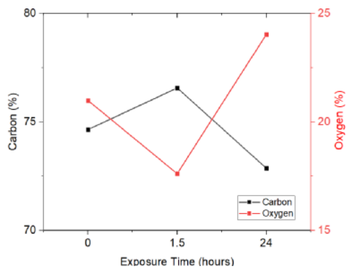
Elemental Composition Analysis from XPS Survey Spectrum

Schematic Survey Spectrum of Characterization on Delamination Side with EVA





Delamination Side with EVA



Delamination Side with PET

xpssimplified.com

After 1.5 hours

- Initial decrease in oxygen content (%) and increase in adhesion was observed.
- Radicals on PET and/or EVA side form, consuming oxygen to form the interfacial bonds.
- Polymerization at the interface between the radicals formed on the PET and dangling bonds from the EVA also means consumption of oxygen.

After 24 hours

- Increase in oxygen content (%) and decrease in adhesion was observed.
- UV-induced oxidation was proceeded, making the both EVA and PET sides more inert, resulting in facile delamination at the PET-EVA interface.

Discussion

- The moisture barrier performance of a variety of commercial encapsulants and edge seals has been determined at 85°C/85%RH conditions
- Desiccant-filled PIB edge seals provide superior moisture barrier performance
- Encapsulant materials are poor moisture barriers, mechanical performance is critical
- EVA exhibits strong initial adhesion to PET, degrades significantly with UV exposure. 3M film with low UV transmittance mitigates degradation
- UV exposure of PIB edge seals increases adhesion, resulting in cohesive failure

Future Work

- Calcium Screening
  - Test at multiple temperature/humidity conditions
  - High performing materials will be selected for high throughput testing at NREL
- Mechanical Testing
  - Study the effects of damp heat aging on adhesion strength
  - Perform chemical analysis on peeled surfaces to determine degradation mechanisms
  - Improve the performance of low adhesion materials using inorganic adhesion layers and surface treatments
  - Environmental aging at NREL

U.S. DEPARTMENT OF ENERGY · NREL · Sandia National Laboratories · Berkeley Lab · SLAC National Accelerator Laboratory · QESST · Next Generation Photovoltaics Center · BAPVC

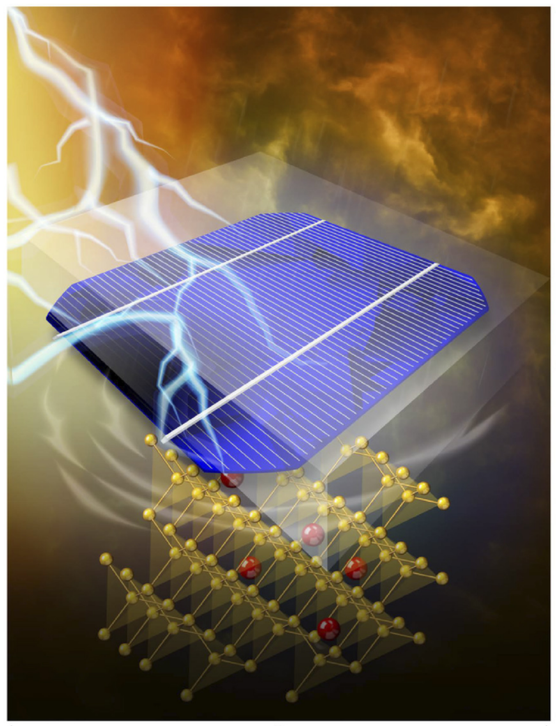
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

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.

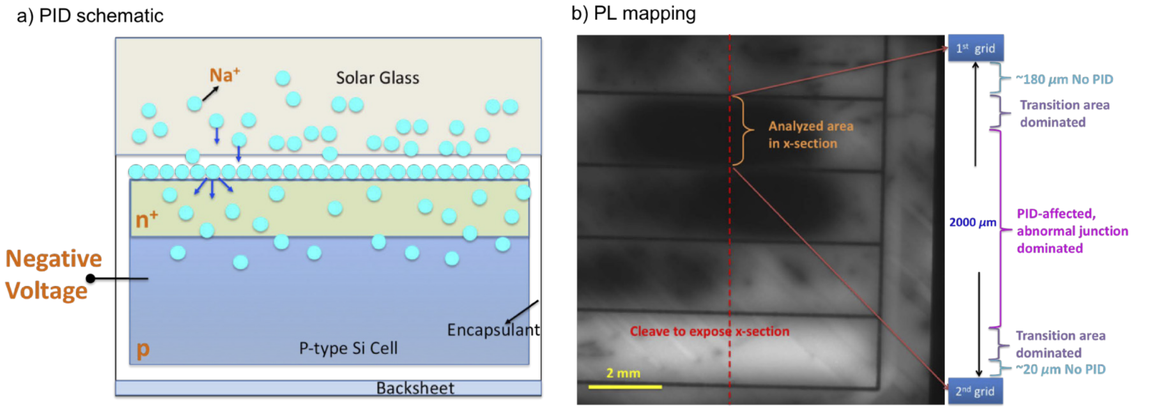
Large-Area Material and Junction Damage in c-Si Solar Cells by Potential-Induced Degradation

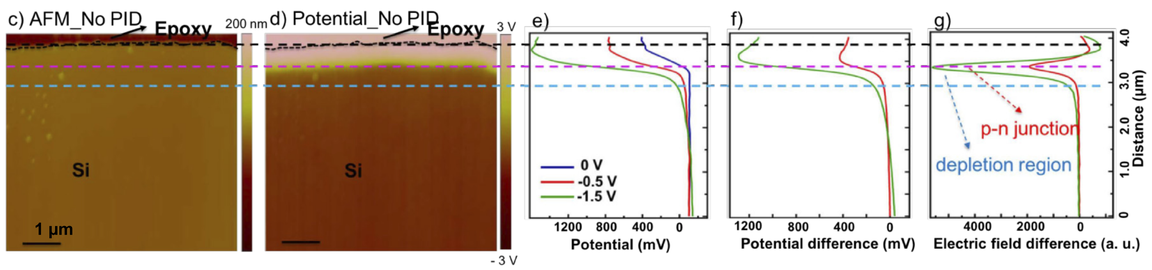
Chuanxiao Xiao, Chun-Sheng Jiang, Steve P. Harvey, Dana Sulas, Xihan Chen, Jun Liu, Jie Pan, Helio Moutinho, Andrew Norman, Peter Hacke, Steve Johnston, and Mowafak Al-Jassim

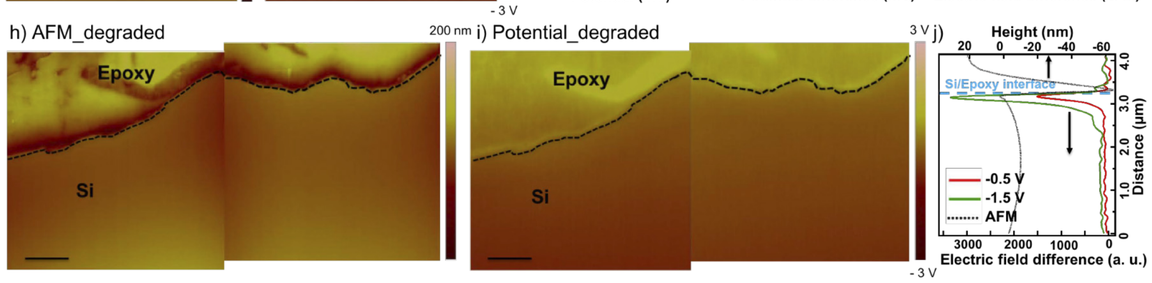
Introduction

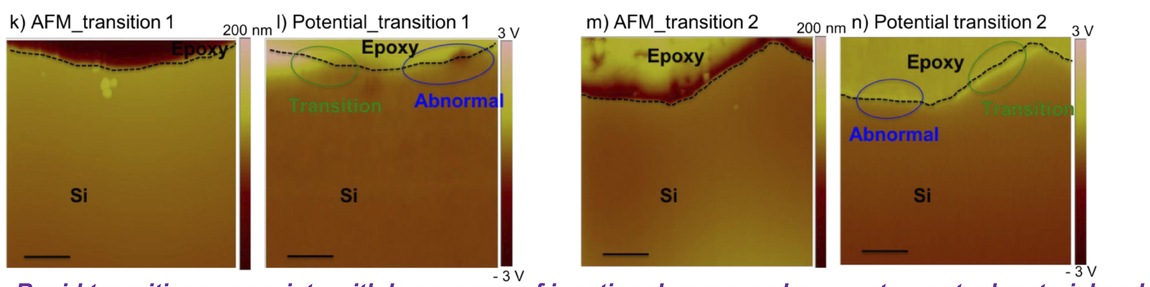


- **A new potential-induced degradation** (PID) mechanism for c–Si is reported. Multiple characterization techniques in various aspects of a material's chemical, structural, electrical, and optoelectrical nature, as well as in atomic, nanometer, micrometer, millimeter, and cell and module scales, are combined. All results point consistently to a new discovery: substantial large-area deterioration of materials and junctions plays a major role.
- Combined **multiple characterization techniques**—Kelvin probe force microscopy (KPFM), electron-beam induced current (EBIC), dark lock-in thermography (DLIT), transmission electron microscopy, time-of-flight secondary-ion mass spectrometry (TOF SIMS), and microwave photoconductance decay (μ-PCD)—as well as density functional theory calculations.
- DOI: 10.1002/solr.201800303. Selected to be featured on the **front cover** of **Solar RRL**. (Copyright @ 2019 John Wiley & Sons, Ltd.)



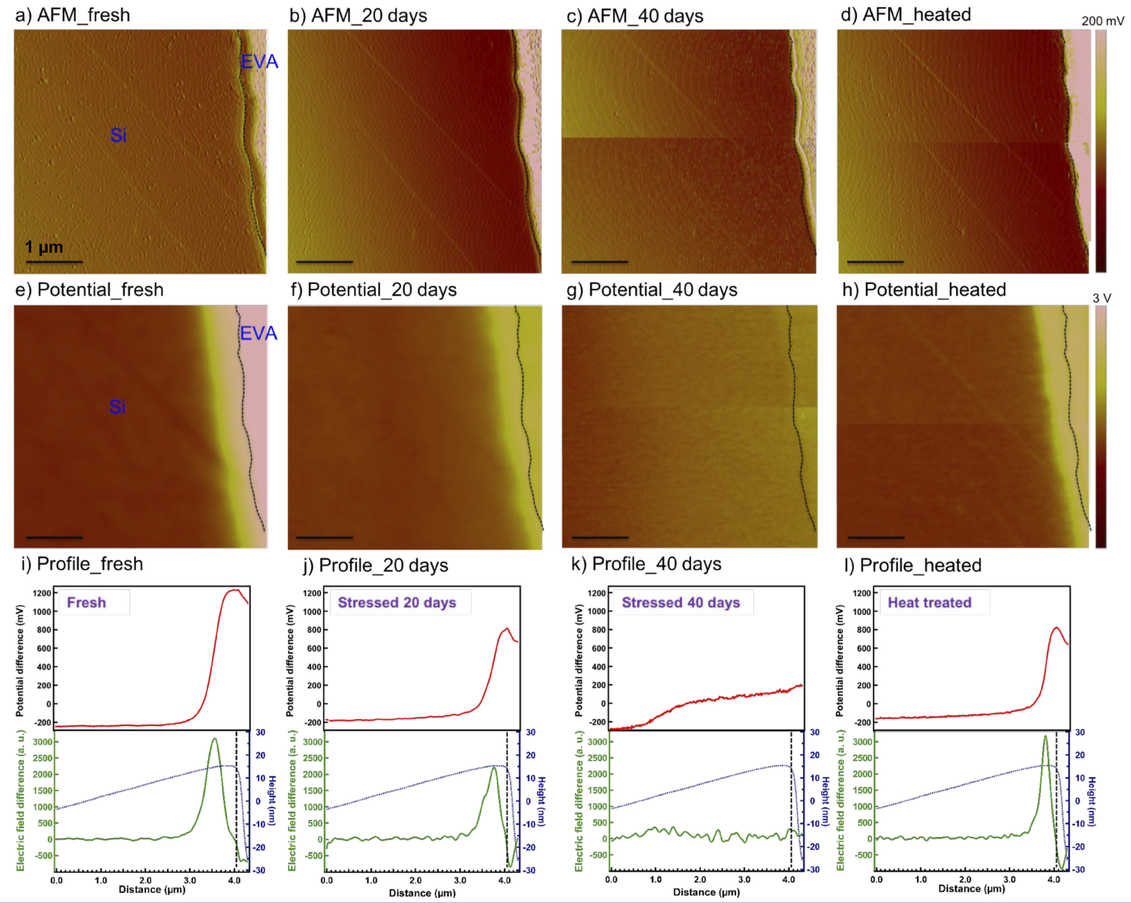




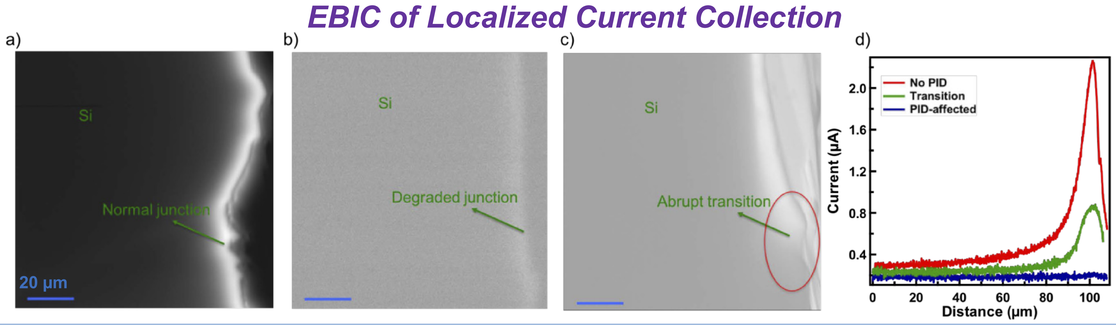


Rapid transitions associate with large areas of junction damage and suggest an actual material and junction degradation, rather than the well-reported local shunting induced by Na-decorated planar defects that penetrate p-n junction.

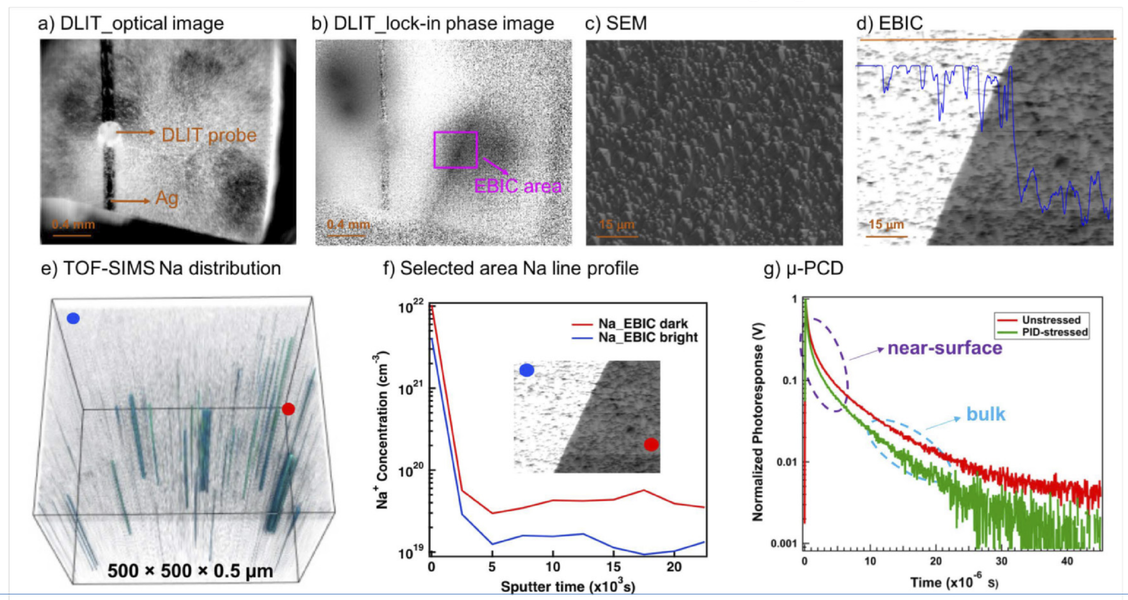
In-situ KPFM during long-term PID stressing



EBIC of Localized Current Collection



Chemical and Electrical Imaging



Summary

- *We proposed a new PID mechanism in conventional silicon modules that is essentially different from and complementary to the current knowledge that PID shunts are localized in small and separate spots.*
- *PID occurs not only at Na-decorated planar defects, but can also occur in large areas and can cause material and junction degradation.*
- *A large amount of Na can cause harmful point defects in silicon solar cells.*

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Feb 26-28, 2019
NREL/PO-5K00-73379

Module, String, Array, and Plant Level Degradations in PV Systems

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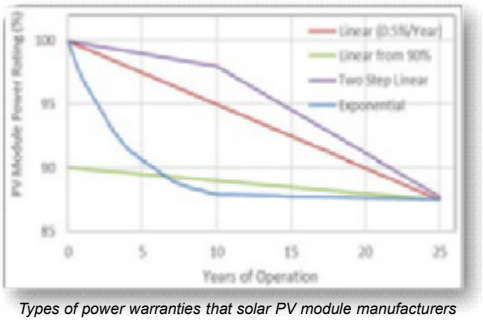
Electric Power Research Institute (EPRI); dfregosi@epri.com; +1 980.495.7487

I. Motivation and Scope

- The degradation rate of a PV plant is a key parameter for estimating energy production over its lifetime.
  - Most studies to-date analyze the degradation rate of a single module or a few modules per system.
  - A wide variation on reported degradation rates create confusion about what rate is applicable to a single plant
  - Applying the degradation rate from component-level studies to plant-level may not be accurate.
- This work presents the calculated degradation rates for PV modules, strings, arrays, and large-scale plant using five years of performance data and periodic outdoor string level I-V measurements.
  - RdTools [2] is used to calculate the degradation rates using the year-on-year (YOY) [3] methodology with sensor-based and clear-sky (CS) approaches.

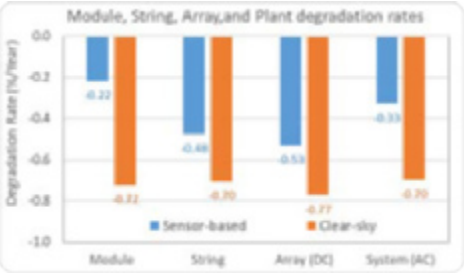


Types of power warranties that solar PV module manufacturers provide, each culminating in 87.5% of nameplate capacity after 25 years of operation

II. Study (A) 9.8 kWdc Systems

- Eight PV systems of 9.8 kWdc comprised of different cell-technologies
- Degradation rates are calculated using performance data and periodic outdoor module and string level I-V tests

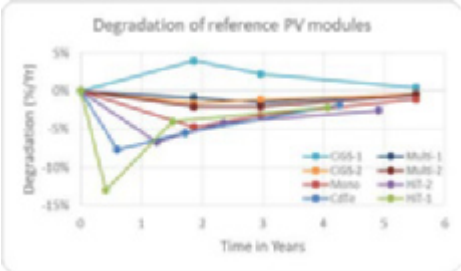
Measurement points on a 9.8 kWdc PV systems



Average degradation rates calculated for a mono-crystalline PV modules, strings, array, and system after 5 years of operation

Variable and different degradation rates were measured for the PV module, string, array, and system

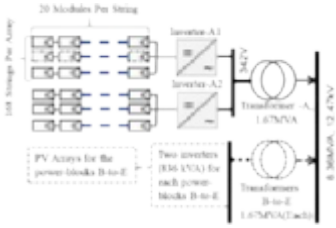
Non-linear degradation rates over time were measured with higher rates during the first few years of operation.



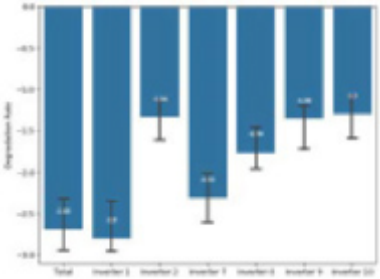
Degradation rate of different PV modules in 9.8 kWdc systems

III. Study (B) 9.6 MWdc Large-Scale Plant

- One 9.6 MWdc PV plant comprised of 10 arrays (960 kWdc), made up of multi-crystalline PV modules of 285W
- Degradation rates are calculated using five years of performance data



Schematic of 9.6 MWdc PV System



Degradation rates (median) of 9.6 MWdc PV system

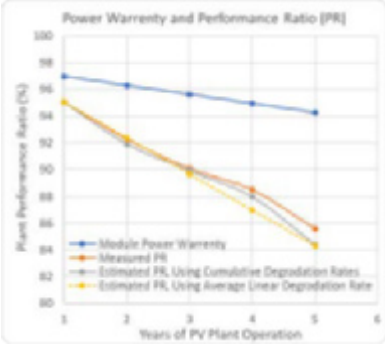
Variations in calculated degradation rate within the power blocks (PV array and inverter set) of a PV system.

PV plant power ***decreasing faster*** (> 2 %/year) than module power warranty.

- ***Source of degradation currently unknown***

Calculated degradation rates are highly sensitives to ***filtering and aggregation*** strategies.

- ***Best practices needed***



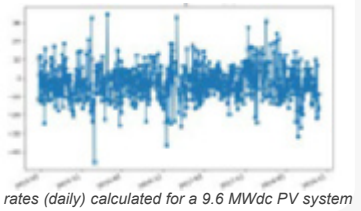
PV Module power warranty and cumulative degradation of a 9.6 MWdc PV system

IV. Challenges in Degradation Study

The challenges for quantifying the degradation rate of a PV module and system include

- Data Quality
  Equipment (sensor) Accuracy, Logging Frequency, Missing Data Points, Data Shifts, Different Timestamps, and so on
- Seasonal Variation
- Selection of Baseline Performance
- Filtering Criteria
- Aggregation Period

Monthly Performance ratio of a 9.6 MWdc PV system

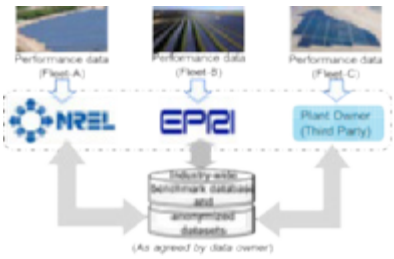


Degradation rates (daily) calculated for a 9.6 MWdc PV system

V. Next Step: Benchmarking Degradation Study

Remaining key research questions includes;

- How does common industry values of 0.5 – 1.0%/Yr degradation compare to reality?
- How does degradation rate change year-on-year? Is a single value sufficient?
- How does the degradation rate of a plant or fleet compare across the industry?



Consistent Calculation methodology. Round-robin datasets to confirm analysis

Envisioned research and outcomes

- Provide benchmark comparison amongst fleet and industry
- Analyze and quantify the degradation of participants' plants
- Facilitate standardizing the degradation rate calculation methodology

VI. References and Further Resources

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2. NREL, "Rdtools,", 2019. [Online]. Available: https://github.com/NREL/rdtools.
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4. D. C. Jordan and S. R. Kurtz, "The Dark Horse of Evaluating Long-Term Field Performance—Data Filtering," IEEE Journal of Photovoltaics, vol. 4, no. 1, p. 317, 2014.
5. D. C. Jordan, T. J. Silverman, J. H. Wohlgemuth, S. R. Kurtz and . V. T. Kaitlyn, "Photovoltaic failure and degradation modes," Progress in PV: Research and Applications, vol. 25, pp. 318-326, 2017.
6. PV System Degradation: Review and Application of Analysis Methods, Electric Power Research Institute, Palo Alto, CA: 2018. 3002013669.

Degradation of commercial PV backsheets under outdoor and accelerated indoor weathering exposures

Sophie Napoli[1], Adam W. Hauser[1], Gregory S. O'Brien[1], Yu Wang[2], Andrew Fairbrother[3], Scott Julien[4], Xiaohong Gu[3], Liang Ji[5], Kenneth P. Boyce[5], Michael D. Kempe[6], Kai-Tak Wan[4], Roger H. French[2], Laura S. Bruckman[2]

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[5]Renewable Energy, Underwriter's Laboratories Inc., Northbrook, IL 60062, USA
[6]Photovoltaics Research, National Renewable Energy Laboratory, Golden, CO 80401, USA

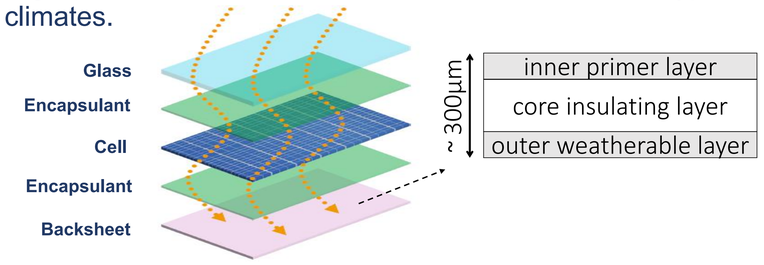
1. Introduction

PV backsheets are essential components of a solar module's life expectancy. They provide:

- weathering and mechanical protection
- safety through electrical insulation

Goal: *a longevity of 25+ years in the field*

High performance materials are needed to resist all types of climates.



2. Overview of the project

"Backsheets: Correlation of Long-Term Field Reliability with Accelerated Laboratory Testing": 3-year DOE-funded project between 6 laboratories and organizations.

Goal: study the weatherability of commercial backsheets to develop a predictive model based on point-in-time data from:

Outdoor real time exposure:

- Direct and indirect backsheet exposures for 7 years in Florida at a 45° angle
- Samples pulled annually and analyzed through non-destructive tests.

Retrieved outdoor exposed modules :

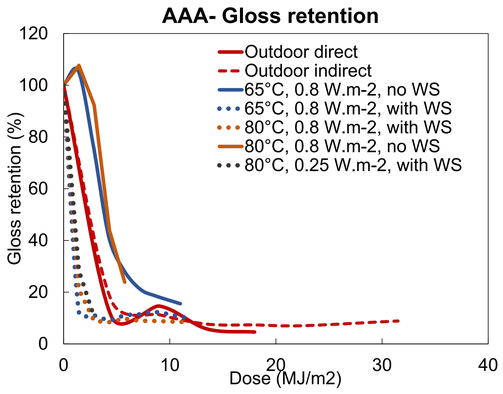
- Analysis of backsheets extracted from retrieved modules
- Various manufacturers, locations, climatic zones and exposure time.
- Total of 57 retrieved modules

Indoor accelerated exposures:

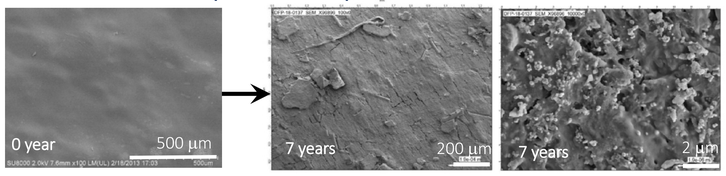
- Four outer layer studied: PA12, PET, PVF and Kynar® PVDF
- Five Xenon's Arc exposures with temperature, water-spray, humidity and irradiation control at 340 nm
- Samples are backsheets facing the light, laminated on glass through an EVA layer

3. Polyamide backsheets

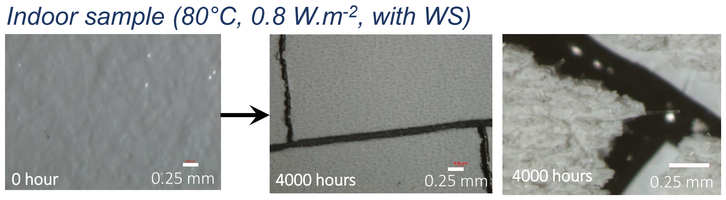
Name	Outer layer	Core Layer	Inner layer
AAA	PA	PA + Glass fiber	PA



Outdoor indirect exposure sample



Indoor sample (80°C, 0.8 W.m-2, with WS)

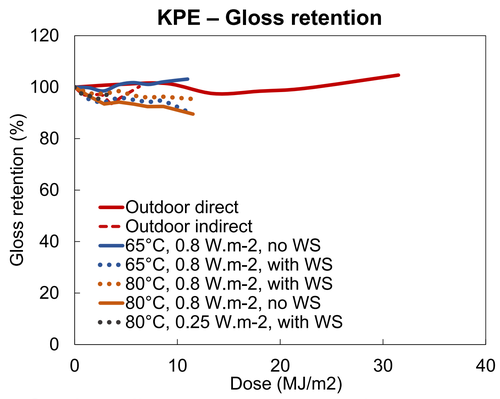


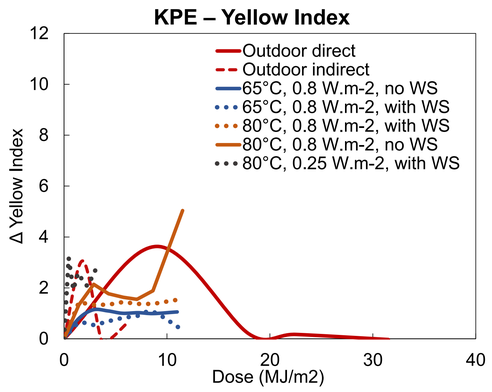
- Little effect of a higher temperature or irradiance on gloss loss rate
- Water spray decreases gloss retention, washes off the degraded outer layer, leads to backsheet cracking for exposure with high temperature
- Outdoor exposure resemble water spray accelerated tests : drop of gloss, outer layer cracking and falling off

- Macro-cracking in Italy (5 years) and Thailand (4 years) → Backsheet cracking
- Micro-cracking in China after 4.5 years
- Quick drop of gloss after one more year of exposure in China
- Heterogeneous gloss loss for modules exposed in the same climate

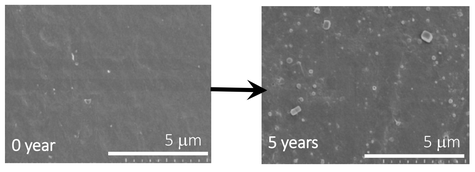
4. Kynar® PVDF backsheets

Name	Outer layer	Core Layer	Inner layer
KPE	Kynar®	PET	EVA

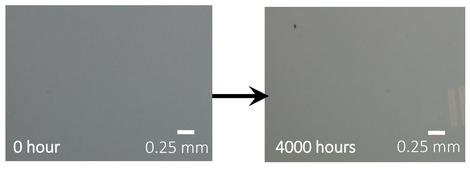


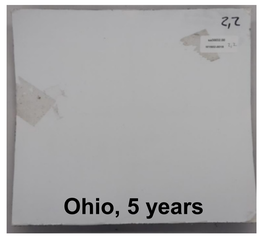


Outdoor direct exposure sample



Indoor sample (80°C, 0.8 W.m-2, with WS)

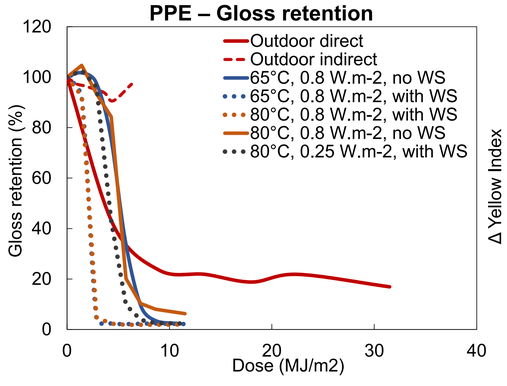


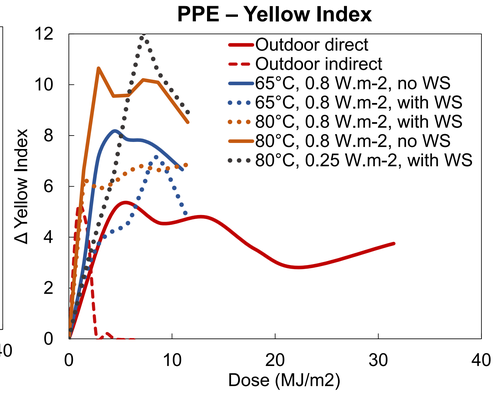


- No significant effect of a higher temperature and irradiance, or addition of water spray
- No cracking, pitting or surface erosion
- No measurable chemical degradation even for the direct outdoor exposure
- Overall good property retention

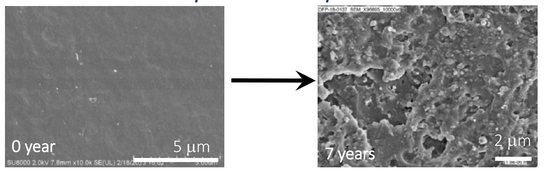
5. PET backsheets

Name	Outer layer	Core Layer	Inner layer
PPE	PET	PET	EVA

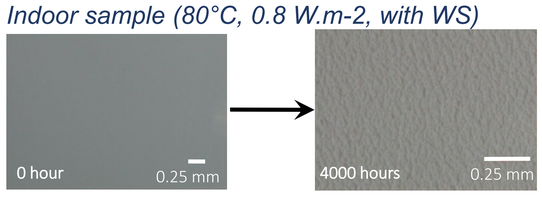


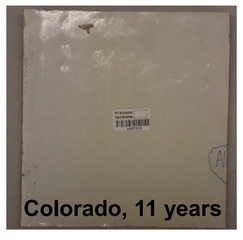


Outdoor direct exposure sample



Indoor sample (80°C, 0.8 W.m-2, with WS)





- A higher chamber temperature leads to faster outer layer cracking
- High irradiance and water spray significantly affects surface degradation rate, outer layer cracking and core layer degradation
- Highest yellow index out of all backsheets indicating chemical degradation of the PET
- Intensive yellowing of retrieved modules (YI>10) and inconsistent gloss values

6. Conclusions

- Non fluoropolymer-based backsheets showed poor weathering capabilities compared to fluoropolymer-based backsheets
- PET-based backsheet are more resistant in the field but still suffer from extensive yellowing
- AAA-based backsheet are fully cracked after only 5 years in Italy and Thailand. Significant degradation was observed on all modules, exposed less than 6 years.
- Kynar®-Film based backsheet showed show excellent surface property retention regardless of environmental conditions

How to Efficiently Share Data Using the Orange Button Data Standard

PV Reliability Workshop 2019

Authors

Jon Previtali, Joel Boeder, Wells Fargo
Glenna Wiseman, Tom Tansy, Jesse Depot, SunSpec Alliance

A Common Data Language for All Solar Project Partners

Orange Button Offers

- RESTful web services API
- JSON encoding
- Open source code library on GitHub
- More than 4,500 defined solar industry terms
- More than 15,000 defined U.S. GAAP terms
- Compatible with XBRL, IEEE, and IEC standards
- An extensible environment

What is Orange Button?

SIMPLIFYING THE EXCHANGE OF SOLAR PROJECT DATA

Collecting and reporting project data contributes up to 30% of solar project costs (source: DOE), making data exchange more expensive than solar hardware. With funding from the U.S. Department of Energy, SunSpec Alliance joined with Smart Electric Power Alliance, National Renewable Energy Laboratory, kWh Analytics, and Solar Energy Industries Association to simplify the exchange of solar project data using the Orange Button data standard.

Orange Button minimizes data transaction costs by making project data machine readable. Compatible with XBRL, a widely used standard for business information reporting, Orange Button links financial and operational data points with a uniform set of project terms taken from manufacturer product information, contracts, and other source documents.

The first version of the Orange Button standard, released in April 2018, contains about 4,500 solar-specific data fields and 15,000 U.S. Generally Accepted Accounting Principles (GAAP) financial terms.

In September 2018, kWh Analytics released Orange Button Translate, software that can instantly convert proprietary data into Orange Button compliant JSON and XML files.

Orange Button tools are free and available to easily move data from one software program to another.

More than 115 companies have joined the Orange Button Implementer's Network to help develop the standard and connect with business partners who are supporting the project.

Useful Links

- General Information & Implementer's Network
  https://sunspec.org/orange-button-initiative/
- Taxonomy Guide and other resources
  https://xbrl.us/xbrl-taxonomy/2018-solar/
- Yeti Taxonomy Viewer
  https://yeti1.corefiling.com/yeti/resources/yeti-gwt/Yeti.jsp
- Orange Button Translate (translation service)
  https://translate.kwhanalytics.com/orangebutton
- Open Source Initiative
  https://sunspec.org/ob-open-source-community/
- Source Code
  https://github.com/SunspecOrangeButton

ORANGE BUTTON
INITIATIVE

Problem Statement

Prior to the publication of the Orange Button Taxonomy in 2018, there was no comprehensive data standard in the Renewable Energy marketplace. Currently, prior to mass adoption of Orange Button, data exchange is based upon a large number of ad-hoc data formats often maintained in spreadsheets or word processor documents. Data often is manually transcribed between individual entities computer systems by hand. This causes transactional friction, difficult in monitoring project performance, system integration expense and compromises the reliability of data.

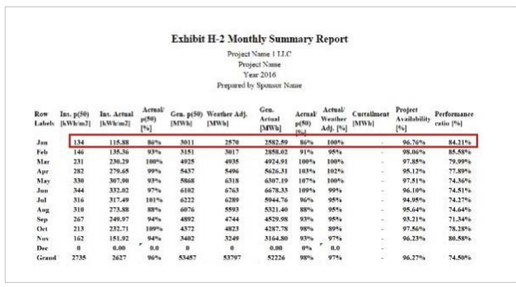


Exhibit H-2 Monthly Summary Report

Project Name 1 LLC
Project Name
Year 2016
Prepared by Sponsor Name

Row Labels	Inv. p(50) [kWh/m2]	Inv. Actual [kWh/m2]	Actual/ p(50) [%]	Gen. p(50) [MWh]	Weather Adj. [MWh]	Gen. Actual [MWh]	Actual p(50) [%]	Actual/ Weather Adj. [%]	Curtailment [MWh]	Project Availability [%]	Performance ratio [%]
Jan	134	115.88	86%	5011	2570	2582.59	86%	100%	-	96.76%	84.21%
Feb	146	138.36	93%	3151	3017	2858.42	91%	95%	-	98.06%	85.58%
Mar	231	230.29	100%	4925	4935	4924.91	100%	100%	-	97.85%	79.99%
Apr	282	279.68	99%	5437	5496	5626.31	103%	102%	-	95.12%	77.89%
May	330	307.00	93%	5868	6318	6307.19	107%	100%	-	97.51%	74.36%
Jun	344	332.02	97%	6102	6763	6678.33	109%	99%	-	96.10%	74.51%
Jul	316	317.49	101%	6222	6289	5944.76	96%	95%	-	94.95%	74.27%
Aug	310	273.88	88%	4976	5593	5321.40	88%	95%	-	95.64%	74.64%
Sep	267	249.97	94%	4892	4744	4529.98	93%	95%	-	93.21%	71.34%
Oct	213	232.71	109%	4372	4823	4287.78	98%	89%	-	97.56%	78.28%
Nov	162	151.92	94%	3402	3249	3164.80	93%	97%	-	96.23%	80.58%
Dec	0	0.00	0.0	0	0	0.00	0%	0.0	-		
Grand	2735	2627	96%	53457	53797	52226	98%	97%	-	96.27%	74.50%

A typical solar Monthly Operating Report (MOR). *Source: sPower*

What is JSON?

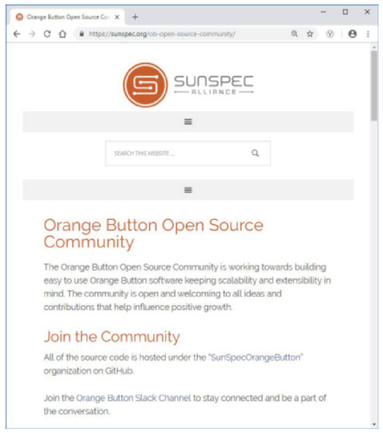
JSON stands for JavaScript Object Notation which is an open standard for exchange of human readable, computer digestible, data points consisting of attribute, value pairs. In XBRL JSON format individual Orange Button facts can be exchanged or stored on computer systems in a manner that is defined by the Orange Button Taxonomy. XBRL also support an older format named Extensible Markup Language (XML).

```
    },
    "value": "3164.8"
  },
  "87f260e9-d8a2-446f-a28e-1081f6bfcaff": {
    "aspects": {
      "entity": "JUPITER",
      "period": "2017-11-01T00:00:00/2017-11-30T00:00:00",
      "concept": "solar:ExpectedEnergyAtTheRevenueMeter",
      "unit": "MWh"
    },
    "value": "3402"
  },
  "0c62ab41-7983-4373-8e6e-c079095fab45": {
    "aspects": {
      "entity": "JUPITER",
      "period": "2017-11-01T00:00:00/2017-11-30T00:00:00",
      "concept": "solar:Curtailment",
      "unit": "MWh"
    },
    "value": "98.76"
```

Example of JSON code. *Source: SunSpec Orange Button Open Source Community*

The Orange Button Open Source Community

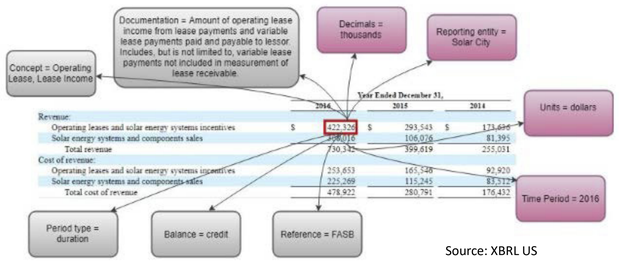
In order to facilitate adoption of the Orange Button standard Open Source software is being developed to allow to lower the technical barriers for usage. The python software library – pyoblib – handles core Orange Button concepts such as supplying an in memory copy of the Taxonomy metadata, importing and exporting JSON/XML Orange Button data, and performing Validation. The library can be used to build a full stack Orange Button application.



Source: SunSpec Alliance

What is the Orange Button Taxonomy?

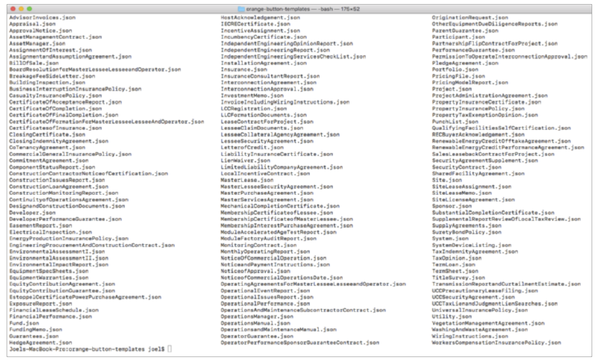
A Taxonomy is the practice and science of classification of things or concepts, including the principles that underline such classification. The Orange Button Taxonomy is defined using the XBRL standard. XBRL is the international standard for the electronic representation of business reports. XBRL associates a particular data value with various aspects and concepts that further define the data value. The value and its associated aspects represents a single fact. The Orange Button Taxonomy is a set of over 4,000 unique terms and definitions (concepts) used by the solar power industry. It is intended to cover data exchange needed for the entire lifecycle of solar projects: development, siting, construction, interconnection, financing, insurance, decommissioning, etc. Because of many similarities, the Orange Button Taxonomy can also be used to support other renewable energy projects, e.g. wind farms.



Source: XBRL US

Various Orange Button JSON

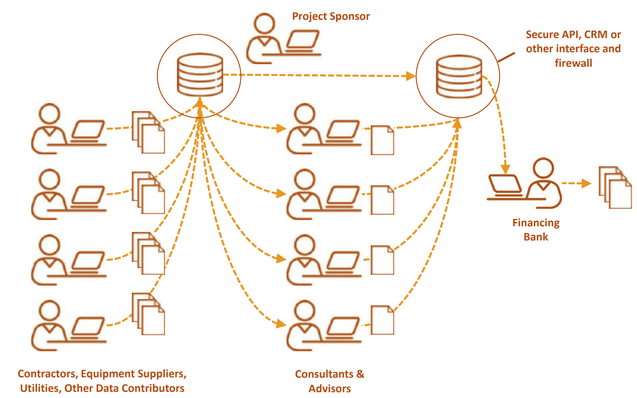
Each logical grouping (Cut Sheet, Operating Report, etc.) of Orange Button data is be placed into a JSON file as depicted here. The files then can be interchanged either via traditional file exchange techniques or automatically via data transmission through an Application Programming Interface (API). There are currently 152 logical groupings in the Orange Button Taxonomy. As mentioned, examples of logical groupings include, Inverter Cut Sheet or an Operating Report.



Logical groupings of concepts available in JSON files. Source: SunSpec Orange Button Open Source Community

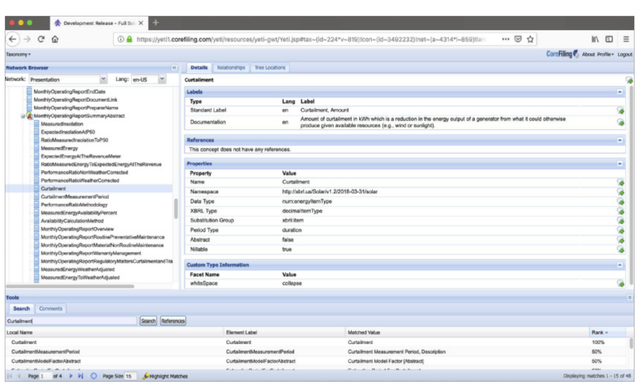
Example Use Case 1: Project Finance Data Flow with Orange Button

Data is entered once and then flows from business system to business system. Automated checks are done to identify errors. Data is reviewed by people along the way in business system user interfaces or via documents. Documents are generated as needed, e.g. contracts, Independent Engineer reports, appraisals.



Yeti Orange Button Taxonomy Viewer

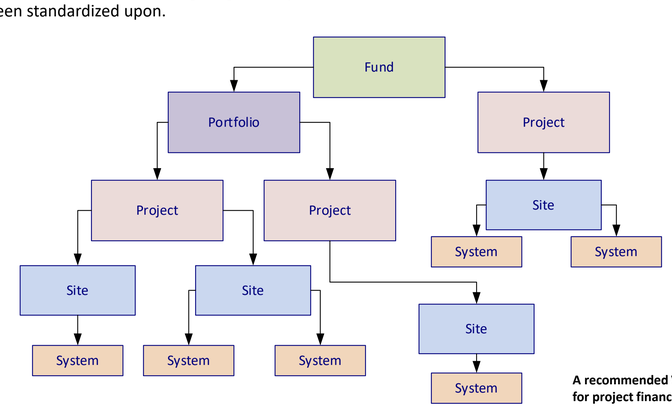
As mentioned, Orange Button Taxonomy has a large number (over 4000) of concepts that may be associated with a fact. The Yeti Taxonomy Viewer allows for lookup of any of these concepts along with metadata points describing each one. Concepts are grouped together into logical associations that represent commonly exchanged elements such as a Inverter Cut Sheet or an Operating Report. The viewer also facilitates group reviews of the Concept definitions during Taxonomy Design. Yeti allows for quick searches of concepts and can thus be used to translate old data to the Orange Button format.



The Yeti Orange Button Taxonomy Viewer. *Source: XBRL US*

The need for common Vernacular throughout renewables

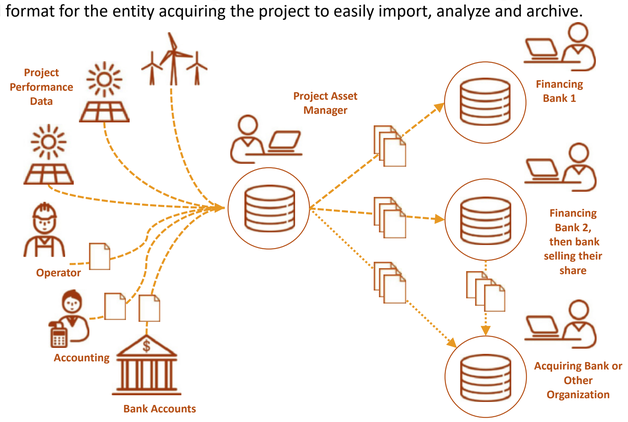
Although a common Taxonomy is a great start in moving to standards more work needs to be done. The industry needs to standardize on its vernacular for project financing. For instance if one reporting organization considers a site to be synonymous to a project while other organizations allow for multiple sites to be in a single project computer software cannot be built and reused throughout the industry in a consistent fashion. The following diagram depicts a recommended vernacular that could be (but has not yet) been standardized upon.



A recommended Vernacular for project financing

Example Use Case 2: Portfolio/Asset Management and Project Sales Data Flow with Orange Button

Monthly Operating Reports (MOR) are generated automatically by combining data from project monitoring systems and commentary from operator, asset manager and accounting business systems, then sent to banks. Other data, e.g. bank account information, insurance certificates are ported to the banks in a similar way. When a bank or the Asset Manager sells a project, economic and energy performance data is in a structured format for the entity acquiring the project to easily import, analyze and archive.



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 5 International Standards, 7 Technical Specifications and 1 Technical Report in 2018

IEC PV Standards published in 2018

IEC 61215-2: 2016/COR1:2018 Corrigendum 1 - Terrestrial photovoltaic (PV) modules - Design qualification and type approval - Part 2: Test procedures
IEC 61853-3: 2018 Photovoltaic (PV) module performance testing and energy rating - Part 3: Energy rating of PV modules
IEC 61853-4: 2018 Photovoltaic (PV) module performance testing and energy rating - Part 4: Standard reference climatic profiles
IEC 62446-1: 2016+AMD1:2018 CSV Consolidated version Photovoltaic (PV) systems - Requirements for testing, documentation and maintenance - Part 1: Grid connected systems - Documentation, commissioning tests and inspection
IEC 62892: 2018 PRV (Pre-release version) Extended thermal cycling of PV modules - Test procedure

Published Technical Report (TR)

IEC TR 63149:2018 Land usage of photovoltaic (PV) farms - Mathematical models and calculation examples

Requirements for Participation in IEC

Join your National TAG
In the US, this means joining ANSI TAG TC82
For more information, contact John Wohlgemuth at JWPVReliability@ieee.org

Amendment to IEC 61730 series

Add weathering tests per IEC 62788-7-2
Add measurement method for DTI
Add requirement for RTI/RTE for junction box and connector materials

IEC PV TS published in 2018

IEC TS 60904-13: 2018 Photovoltaic devices - Part 13: Electroluminescence of photovoltaic modules
IEC TS 62257-7-3: 2018 Recommendations for renewable energy and hybrid systems for rural electrification - Part 7-3: Generator set - Selection of generator sets for rural electrification systems
IEC TS 62257-8-1: 2018 Recommendations for renewable energy and hybrid systems for rural electrification - Part 8-1: Selection of batteries and battery management systems for stand-alone electrification systems - Specific case of automotive flooded lead-acid batteries available in developing countries
IEC TS 62257-9-5: 2018 Recommendations for renewable energy and hybrid systems for rural electrification - Part 9-5: Integrated systems - Laboratory evaluation of stand-alone renewable energy products for rural electrification
IEC TS 62738: 2018 Ground-mounted photovoltaic power plants - Design guidelines and recommendations
IEC TS 62915: 2018 Photovoltaic (PV) modules - Type approval, design and safety qualification – Retesting
IEC TS 62989: 2018 Primary optics for concentrator photovoltaic systems

New version of IEC 61215 series

Add cyclic mechanical load test before 50 thermal cycles
Add PID testing for crystalline Si modules
Explain how to test bifacial modules
Explain how to test flexible modules
Clarify the requirements related to power measurements.
Add weights to junction box during 200 thermal cycle test

ARESCA

American Renewable Energy Standards and Certification Association

< www.aresca.us >

IEC

IECRE

IECRE
SITE INSPECTION
DEMONSTRATION

George Kelly (ARESCA)
Steve Hogan (ARESCA)
Liang Ji (UL)
Matthias Heinze (TUV)
Kenny Villegas (Intertek)

NREL PV Reliability Workshop
Lakewood, Colorado, US
28-February-2019

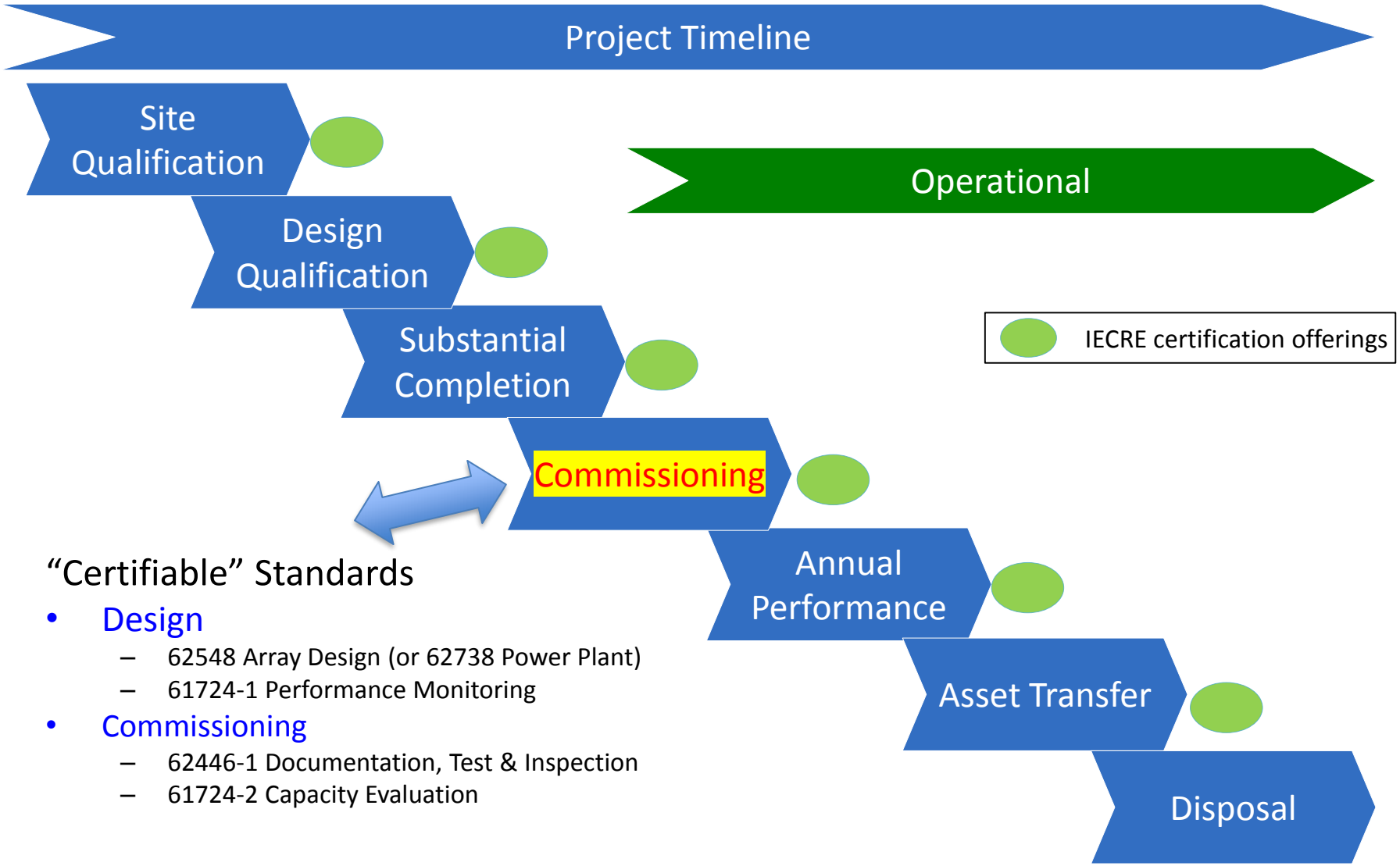
Questions?

Contact secretary@aresca.us

Statement of Work

- PVQAT and NREL have been working to help develop a comprehensive Photovoltaic (PV) system certification that includes review of the component design, installation, commissioning, operation, and maintenance.
- The International Electrotechnical Commission Renewable Energy Photovoltaic (IECRE-PV) system has been formed. Necessary standards and operating documents have been created.
- The next step to bring standardized system qualification to fruition is to demonstrate a pilot IECRE-PV certification of a system.
- Such a demonstration can encourage adoption of the system by showing the community how the certification process works and making recommendations for modifications to supporting standards and certification rules.
- The American Renewable Energy Standards and Certifications Association (ARESCA) coordinated inputs from the Solar Energy Industry Association (SEIA), NREL, Certifying Agencies, and other stakeholder groups to test the efficacy of IEC standards.

System timeline view



"Certifiable" Standards

- Design
  - 62548 Array Design (or 62738 Power Plant)
  - 61724-1 Performance Monitoring
- Commissioning
  - 62446-1 Documentation, Test & Inspection
  - 61724-2 Capacity Evaluation

Particpants

- During the demonstration project, three PV systems were inspected. These projects were chosen based on:
  - Size and type of system
  - Interest by the owners to pursue certification
  - Status of completion
- Of significant benefit (and coordination effort!) each one of the systems was owned by a different company and each was inspected by a different Certification Body.
- It was also significant to note that the PV owners who volunteered to be inspected were already following industry best practices, and in many cases exceeding the requirements of the international standards.

Sites

- Florida 75MW Fixed Tilt

- South Carolina 25MW Tracking

- California 1MW Carport

Summary of Findings

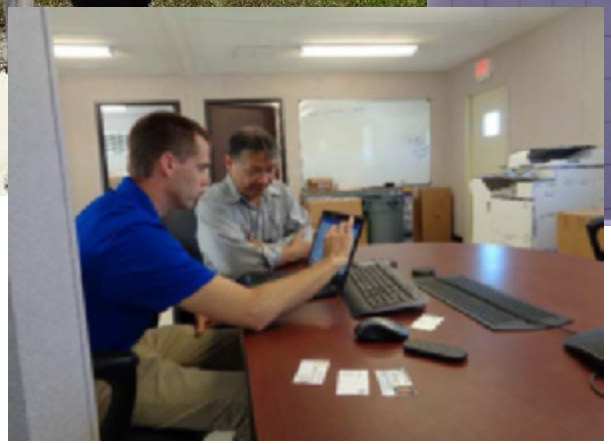
- Almost everything works well, conforms to standards, and generally looks nice

Vegetation management

Cable management

Arc flash hazard

- There are a few common problem areas



- There is a massive amount of data (maybe too much) available and monitored by competent personnel

Feedback to TC 82

TC82 WG3 - PV Systems

- There is an urgent need for additional guidance regarding vegetation control under and around PV arrays. This could be part of 62446-2 or the subject of a new standard.
- The design of arrays should include consideration of arc flash hazard for maintenance of combiner boxes, and a recommendation to keep hazard levels below thresholds which require extensive PPE.
- The number of various weather data sensors specified in 61724-1 seem excessive compared to existing practice, which is apparently more than sufficient.
- Trackers are generally not qualified to the 62817 (published by WG7). The WG should discuss the present requirements and consider whether modifications are needed to encourage more widespread use of the standard, as well as 63104 (Tracker safety qualification). It is likely there is a compromise between ideal performance and affordable best practices.

Feedback to TC 82

TC82 WG6 - BOS Components

- Cable management is an ongoing challenge which needs to be improved in general. The WG should consider standards for components such as cable ties, cable clamps and similar devices. Guidance on best practices for installation should also be developed, probably in conjunction with WG3 (62548 and/or 62738).
- Mechanical fasteners were found to be loose or missing in several cases, sometimes resulting in modules falling off the structure under wind loads. It is not clear whether WG6 should try to address this issue through component standards. It is likely that there are existing standards from other industries which apply to similar applications of threaded fasteners in metallic extrusions. Alternatively, there could be requirements added to the installation quality management standard (63049) which is under the responsibility of WG3.

Feedback to IECRE

IECRE WG401 - Rules of Procedure

- The relationship between Certification Bodies and Inspection Bodies should be more clearly described in the PV Rules of Procedure. This was a source of confusion for the participants

IECRE WG402 - Certification Requirements

- There should be a standard format for recording the results of PV system certifications, similar to the Test Report Form (TRF) used in the IECEE system. Under this project, we found that each CB had their own internally-developed format.

IECRE WG404 - Promotion & Marketing

- The certification requirements in OD-401 include several prerequisite certifications (62941, 63049 and 62817) that are not typically fulfilled. Until they become more widely available in the industry, these certifications should be either removed, made optional, or allowed for waiver.
- The amount of data required for capacity evaluation is not clearly understood. Each plant operator had plentiful data available, but each CB used a different method for selection of data. This should be specified in OD-401 or clarified in 61724-2, with collaboration from TC82 WG3.

Thank You

Questions?

Contact secretary@aresca.us

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

Materials forensics for understanding PV module materials durability

Laura Schelhas [1], Michael Toney[1], Stephanie Moffitt[1], Margaret Gordon[2], Patrick Burton[2], Andriy Zakutayev[3], Conor Riley[3], Peter Hacke[3], Nick Bosco[3] ,Robert Fleming[4], Corey Thompson[4], Pak Yan Yuen[5], Reinhold Dauskardt[5]

[1]SLAC National Accelerator Laboratory; [2]Sandia National Laboratory; [3]National Renewable Energy Laboratory; [4]WattGlass, Inc. ; [5]Stanford University

DuraMAT Capabilities

1. Data Management & Analytics, DuraMAT Data Hub
2. Predictive Simulation
3. **Advanced Characterization & Forensics**
4. Module Testing
5. Field Deployment
6. Techno-Economic Analysis

Capability Goals

- Develop advanced experimental methods to better understand module materials & interfaces
- Provide data to understand module failures/degradation
- Aid development of new and/or improved module materials by teaming with DuraMAT industrial & academic partners who provide materials for characterization

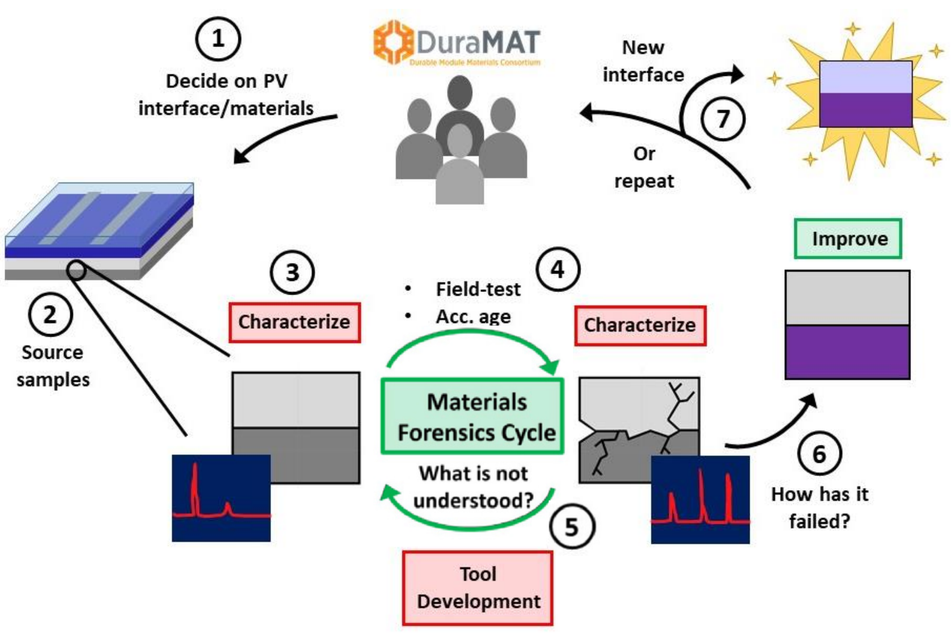
Accomplishments

- Collected data on anti-soiling coatings to determine durability after damp heat and abrasion testing
- Developed large area tools for rapid and reproducible characterization of coatings
- Publications investigating encapsulant/metallization interface degradation and backsheet failure mechanisms

Outcomes and Impact

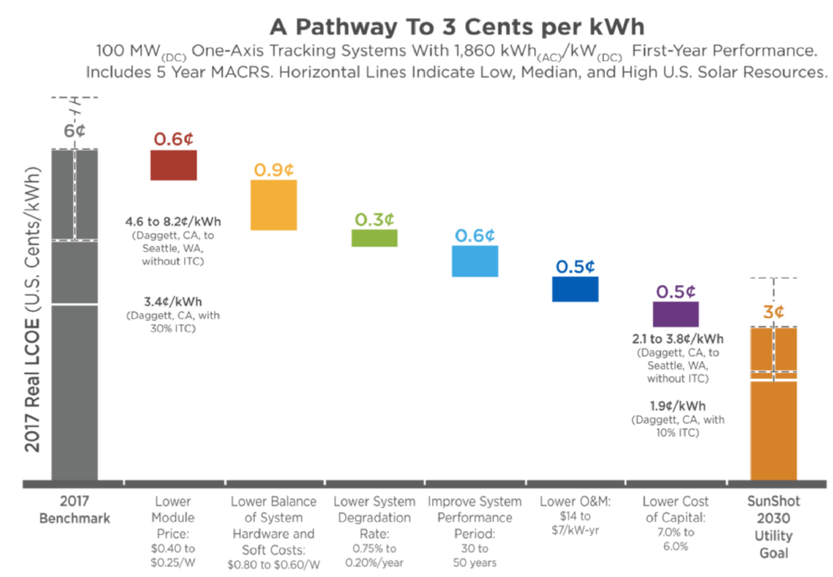
Short Term: Provide advanced materials characterization not currently available to DuraMAT stakeholders. This is used to rapidly inform their materials improvement and validation by providing high-quality, in-depth characterization of module materials
Long Term: The knowledge gained provides a path to improved materials design by DuraMAT stakeholders and may ultimately lead to the discovery of new materials and successful adoption of materials from other industries.

Capability Overview



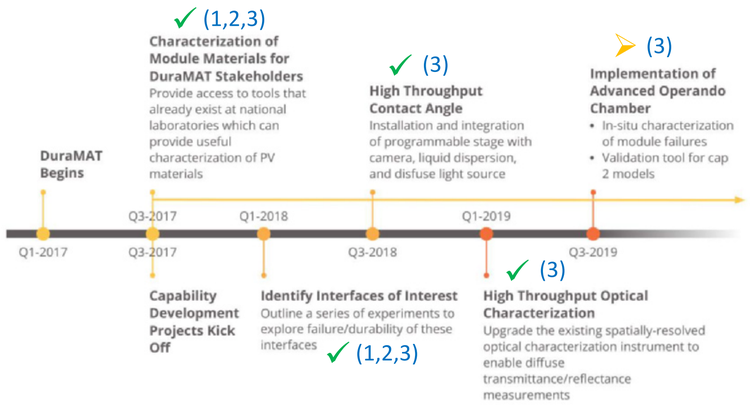
1. Discuss w/ **DuraMAT stakeholders**, identify essential interfaces/materials for further study
2. Source materials w/ technoeconomic value (**Cap6**) from **DuraMAT stakeholders**
3. Characterize pristine interfaces/materials w/ advanced tools available in Cap3. All data stored by **Cap1-Data Hub**
4. Stress interfaces/materials through field tests and/or accelerated aging in collaboration with **Cap4 and 5**, characterize and compare aged samples w/ pristine sample data
5. Reassess, if knowledge from steps 3 + 4 fails to identify the degradation mechanism, design new/improved/advanced tools
6. DuraMAT **stakeholders** use insight gained from characterization of pristine + aged samples in development of new materials, **Cap2** uses data for model validation
7. Assess results and impact, repeat cycle for further improvement or begin cycle again to identify new material/interface

Cost Drivers



Capability 3 Tasks & Timeline

- **General Characterization and Forensics (Projects 2 and 3)**
Provide access to characterization tools existing at national laboratories, including those outside the current DuraMAT team, and provide useful characterization of PV materials.
- **Interfaces and Surfaces (Projects 2)**
Apply interface and surface characterization tools and methods to understand and therefore mitigate failures at interfaces.
- **Advanced Characterization Techniques and Method Development (Project 1)**
Further understanding of failure + degradation mechanisms in module materials w/ development of new characterization techniques



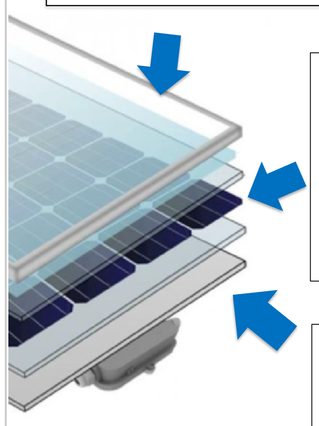
Interfaces and Surfaces

High priority PV materials and interfaces

3. Glass + Coating + Soil
Important problem areas:
- Durability
- Functionality

SAXS, XAFS, large-area characterization, soil printing

Industry SLOI: Advanced Multifunctional Coatings for PV Glass to Reduce Soiling Losses
BAPVC: New High-Impact Concepts in Solar Photovoltaic (PV) Module Packaging



2. Encapsulant + Metallization
Important problem areas:
- Delamination
- Corrosion

N. Bosco, S. L. Moffitt, L. T. Schelhas, "Mechanisms of Adhesion Degradation at the Photovoltaic Module's Cell Metallization-Encapsulant Interface," *Progress in Photovoltaics*, (submitted)

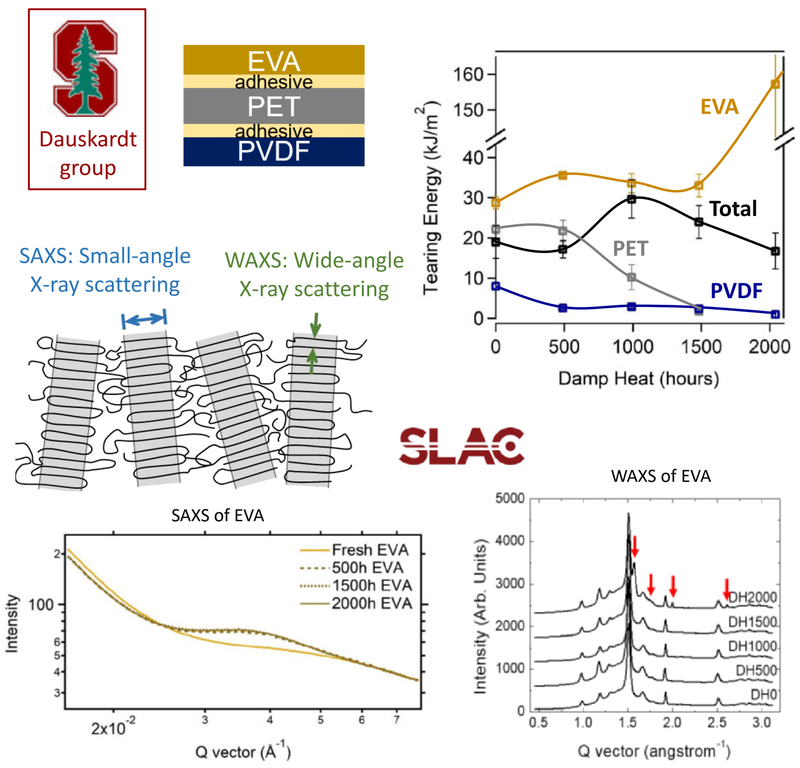
XPS

1. Backsheets (layered polymers):
Important problem areas:
- Embrittlement
- Adhesion

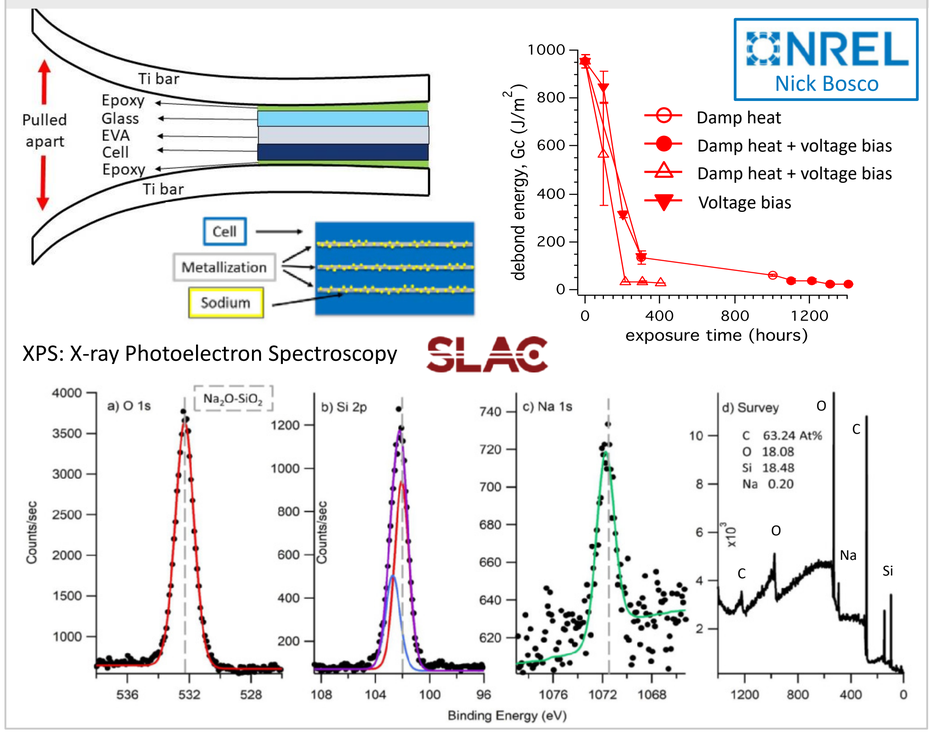
Pak Yan Yuen, Stephanie L. Moffitt, Fernando D. Novoa, Laura T. Schelhas, Reinhold H. Dauskardt, "Tearing and reliability of photovoltaic module backsheet structures," *Progress in Photovoltaics*, (in progress)

SAXS, WAXS

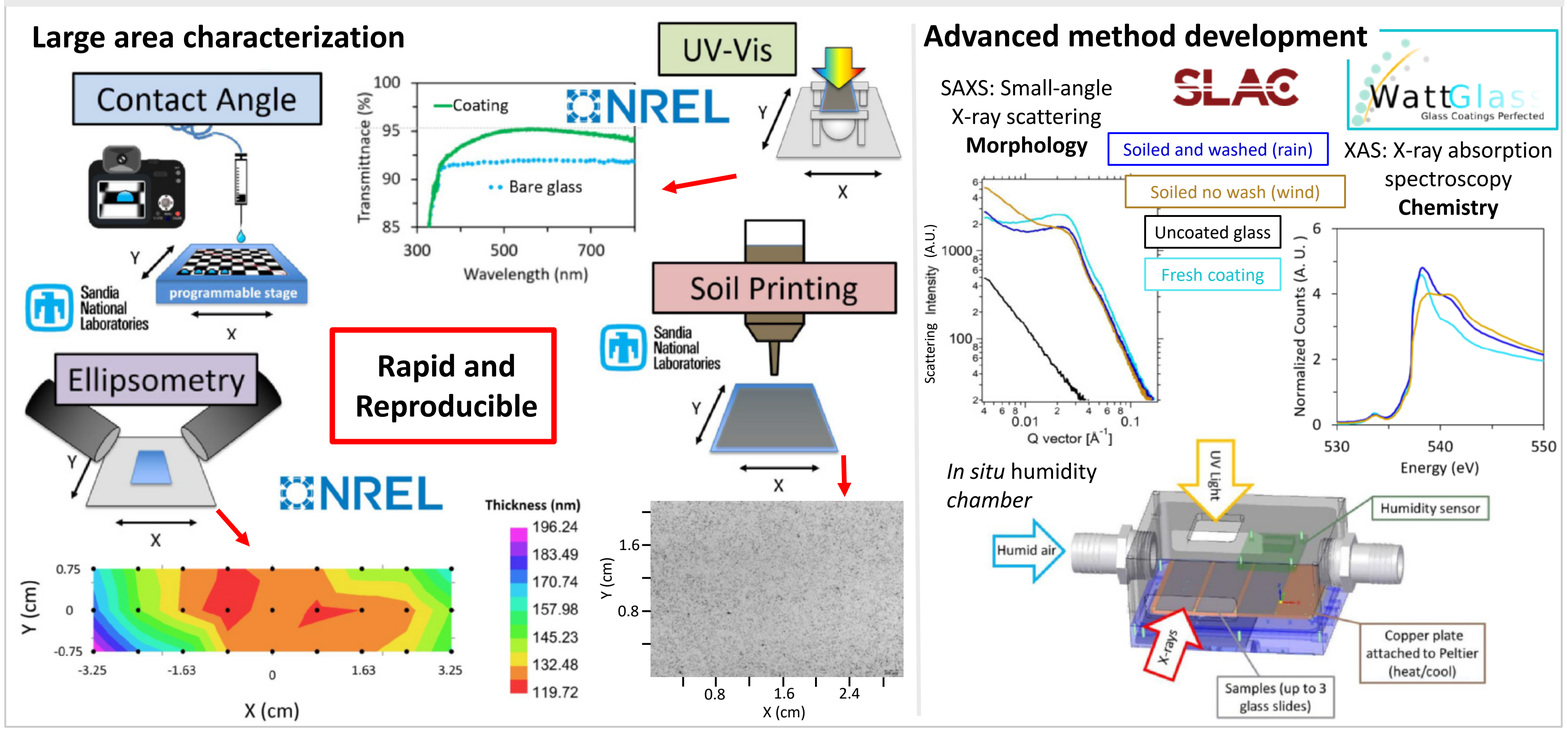
1) Backsheets



2) Encapsulant + Metallization



3) Glass + Coating + Soil



U.S. DEPARTMENT OF ENERGY · NREL NATIONAL RENEWABLE ENERGY LABORATORY · Sandia National Laboratories · BERKELEY LAB · SLAC NATIONAL ACCELERATOR LABORATORY

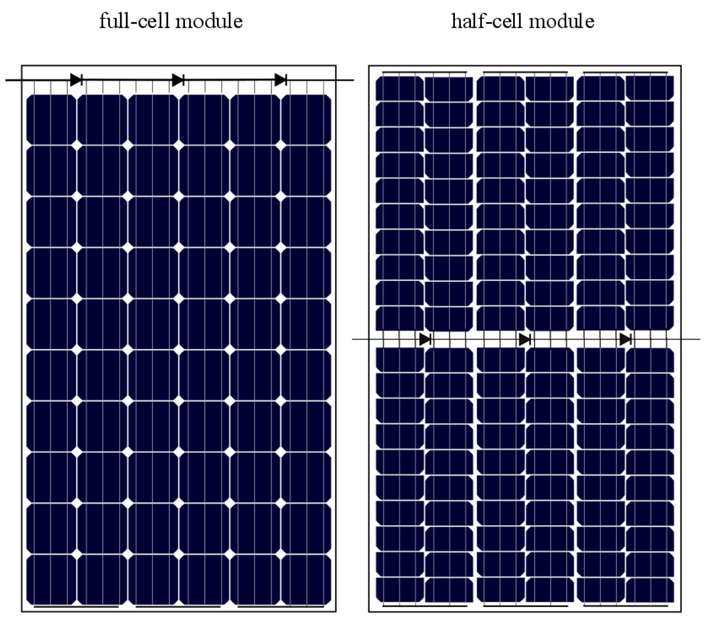
Hotspots in Half Cell Modules Undetected by Current Test Standards

Jiadong (Harry) Qian[1], Carlos Enrico Clement[2], Marco Ernst[1], Yong Sheng Khoo[2], Andrew Thomson[1], and Andrew Blakers[1]
[1]Research School of Engineering, Australian National University, Canberra, ACT, Australia
[2]Solar Energy Research Institution of Singapore, Singapore 117574
E-mail: jiadong.qian@anu.edu.au

- Solar module using half-cut c-Si cells and series-parallel-series cell connections have different hotspot effect from conventional modules.
- Hotspot effect in a half-cell module can occur when shaded by a similar area with a full-cell module .
- The peak temperature at the partially shaded cell in a half-cell module can be up to 19 °C lower than the full-cell module.
- Unshaded cells are reverse biased and generating heat when hotspot effect occurs.
- The most severe hotspot effect in a half-cell module occurs when two cells are shaded in separate cell-strings.

FULL-CELL MODULE VS HALF-CELL MODULE

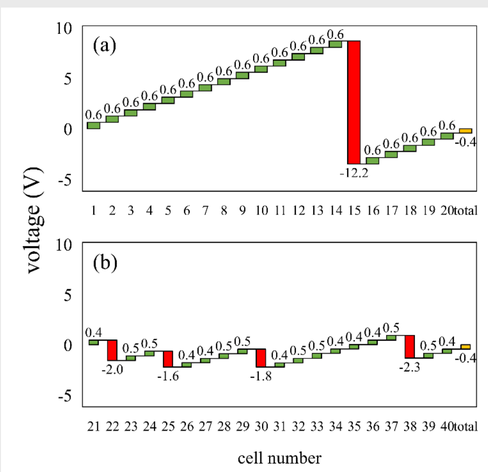
- Modules using half-cut c-Si solar cells have lower series resistance and better light management compared with conventional full-cell modules.
- To maintain similar current and voltage, a series-parallel-series connection is often used to keep the current-voltage output similar with full-cell modules.
- In a 120-half- cell module, each of the three bypass diodes is connected in parallel with two 20-cell strings to form one sub-module.
- Three sub-modules are then connected in series to form a module.

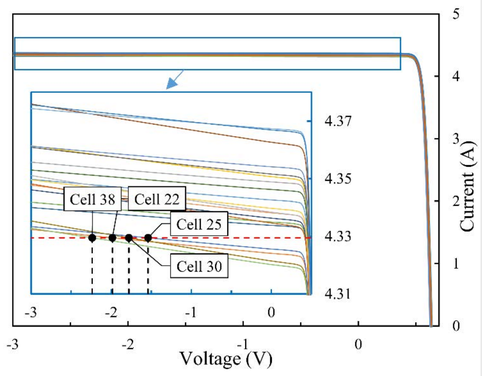


SIMULATION RESULTS AND HOTSPOT EFFECT AT UNSHADED CELLS

- Random half-cell parameters are generated. Cell 1-15 and Cell 16-20 are two parallel connected strings.
- A shade with variable area is simulated at Cell 15.
- When shade area is large enough, four cells among Cell 16-20 are reverse biased due to three constraints:
  1. Module operating current = the sum of the two string current;
  2. Parallel connected strings share the same total voltages;
  3. All cells in a string have the same operating current.

➢ The **weakest cells** in the unshaded string are reverse biased.



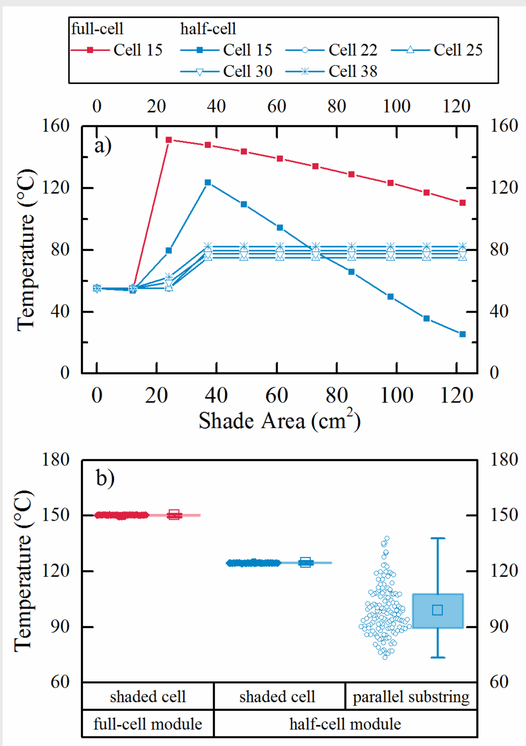


- The cell temperatures are simulated using Matlab in two-dimension.

➢ Although the heat dissipation intensity at hotspot area in a half-cell module is similar to the full-cell module, the relative cell size difference causes **up to 19 °C drop** in the peak temperature in a half-cell module compared with a full-cell module.

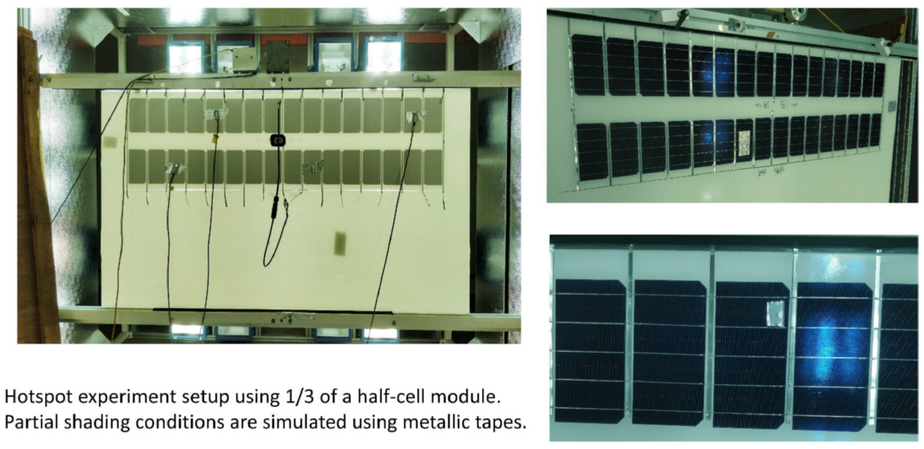
➢ The four unshaded reverse biased cells are simulated to be around **80 °C**.

➢ The peak temperature of the unshaded cell is correlated to the variance of cell I_{sc} and can reach as high as 130 °C in an unfortunate case.



EXPERIMENT VERIFICATION USING SUB-MODULE IN LIGHT SOAKER

- Sample modules are fabricated consisting 1/3 of either a full- or half-cell module. Connections to both polarity of each cell and the entire modules are made accessible.
- The modules are short-circuited and exposed to an irradiance of 1000 W/m² when one cell is shaded significantly.
- Module *I-V* scan is conducted to verify the electronic simulation and the operating voltages of all cells are measured at different shading conditions.



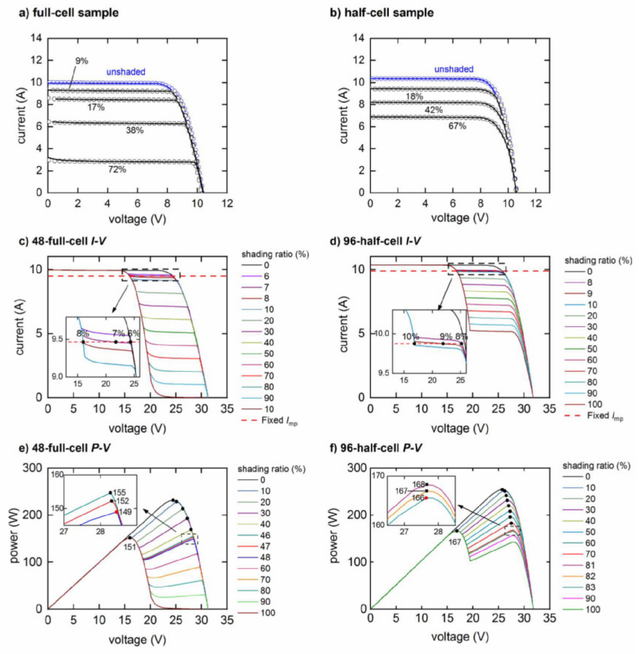
Hotspot experiment setup using 1/3 of a half-cell module. Partial shading conditions are simulated using metallic tapes.

MODULE OPERATION WITH DIFFERENT SHADINGS

- Full module *I-V* curves are simulated with different shading ratios on a cell to show the impact of maximum power point tracking on the bias at the shaded cell.

1. Using a string inverter, the operating current of partially shaded PV module is determined by the external circuit.
2. Using module level power electronics, the module operates at the maximum power point.

➢ Corrected for the cell size, the minimum shading area to cause reverse bias at the shaded cell is similar in both a full- or half-cell module.



IR IMAGES OF HOTSPOT EFFECT IN HALF-CELL MODULE

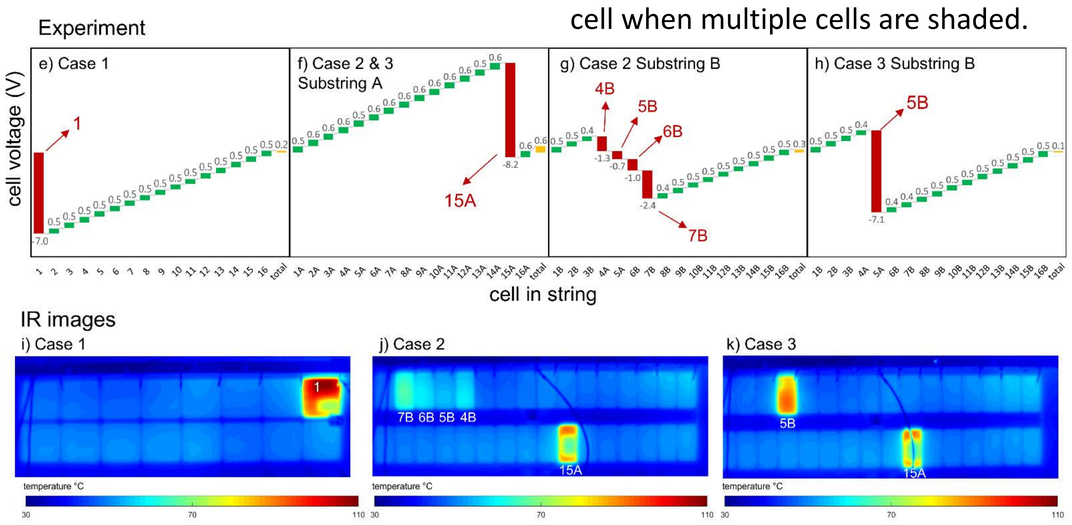
- Case 1, a cell in the full-cell module is shaded by 30%;
- Case 2, a Cell in Substring A of a half-cell module is shaded by 60%;
- Case 3, the cell in Substring A remains shaded and another cell in the parallel connected Substring B is shaded by 5%.

➢ Similar reverse bias at the shaded cells in both modules.

➢ Four unshaded cells are reverse biased in Case 2.

➢ Small shading would concentrate the reverse bias in the unshaded string.

➢ The worst-case hotspot effect in a half-cell module occurs at the slightly shaded cell when multiple cells are shaded.



Australian National University

Modeling Thermo-Mechanical Stress of Flexible CIGS Solar Cells

PURDUE UNIVERSITY NORTHWEST

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PNW School of Engineering

Introduction

- CIGS thin films for solar cell
  - Widely used for flexible solar cells
  - Bendable and rollable
  - Temperature effect and mechanical effect should be investigated
    - Annealing, External loading, and Hotspot

Flexible solar cells

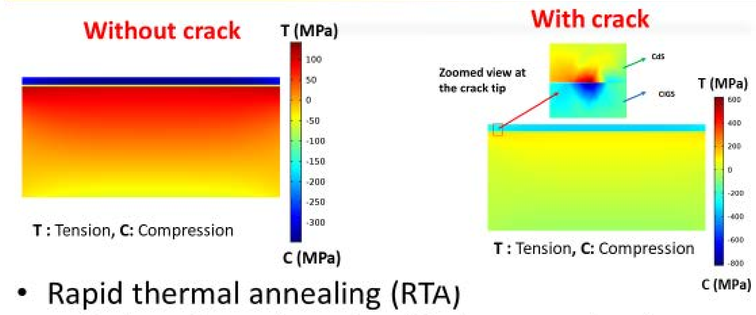
Rollable solar cells

Modeling of CIGS

- Composition
  - ZnO: 200nm
  - CdS: 50nm
  - CIGS: 3μm
  - Length: 10 μm
  - Plain strain condition
  - Linear elastic

	CdS	ZnO	CIGS
Young's modulus (GPa)	46	173	78.5 (average)
Poisson's ratio	0.344	0.33	0.35 (average)
Density (g/cm³)	4.8	5.6	5.9
Thermal expansion coefficient (10^{-6} K^{-1})	4.5	3.8 (average)	9.5 (average)

Annealing (Rapid Thermal Annealing)



- Rapid thermal annealing (RTA)
  - Activate dopant impurity with short annealing time
  - Ranges from 200 °C to 400 °C
- Thermal stress due to RTA
  - Cooling down to room temperature from RTA
  - With crack and without crack between CdS and CIGS

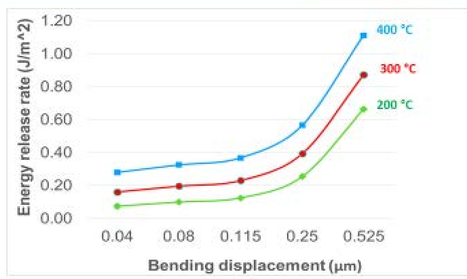
Thermal stress due to RTA

Stresses of CIGS cell after cooling down to room temperature from annealing at 400 °C. , C : Compression, T : Tension

	Stress with crack (MPa)	Stress without crack (MPa)
ZnO layer (Avg)	-257 (C)	-281 (C)
CdS layer (Avg)	-59 (C)	-66 (C)
CIGS layer (Avg)	18 (T)	20 (T)
Maximum stress for T	730 (T)	147 (T)
Maximum stress for C	-1063 (C)	-348 (C)

- Average layer stress
  - Compression in ZnO and CdS
  - Tension in CIGS
- Effect of a crack between CdS and CIGS layer
  - Crack decreases the stress of each layer

Effect of Bending on Energy Release Rate



J-integral

$$J = \int \left(W n_x - T_i \frac{\partial u_i}{\partial x} \right) ds$$

W is the strain energy density as described below

$$W = \frac{1}{2}(\sigma_x \varepsilon_x + \sigma_y \varepsilon_y + \sigma_{xy} 2\varepsilon_{xy})$$

T is the traction vector defined as

$$T = [\sigma_x n_x + \sigma_{xy} n_y, \sigma_{xy} n_x + \sigma_y n_y]$$

σ_{ij} is stress components, ε_{ij} is strain components, n_i is normal vector components.

- Energy release rate (G)
  - When G is lager than a critical value, crack propagates
  - Can be calculated using J-integral
- Higher annealing temperature results in higher G
- Higher bending force generates higher G

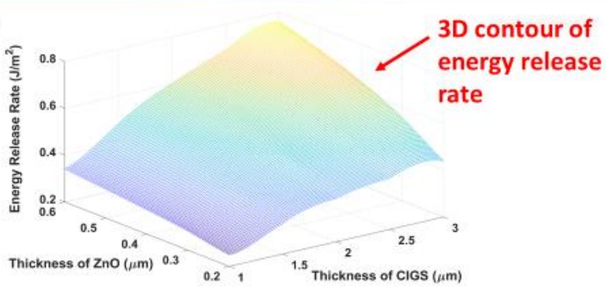
Thermal stress due to hotspot

- Hotspot
  - Increase the cell temperature
  - Tension in CIGS
- Effect of hotspot temperature on thermal stress
  - Crack decreases the stress of each layer

Stresses and J-integral of CIGS cell with an initial crack after cooling down to room temperature from various hotspot temperatures (using the cell with 400 °C annealing and 1% max bending). Unit of stress in MPa. C : Compression, T : Tension

Annealing temperature	200 °C	300 °C	400 °C
ZnO layer stress (Avg)	-133 (C)	-207 (C)	-281 (C)
CdS layer stress (Avg)	-33 (C)	-49 (C)	-66 (C)
CIGS layer stress (Avg)	9 (T)	15 (T)	20 (T)
Maximum stress for T	70 (T)	109 (T)	147 (T)
Maximum stress for C	-165 (C)	-256 (C)	-348 (C)

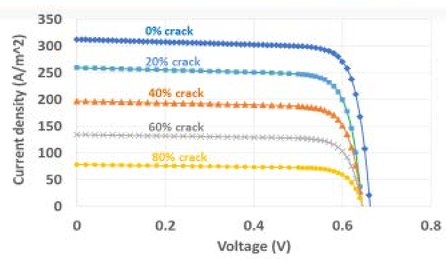
Effect of Layer thickness on Energy Release Rate



400 °C annealing temperature and cooling to room temperature, bending with 1% maximum strain followed by 400 °C hotspot temperature. Thickness of ZnO is 0.2 μm

- Quantitatively relate layer thickness with delamination probability
- The energy release rate of 3μm CIGS layer thickness is 1.8 times higher than that of 1 um CIGS layer thickness when the thickness of ZnO layer is 0.2 μm

Crack length effect on electrical performance



The effect of delamination percentage of CdS/CIGS interface on the electrical performance of the CIGS cell.

- As delamination (crack) length increases, short circuit current density decreases while open circuit voltage is minimally influenced by the crack size

Conclusion

- Effect of annealing temperature, bending loads, and hotspot temperature on the thermo-mechanical stress of each active layers was investigated for CIGS solar cells
- With higher annealing and hotspot temperatures, thermal stresses and energy release rate in the cell are higher when CIGS cell is cooled down to room temperature.
- Short circuit current density decreases as crack size increases. However, open circuit voltage is minimally influenced by the crack size.

DC Arc-Flash Risk in a Photovoltaic Plant

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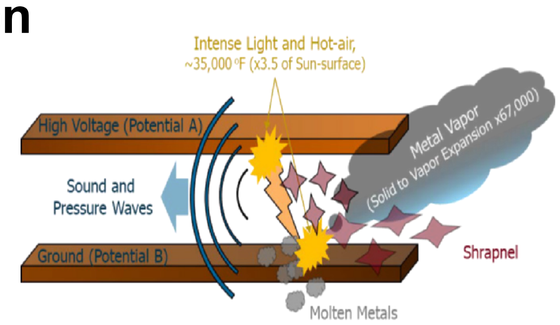
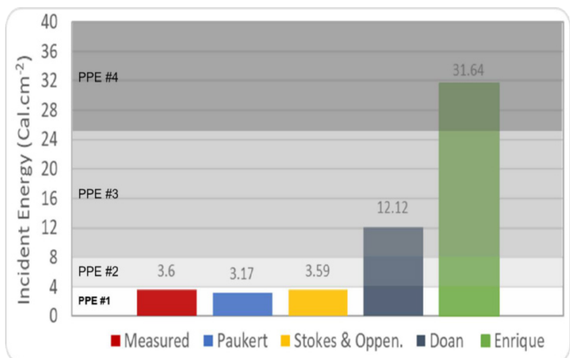
****National Grid, Waltham, MA, 02451**

I. Background and Motivation

- An ***arc-flash*** is a rapid release of thermal energy, pressure waves, and electromagnetic interference from a high-power electrical system, caused by unintentional shorting or equipment malfunction
- ***Incident energy*** (IE) quantifies the thermal hazard posed by an arc-flash and dictates what level of personal protective equipment (PPE) workers are required to wear when servicing equipment.
- Overly burdensome ***PPE*** may increase a worker's discomfort and decrease dexterity, while inadequate PPE also comes with increased safety risks.
- A very little is known about ***direct current*** arc-flash and its hazards. This is a significant knowledge gap, as an increasing number of dc systems are being deployed: solar photovoltaic



Arc-flash is hazardous to people and equipment



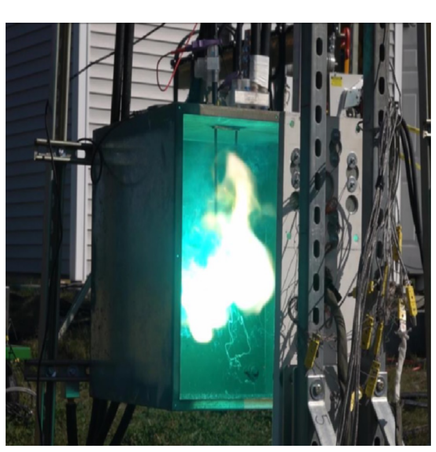
Incident energy spans multiple PPE categories depending on the calculation model used.

Category 1 | Category 2 | Category 3 | Category 4

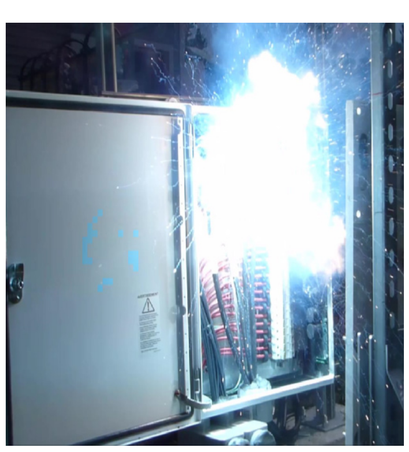
II. Objectives and Approach

This project intends to increase understanding of DC arc-flashes, their hazards in PV system, and codify results in IEEE 1584 by:

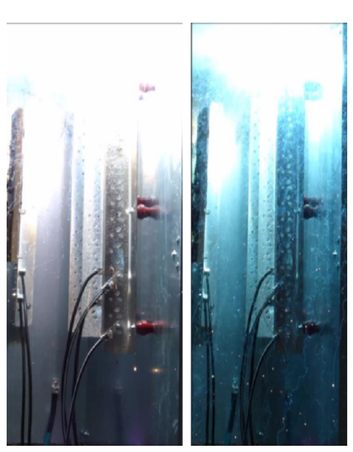
- Performing ***dc arc-flash experiments*** on actual and mock-up PV equipment in utility-scale PV plants and the laboratory.
- Developing detailed physics-based ***arc-flash models*** that corroborate lab tests and can aid equipment design; and
- Publishing an easy-to-use, publically-available ***incident energy calculator*** to more accurately predict *IE* of high-power equipment in utility-scale PV plants in utility-scale PV plants.



Arc-in-a-box: IEEE 1584 Test (20 in × 20 in × 20 in)



Utility-scale PV Combiner Box

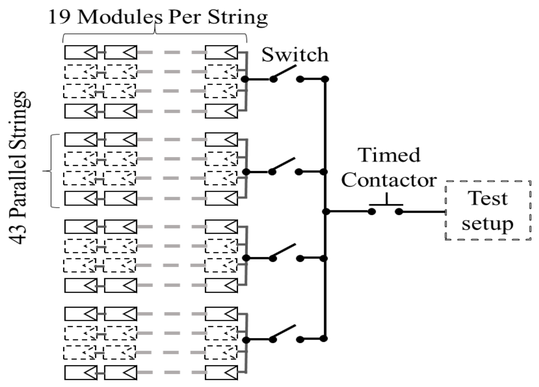


Utility-scale PV Inverter (Central), Mock-ups

We are seeking string inverters for arc-flash experiments. Non-functioning units ok!

III. Field Experiment Detail

- A series of arc-flash experiments were performed on a ground-mounted utility-scale, 1 MWdc PV plant.
  - 171 parallel strings with designed open circuit voltage (V_{OC}) of the array is 1,000Vdc.
- Arc-flash experiments were designed to measure *IE*, I_{Arc} and V_{Arc} for a test calibration box (20 in × 20 in × 20 in), an actual combiner box and a mock-up of a central inverter (1 MW).
- *IE* was measured using array of slug calorimeters based on ASTM 1959 and positioned at 18-inches from the arc-initiation point.

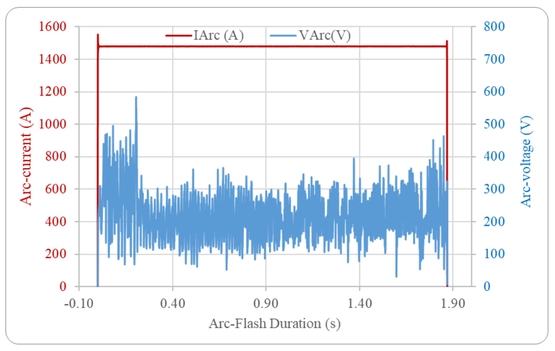


One-line diagram of the 1 MWdc PV array

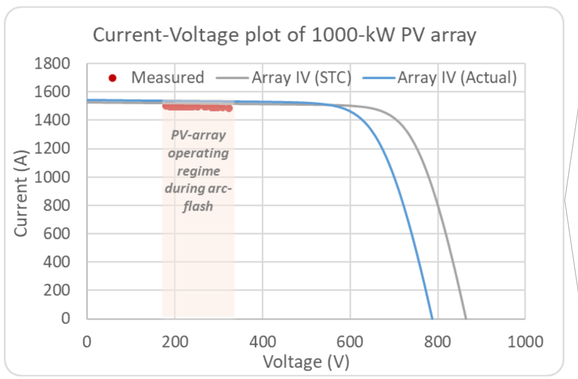
DC contactor and switches for control

IV. Key Findings

1. A sustainable arc-flash has been demonstrated using a PV array as the dc source with relatively constant I_{Arc} and fluctuating V_{Arc}.



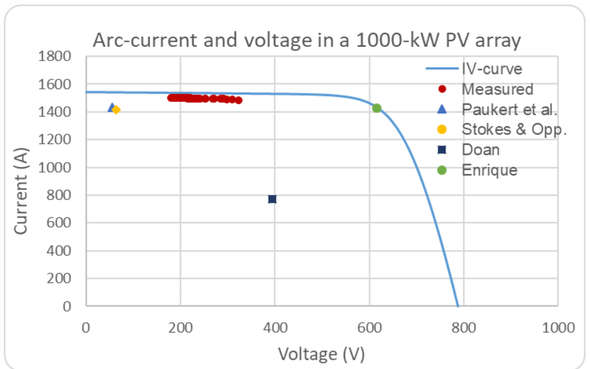
Time response of a I_{Arc} and V_{Arc} during an arc-flash



I-V curve of a PV array under arc-flash

2. PV array operates along the constant-current regime in the IV-curve with $I_{SC} < I_{Arc} < I_{MPP}$.

3. None of the simplified dc arc-flash models correctly predict the measured I_{Arc}, V_{Arc}, and *IE* values.



Measured and predicted I_{Arc} and V_{Arc}.

V. References and Further Resources

1. National Fire Protection Association, NFPA 70E, 2018.
2. R. Ammerman et. al, "*DC-Arc Models and Incident-Energy Calculations*," IEEE TIA, vol. 46, no. 5, pp. 1810, 2010
3. A. D. Stokes and W. T. Oppenlander, "*Electric arcs in open air*," Journal of Physics. D:, vol. 24, no. 1, pp. 26, 1991
4. J. Paukert, "*The Arc Voltage and the Resistance of LV Fault Arcs*," in 7th International Symposium on Switching Arc Phenomena, TU Lodz, Poland, 1993.
5. D. R. Doan, "Arc Flash Calculations for Exposures to DC Systems," IEEE Transactions on Industry Applications, vol. 46, no. 6, pp. 2299 - 2302, 2010
6. DC Arc Flash on Photovoltaic Equipment, Electric Power Research Institute, Palo Alto, CA: 2018. 3002014124.
7. Direct Current Arc-Flash Hazards of Solar Photovoltaic Systems, Electric Power Research Institute, Palo Alto, CA: 2018. 3002014641.

This work is funded in part by the U.S. Department of Energy Solar Energy Technologies Office, under Award Number DE-EE-0008156

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

Reliability of modules with high efficiency solar cells with copper plated contacts

(Arizona State University/QESST)

Joseph Karas[1], Archana Sinha[2], Viswa Buddha[2], André Augusto[1], Mani G. TamizhMani[2], Stuart Bowden[1]

[1]Solar Power Laboratory, Arizona State University, Tempe, Arizona; [2]Photovoltaic Reliability Laboratory, Arizona State University, Mesa, Arizona

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DuraMAT Capabilities

1. Data Management & Analytics, DuraMAT Data Hub
2. Predictive Simulation
3. **Advanced Characterization & Forensics**
4. **Module Testing**
5. Field Deployment
6. Techno-Economic Analysis

University Goals

- **We are evaluating Cu-plated module reliability by:**
- Testing modules with different encapsulants using the IEC61215 testing protocol:
  - POE vs. EVA; Glass-Backsheet vs. Glass-Glass
- Go beyond IEC protocol to observe failure mechanisms in Cu-plated modules

Accomplishments

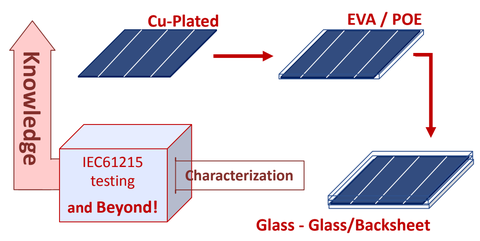
- ✓ Fabricate c-Si solar cells with Cu-plated contacts (BSF/PERC and SHJ), obtaining Ag-printed sister samples where possible.
- ✓ Fabricate 1-cell modules, varying encapsulants & backs.
- ✓ Perform detailed cell and module-level characterizations.
- ✓ Expose samples to environmental testing (85°C/85% DH and -40°-85°C TC)
- ✓ Post-exposure characterization.

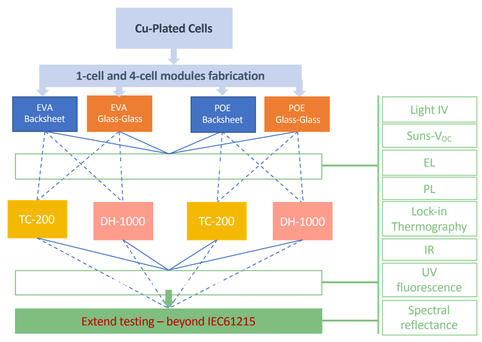
Outcomes and Impact

- Record c-Si solar cells have Cu-plated metal contacts.
- ITRPV stresses the importance of reducing Ag consumption for sustainable PV growth.
- There are very few reliability studies on Cu-plated modules.

➢ **This project aims to close that gap.**

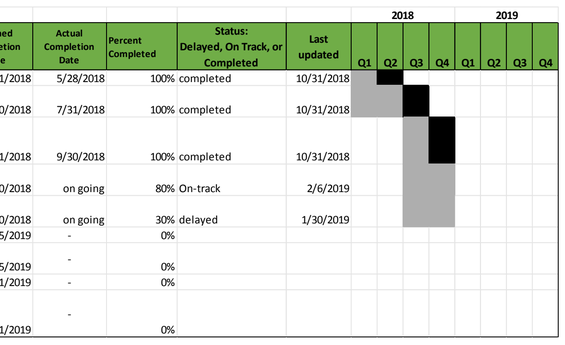
Capability Development



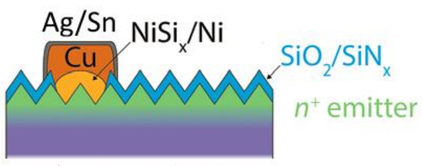


Timeline

Status	Milestone Description	Project Lead	Task Start Date	Planned Completion Date	Actual Completion Date	Percent Completed	Status: Delayed, On Track, or Completed	Last updated
Completed	Manufacture 1-cell ASU SHJ Cu-plated modules (Q1 and Q2).	Stuart Bowden	10/1/2017	3/31/2018	5/28/2018	100%	completed	10/31/2018
Completed	Perform reliability tests on 1-cell ASU SHJ Cu-plated modules (Q1, Q2, Q3).	Mani G. TamizhMani	10/1/2017	6/30/2018	7/31/2018	100%	completed	10/31/2018
Completed	Removal of cells from modules and characterization using EDS, Lock in thermography and photoluminescence to isolate the areas of reliability breakdown. (Q2)	Mani G. TamizhMani	10/1/2017	3/31/2018	9/30/2018	100%	completed	10/31/2018
On-track	Alteration of process sequence based on initial reliability results. Manufacture 4-cell SHJ Cu-plated modules (Q3, Q4, Q5).	Stuart Bowden	10/1/2017	9/30/2018	on going	80%	On-track	2/6/2019
Delayed	Perform thermal cycling reliability tests on 4-cell SHJ Cu-plated modules (Q3,Q4, Q5).	Mani G. TamizhMani	10/1/2017	9/30/2018	on going	30%	delayed	1/30/2019
New	Manufacture 1-cell modules with SHJ Cu plated cells. (Q5, Q6).	Stuart Bowden	2/15/2019	4/15/2019	-	0%		
New	Perform DH with bias on 1-cell SHJ Cu-plated modules to evaluate corrosion and PID (Q6, Q7)	Mani G. TamizhMani	4/1/2019	7/15/2019	-	0%		
New	Manufacture 1-cell SHJ Cu-plated modules (Q6, Q7).	Stuart Bowden	5/15/2019	7/31/2019	-	0%		
New	Perform DH with UV on 1-cell SHJ Cu-plated modules (Q7, Q8). This task requires NREL facilities. We are in negotiations with NREL (Q7, Q8)	Stuart Bowden / Mani G. TamizhMani /NREL	7/15/2019	10/31/2019	-	0%		

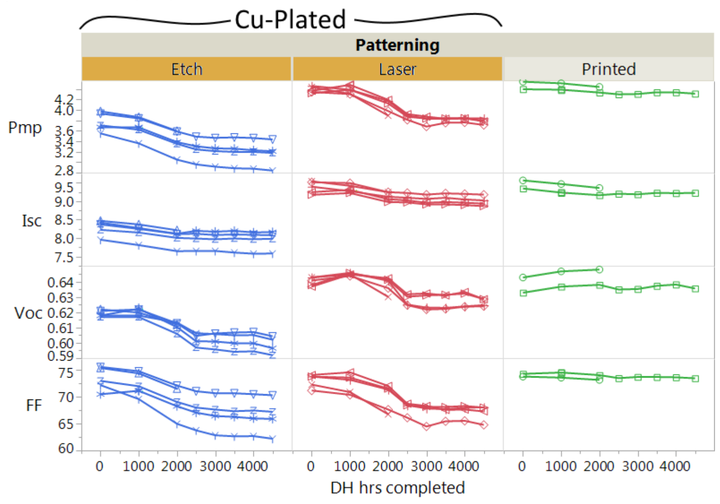


BSF Cells in DH- Effect of Contact Material

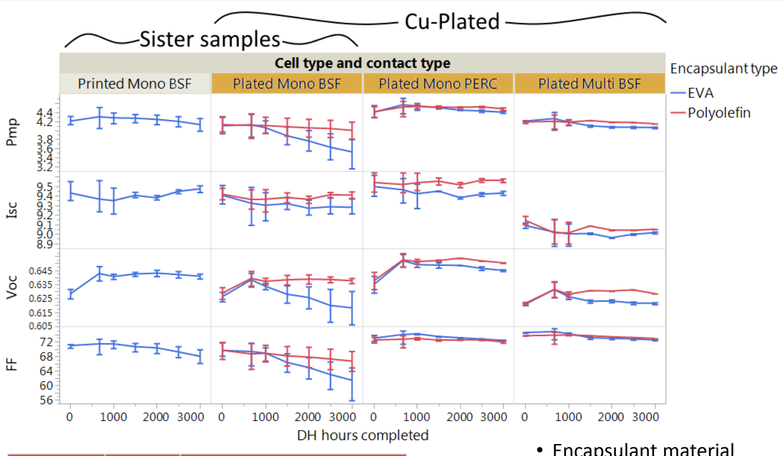


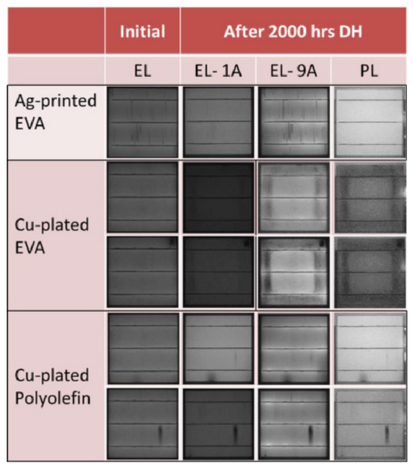
Adapted from Haschke et al., E&ES, 2017.

- Cu-plated samples degrade more than Ag-printed samples in extended DH.
- Degradation impacts Isc, Voc, FF. (previous studies show primarily FF loss from Rs increase)

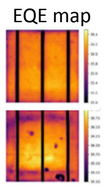


BSF Cells in DH- Effect of Encapsulant

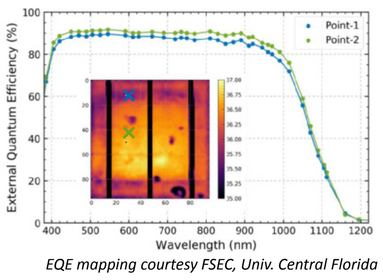




EQE map



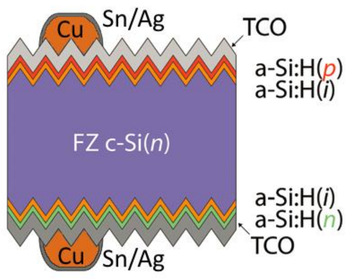
- Encapsulant material effects degradation:
  - EVA causes degradation in Cu-plated samples
  - POE prevents degradation
- Degradation occurs primarily at edges
  - Visible in EL, PL, EQE
    - Also ILIT/DLIT (not shown)
- EQE loss at perimeter occurs at all wavelengths



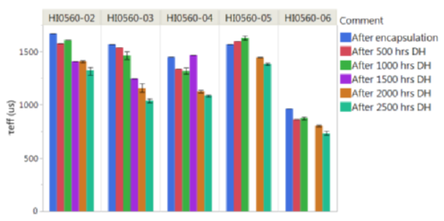
EQE mapping courtesy FSEC, Univ. Central Florida

- This suggests *increased junction recombination* at degraded areas as the primary reason for degradation. FF loss from increased *Rs* also plays a role.
- Physical mechanisms still unclear

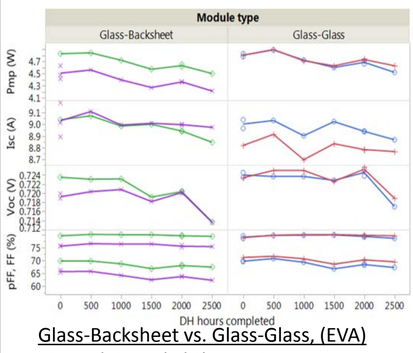
Cu-Plated SHJ Cells in DH

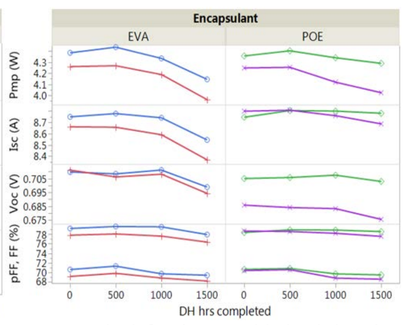


Adapted from Haschke et al., E&ES, 2017.



- Lifetime loss occurs in DH for SHJ precursors (encapsulated in EVA with permeable backsheet).
  - Suggests Voc/pFF loss in cells may occur, unrelated to contacts



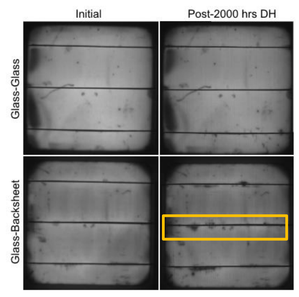


Glass-Backsheet vs. Glass-Glass, (EVA)

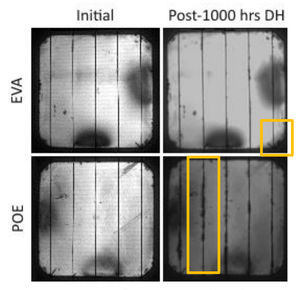
- Degradation slightly greater in G-BS (7% vs 4-6%)
- Primarily FF loss, some Isc & Voc loss
  - Similar losses between G-BS and G-G

EVA vs. Polyolefin, (permeable backsheet)

- Degradation greater in EVA (6-7% vs 2-5%)
- Roughly similar FF loss in all samples
  - EVA- greater Isc, Voc, pFF loss

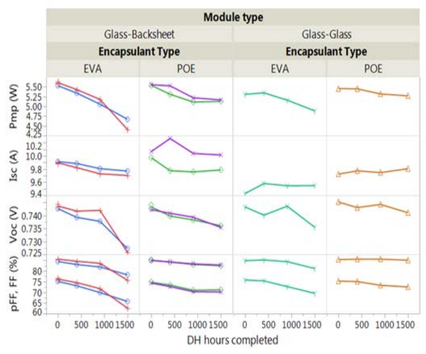


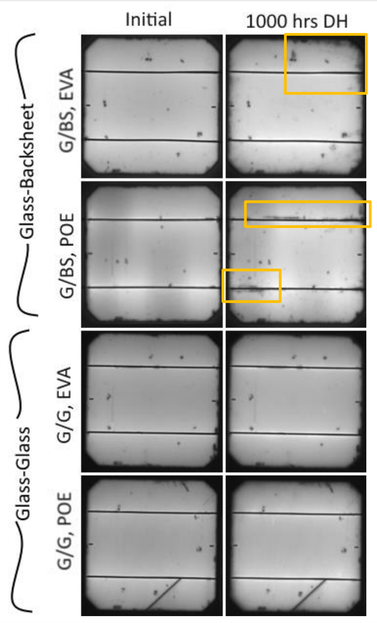
EL artefacts at busbars for glass-backsheet samples



EVA- artefacts at cell edges
POE- artefacts at busbars

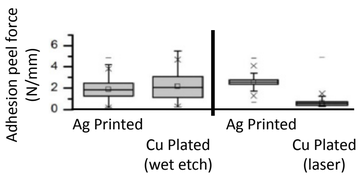
High Efficiency Cu-Plated SHJ Cells in DH



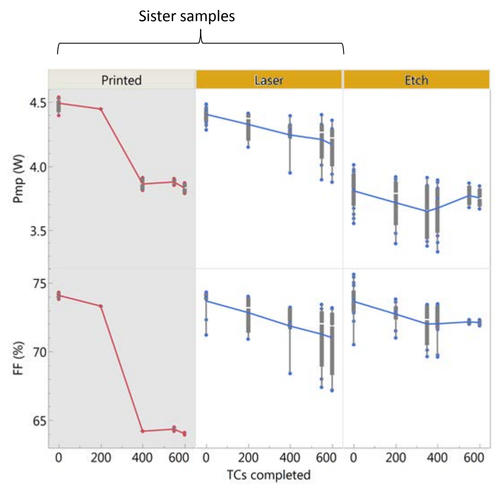


- Substantial degradation (6-10%) for Glass-Backsheet modules after 1000 hrs DH
  - Slightly worse for EVA
- EVA- EL artefacts at cell edges
- POE- EL artefacts at busbars
- Glass-Glass degrade less (0.6-2%)
  - Slightly worse for EVA
  - No obvious EL artefacts

Cu-Plated BSF Cells in TC

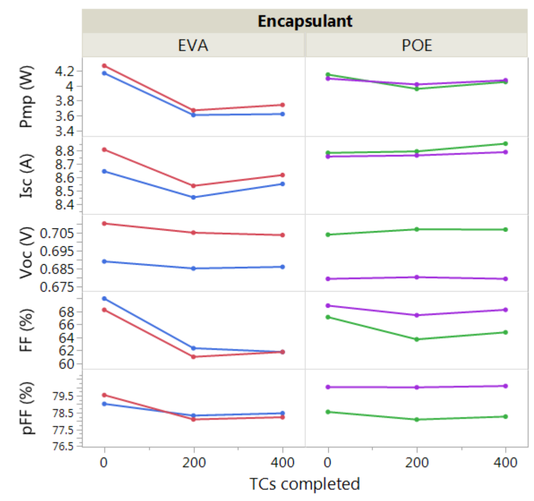


← Cu-plated contacts tend to have inferior adhesion (180° peel test)
- This can be improved in various ways

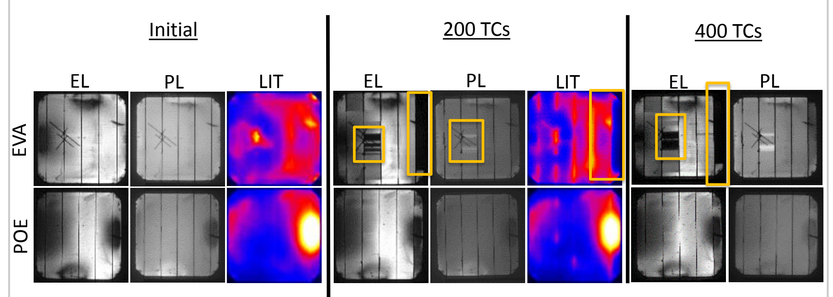


← Poor adhesion ≠ failure in TC
- No front contact delamination detected after TC 600+, even for adhesion <0.5 N/mm.
- Pmp loss for Cu-plated samples : 3-5% after 800 TCs.

Cu-Plated SHJ Cells in TC



← Cu-Plated SHJ cells in EVA *do* degrade substantially in TC (13-14% Pmp loss).
- Loss in FF, but also Isc, pFF
- POE-encapsulated samples undergo less degradation (0.5-2.6% Pmp loss).



- Initial passivation/ITO nonuniformities
- Dark artefacts in EL/light areas in PL
  - Suggest physical contact delamination -> electrical deactivation
- Do we expect more thermomechanical stress in EVA vs. POE?
- Some artefact changes also detectable in LIT?
  - Consistent with pFF changes

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Fast acquisition of UV-Fluorescence images and automated crack detection

William B. Hobbs[1], Braden Gilleland[1,2], Joseph B. Richardson[1,3]

[1]Southern Company; [2]Georgia Institute of Technology; [3]University of Alabama at Birmingham. Contact: whobbs@southernco.com

Southern Company

Introduction

Ultraviolet Fluorescence (UVF) is an emerging field inspection technique which enables the detection of cracks and other faults [1]. Köntges, Morlier, et al., have investigated the potential of UVF to detect cracks and hotspots, measure degradation in the encapsulant, and discriminate between new and old cracks [1]-[3]. They have developed and demonstrated a field system capable of imaging up to 200 modules/hour [1].

We present an updated design of a UVF field inspection system with a high-power UV source [4], capable of imaging 1000+ modules/hour, and an overview of an automatic processing utility capable of detecting cracks and accumulating plant-wide fault statistics.

Inspection System

The inspection system in shown in Fig. 1. A consumer camera with a large aperture and reasonable low-light performance was selected (Fuji X100F). The UV source is a standard external flash without UV-blocking coatings or lenses and a UV-pass/visible blocking filter. Long battery life, fast recycle times, and easy modification to remove UV-blocking elements are important. A monopod with a tilt head, handle, and a remote shutter release are used to position the camera above modules and take images.

The total cost is < $3500, weight is less than 4 kg, and the kit fits in carry-on luggage.

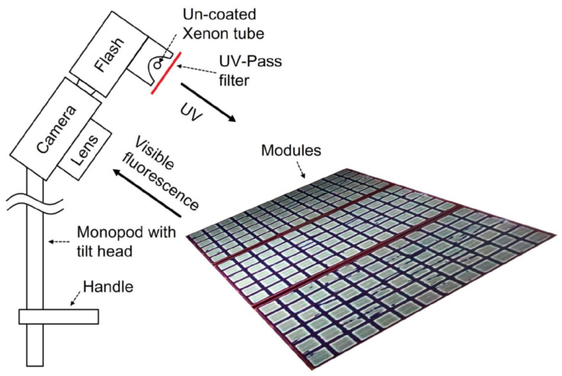

Fig. 1. Diagram of the UVF inspection system.

Automatic Processing Utility

Machine learning using TensorFlow's object detection API [5] was used to detect cracks. The processing workflow is illustrated in Fig. 2. Inputs to the machine learning model were simplified by segmenting images to individual cells. Cells were input into the detection model, which was built by retraining one of TensorFlow's Faster-RCNN models using a training set of cracked cells from a single site. This set contained 1,810 unique cracked cells, augmented 8 times to get a training set of 14,480 images.

The utility is planned to be made open source and was developed to be extensible to other PV sites. Check https://github.com/southern-company-r-d/OpenUVF in the coming weeks.

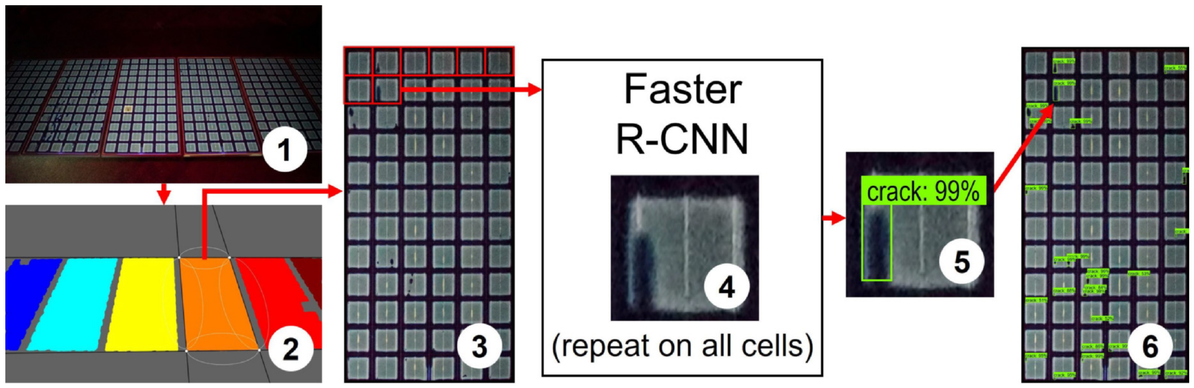

Fig. 2. Processing workflow steps, including 1) original image; 2) binarization, closing, and module segmentation; 3) perspective correction and cell segmentation; 4) TensorFlow F-RCNN crack detection; 5) detected cracks; and 6) module re-stitching.

Inspection Results

Multiple sites of various ages and manufacturers have been inspected. A subsample of results are shown in Fig. 3. Plants with older modules (1 and 2 in Fig. 3) exhibit a square UVF pattern, while most younger modules exhibit a ring (3, 5-6).

Throughput was measured at 4 sites and was consistently over 1000 modules/hr for single-module rows, and over 2000/hr for racking with modules mounted two-high.

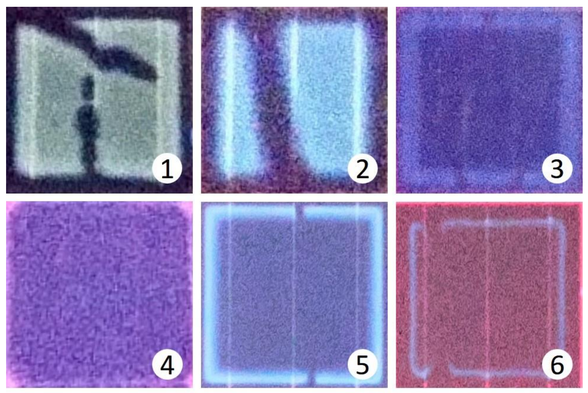

Fig. 3. Sample UVF profiles from 6 sites. Modules 1-2 manufactured 2011-2012, modules 3-6 2015-2017.

UFV was demonstrated to be able to detect what appear to be cracks along busbars, which are hidden under tabbing wires and not visible in electroluminescence (EL). An example is illustrated in Fig. 4, where busbar cracks are prevalent and bleaching occurs over some cells with no visible defect in EL. Additional destructive and non-destructive testing is planned to confirm the presence of these cracks.

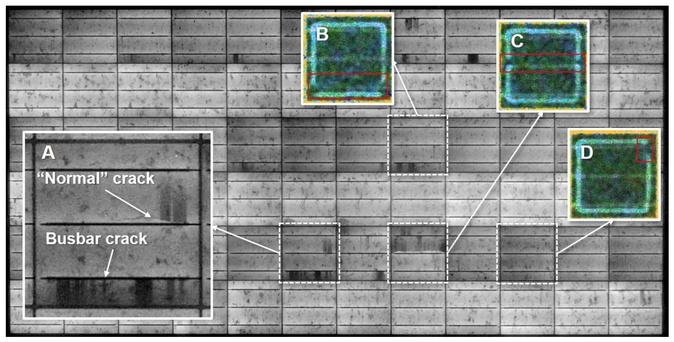

Fig. 4. EL of a module with UVF details. Highlighted cells show EL-visible cracks along busbars (A, B), normal cracks (A, C), and EL-hidden cracks (D).

Crack Age Estimation

A plant that was subjected to high winds was imaged using EL and UVF approximately 3 weeks after the storm (Fig. 5). Differences in UVF may be able to differentiate between cracks that existed before the storm and cracks caused by the storm. More testing is planned to explore this.

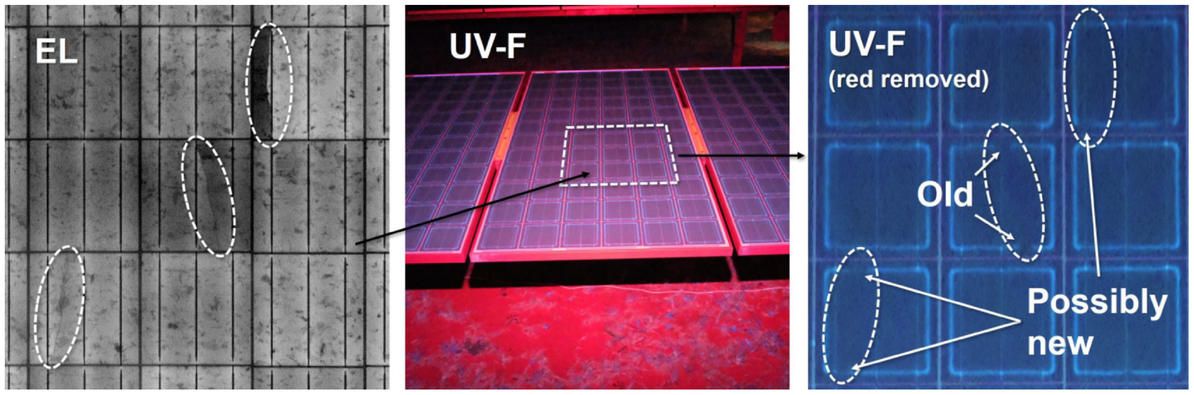

Fig. 5. Sample module with suspected storm damage. EL (left) highlights three cell cracks. UVF taken about 3 weeks after the storm (original image, center; processed, right) shows variation in bleaching of fluorescence that may differentiate old cracks from new ones.

Automatic Processing Results

Crack detection accuracy was 97.4% with a unique set of 3172 (augmented) cells, including a diverse set of image qualities and crack geometries. Module segmentation steps did not perform as consistently, only segmenting 60% of modules. Improvements to field protocols (i.e., camera alignment) could reduce most of this error, however improved segmentation may be needed. An example output of the entire utility is shown in Fig. 6, along with an EL image of the same module.

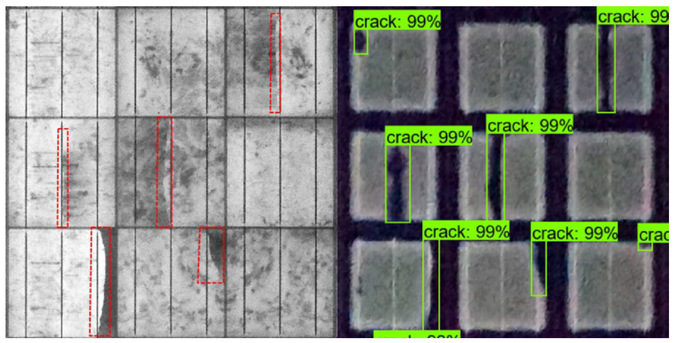

Fig. 6. Portion of a module in EL (left) and UVF (right). Cracks detected manually in EL are highlighted in red and cracks detected automatically in UVF are shown in green.

Conclusions & Next Steps

At over 1000 modules/hr and with automated processing, these systems could greatly improve PV inspections. Being a nearly 20X increase over to EL [6], UVF could be combined with IR and used to identify modules for EL, providing a more representative sample of a plant. While UVF has been demonstrated from drones [7], we believe our systems will improve drone applications, and use of a drone may improve our image segmentation reliability. More testing to understand crack age is planned and will greatly aide in insurance claims.

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[7] J. Lin, "Experience and challenges for UV fluorescence inspection with a drone", *ISFH UV Fluorescence Workshop*, Emmerthal, Germany, 2018.

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

Rebound-indent tester for photovoltaic backsheets

SLAC National Accelerator Laboratory

C. Mathew Mate, Laura T. Schelhas, Stephanie L. Moffitt

Description

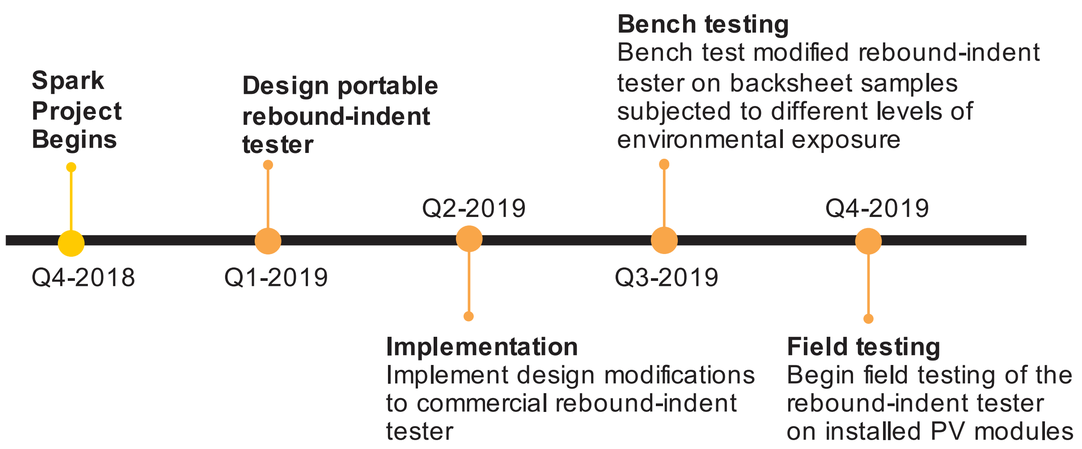
Spark project

- to develop a portable tester for characterizing the degree of mechanical degradation of the polymer backsheet on installed PV modules, and
- to develop a deeper understanding of how backsheet degradation occurs

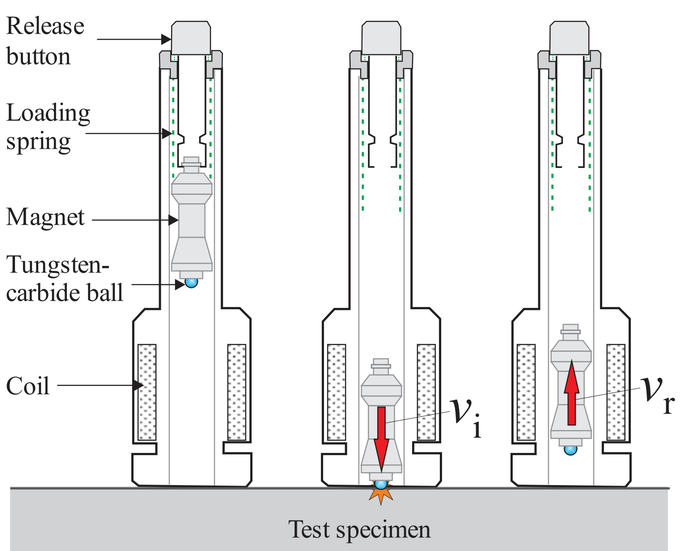
DuraMAT Capabilities

1. Data Management & Analytics, DuraMAT Data Hub
2. Predictive Simulation
3. Advanced Characterization & Forensics
4. Module Testing
5. Field Deployment
6. Techno-Economic Analysis

Timeline



How a rebound-indent tester works

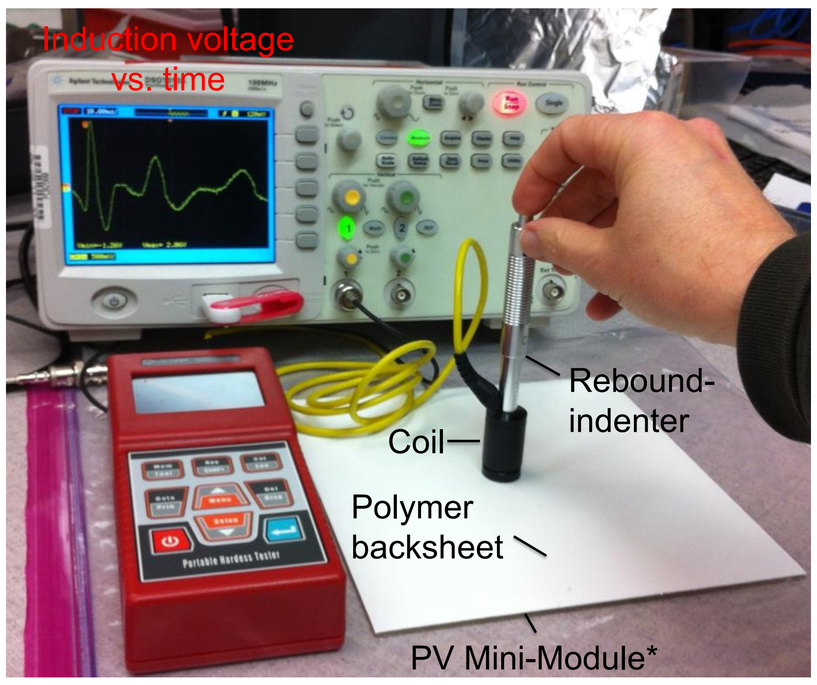


In a rebound hardness or indent test, an impact body with an indenter is spring loaded and then shot towards the sample specimen so that the indenter impacts the sample with a well-defined impact energy $E_i = ½mv_i^2$. The ratio of impact to rebound velocity v_r/v_i is equal to the ratio of the peak induction voltages on the coil during approach and rebound.

For metals, most of the energy loss is from plastic deformation.
➢ Leeb hardness, HL = $1000 \times v_r/v_i$

For polymers, most of the energy loss is from viscoelastic damping.
➢ Restitution coefficient, $\varepsilon = v_r/v_i$.

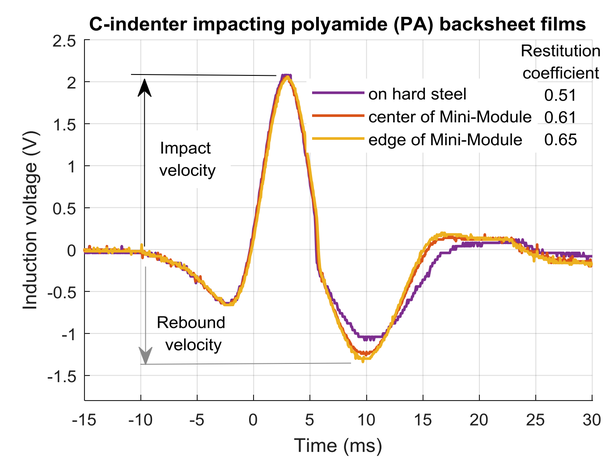
Initial implementation



*Mini-module provided by Michael Owen-Bellini, NREL

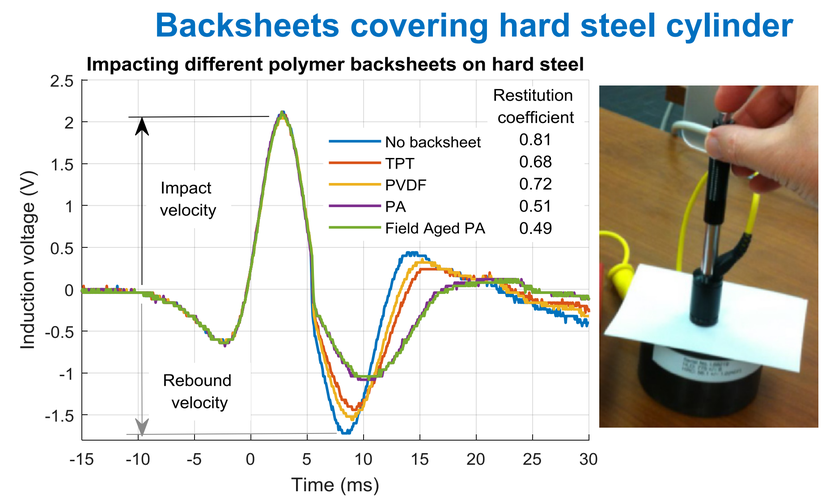
Initial results

Backside of mini-module



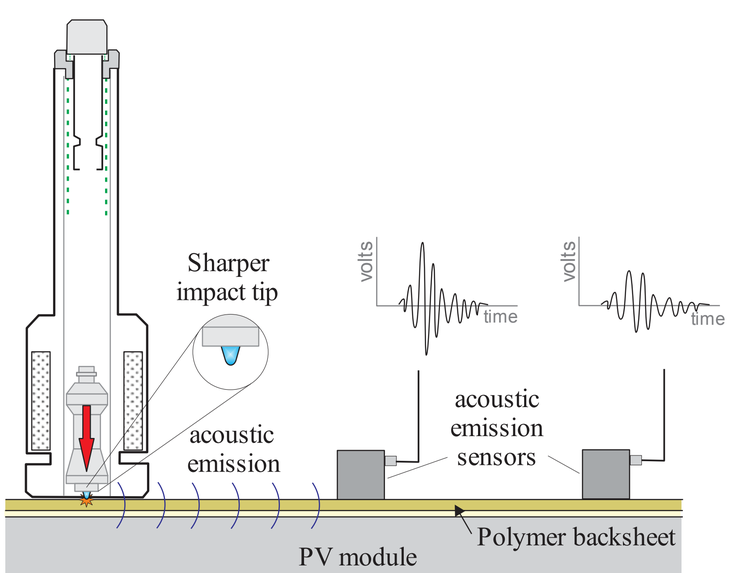
- The higher rebound velocity on the mini-module is probably due to the glass and PV cell having a higher elasticity than the hard steel.
- Slightly higher rebound velocity at edge of mini-module where the cell doesn't extend.

Backsheets covering hard steel cylinder



- Restitution coefficient ranges from 0.49 to 0.68 for the different polymer backsheets tested.
- Field aged and stress backsheets have almost the same restitution coefficients as fresh backsheets.

Intended modifications to rebound-indent tester



1. Modify impact body to have sharper indenter tip
   - ➢ This concentrates the contact stresses closer to the polymer backsheet
2. Place two acoustic emission sensors on the backsheet during test
   - ➢ This should allow for the measurement of the speed of sound and dispersion of the acoustic emission in the polymer backsheets.
   - ➢ This may also sense the formation of cracks during the impact. (The impact velocity will be reduced if crack formation is a problem.)

Future work

Correlate the results from the acoustic emission signals (speed of sound, dispersion, crack formation, etc.) to the degree and types of mechanical degradation in field-aged and lab-stressed backsheets.

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PHOTOVOLTAIK-INSTITUT BERLIN

LeTID INVESTIGATIONS ON PERC MODULES: A BENCHMARK TEST OF COMMERCIAL PRODUCTS

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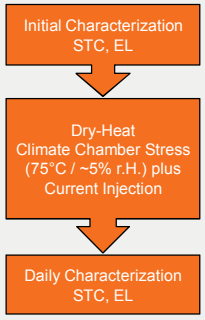
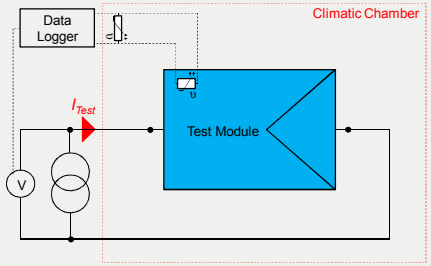
→ Introduction

Due to commercial pressure the speed of innovation in the photovoltaic industry is enormous. This is accompanied by very short development cycles for the manufacturers which, however, still have to guarantee the long-term stability of new products over many decades. This intrinsically leads to the risk that products may come onto the market which sometimes can show effects in the field that were not recognized during R&D.

One typical example is the PERC cell technology which has been introduced extremely quickly into mass production in recent years, and for which problems get reported in practical use. Here, a second type of light-induced degradation is the focus which became famous under the term LeTID in the literature. Many manufacturers report about having implemented measures in their production process that should suppress LeTID. However, LeTID degradation of a PV module in the field can take years which is the reason why laboratory test procedures are under development to allow a quick analysis of the effect. Most common now is to apply an injection current in the dark at elevated temperatures. In this publication we report about such measurements on different types of commercial PERC panels.

Experimental Setup





Module Type Acronym	Solarcell Technology
M1	mono c-Si
M2	mono c-Si
M3	mono c-Si
M4	mono c-Si
M5	multi c-Si
M6	mono c-Si
M7	multi c-Si
M8	mono c-Si

***Fig. 1*: Test sequenz and list of tested modules**

We have tested 5 pcs. each of eight commercial PERC module types (multi and mono c-Si). The modules were stressed at 75°C / ~5% r.H. with different injection currents of I_{Test} = (0.0A, 0.5A, 2.0A, 5.0A, 10A) which were applied to the panels. Modules are characterized daily, and module temperature and the module voltage are monitored.

Results and Analysis

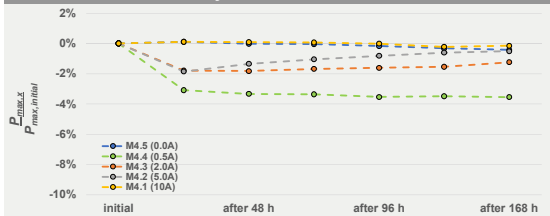


***Fig. 2*: Power degradation at STC**

Figure 2 shows an example the power degradation curves of module type M4 as the function of injection current level and stress time. Depending on current level the power minimum occurs after different stress times. The real power loss at higher currents may be greater than shown here, since the degradation process in such cases is much faster than the measurement interval. Degradation is followed by a regeneration phase.

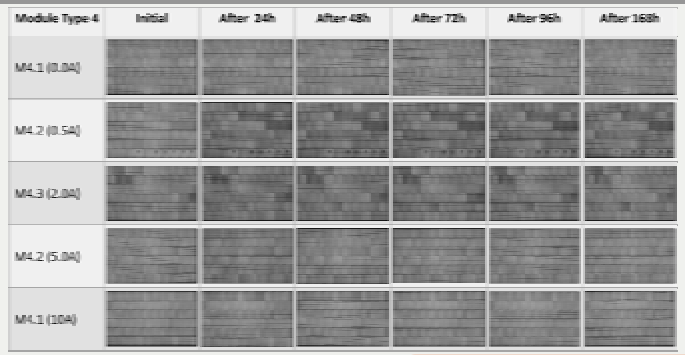


***Fig. 3*: Electroluminescence analysis**

The EL images are also shown for the module type M4. With increasing current injection level and stress time the image contrast gets less pronounced. This correlates well to the previously displayed power measurements, i.e. a fast recovery at high current injection levels.

However, at I_{test} = 0.5A the module´s EL images show nicely a changing intensity which reflects the LeTID effect.

in-situ Module Voltage Logging

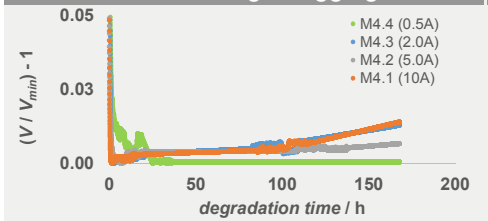


***Fig. 4*: *in-situ* voltage measurements at module type M4**

At high current levels the voltage seems to be stable close to its initial value. Better resolution indicates that after a very short power loss the module already recovers. At lower currents we first see a voltage drop (= degradation) followed by slow a voltage increase: the recovery process.

LeTID Benchmark

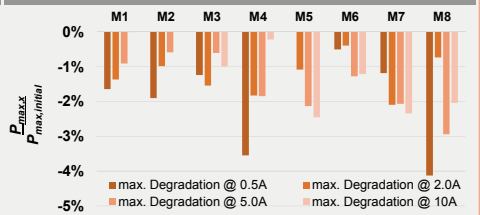


***Fig. 5*: Overview about all module results**

The graph summarizes all test results after 168 hours. All tested modules are LeTID sensitive with their maximum degradation occuring at different current levels. For low injections currents multi-c-Si products (M5 and M7) seem to be slightly higher affected than mono c-Si panels.

→ Conclusions

- **We tested 8 different types of commercial PERC-Modules (2x multi c-Si & 6 mono c-Si). The test conditions were 75°C / ~5% r.H. with different current injection levels (I_{Test} = 0.5A, 2.0A, 5.0A, 10A). In parallel we logged the voltage drop at the modules during the stress.**
- **For all products we detect LeTID with maximum degradations varying between -1% and -4%. Maximum degradation depends on current level and current injection time.**
- **The in-situ voltage logging indicates that at high current levels the modules recover quickly. However, for a better resolution we need to further improve our test setup.**
- **For low injection currents multi c-Si seems to behaves slightly worse that mono c-Si**
- **LeTID gets reflected in the EL image. The EL intensity change correlates nicely with the module power loss.**

TECHNICAL BANKABILITY OF NOVEL PHOTOVOLTAIC TECHNOLOGIES

Technology Advisory Practice, ICF International Inc.

Vardaan (Dan) Chawla, Todd Tolliver, Leah Holton, Mark Reusser

What is Technical Bankability?

When considering investment, lenders and investors require various levels of diligence when considering novel technologies. Novel products are considered "financeable" or "bankable" by lenders or investors once they have demonstrated their capabilities sufficiently so that financiers no longer assign additional risk compared to existing products in the market. Consistency and predictability in the performance of a product is key to its financeablility, most notably its energy yield, reliability, degradation rate, and its useful life, all of which are used by the financiers to prepare the financial model for the project. Initial energy yield estimates are used by financiers to set the baseline revenues expected from a project. Reliability is a key metric for the technical bankability of a product as it predicts the number of unplanned outages the facility might experience between planned maintenance intervals. Predictability in the degradation rate is another key aspect of financeability in that uneven or unpredictable degradation rates creates uncertainty in the revenues later in the project. Finally, the useful life of a product is a key issue for financiers in that the life of the facility must exceed the term of the debt, but has recently become a major topic of concern for owners who intend to generate revenues with the asset for a decade or more beyond the term of the debt.

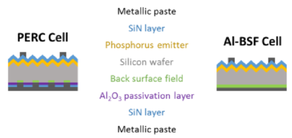
Why is it challenging for novel products?

How to address issues of predictability, reliability, degradation rate, and useful life can be especially challenging for new products as they do not have the field history of existing proven products. Financiers, often supported by Independent Engineers, consider the experience of the designers/manufacturers, accelerated testing and similarity to conventional products to help support their investment decisions.

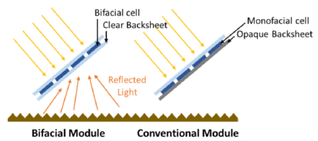
Case Studies

We will look at the cases of PERC, Bifacial, Glass-Glass, Shingled and Half Cell modules, the risks associated with them that have been addressed, and the gaps that need to be closed before they may be financed without assignment of additional risk.

PERC Modules



Bifacial and Glass-Glass Modules



Half Cell and Shingled Modules

Half Cell Shingled

Introduction to ICF International

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 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 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.

PERC Solar Cells and Modules

In 2018, PERC technology spread across the solar industry and by some estimates, now makes up 30-40% of the worldwide module manufacturing capacity. At the end of 2018, the ten largest crystalline silicon module manufacturers all offered a monofacial PERC module product.

Technical Bankability Concerns

The PERC cell is different from a conventional Al-BSF solar cell in that there is an additional passivation layer added to the rear surface of the silicon substrate. This is an incremental and cost effective improvement in the cell design, but can create some additional risk.

Bankability Concern	Risk Level
New Materials Al_2O_3	Low
Additional Manufacturing Steps Rear Side Passivation and Rear Contact Opening	Low
Traditional Degradation Mechanisms LID, PID, Annual	Low
Light and Elevated Temperature Induced Degradation (LeTID)	Medium

The bankability concerns associated with new materials and manufacturing steps as well as the traditional degradation mechanisms like LID, PID etc. have been generally addressed for PERC modules. The critical bankability gap that remains is LeTID.

Light and Elevated Temperature Induced Degradation

Multiple research groups have shown that both multi-crystalline and mono-crystalline PERC modules can degrade when exposed to both light and temperatures above 50˚C. In 2018, the industry made significant progress to address this issue.

- There is now a push to introduce LeTID specific testing to the IEC 61215 standard.
- Most third party testing laboratories now offer LeTID specific testing, which is being utilized by some module manufacturers.
- Many module manufacturers have recently published overviews of their mitigation strategies for LeTID.

Half Cell and Shingled Modules

In Half Cell modules, a fully processed cell is cut into two smaller cells and interconnected to reduce the current, and as a result, the resistive loss in the module. Shingled modules are an extension of the Half Cell concept, except that the cells are typically cut into multiple smaller cells (5-6) and then interconnected.

Technical Bankability Concerns

While Half Cells are smaller than conventional cells, they interconnect using the same materials and equipment, which reduces the risk associated with them. Shingled modules introduce new materials (conductive adhesives) and manufacturing steps (interconnection).

Bankability Concern	Risk Level	
	Half Cell	Shingled
Design changes Junction box, electrical design	Low	Low
New Materials Conductive adhesive (shingled)	Low	Medium
New Manufacturing Steps Cell laser cutting, interconnection (shingled)	Medium	High
Failure Modes and degradation Microcracks, hotspots, long term performance of conductive adhesives (shingled)	Medium	High

Cell Cutting

Typically cell cutting is accomplished by scribing with a laser and then applying a mechanical force to break the cell in half. The mechanical stress has the potential to cause microcracks which can lead to additional degradation in the module. Additionally, the cut edge of a cell is typically un-passivated, which can lead to a risk of shorting if not appropriately addressed.

Conductive Adhesives

While conductive adhesives have been used extensively in the electronics industry, they are new to the solar industry. Data related to the long term performance of these adhesives in solar modules is limited.

Bifacial and Glass-Glass Modules

"Bifacial modules"—one of the hottest topics in the solar industry today—is a generic term for photovoltaic devices that can absorb sunlight from both the front and rear surface. Additional energy gains of up to 25-30% have been reported by the use of bifacial modules in solar power projects, but these claims have yet to be proven on a large scale.

Technical Bankability Concerns

The rear surface of a conventional Al-BSF solar cell is typically an aluminum layer that does not allow for the transmission of light. In a bifacial module, the rear surface of the cell and module must be changed to a transparent material.

Bankability Concern	Risk Level
Module Design Changes Rear side glass, thinner glass	Low
Cell Design Changes Screen print, aluminum paste	Low
Traditional Degradation Mechanisms LID, PID, Annual	Medium
System Level Simulation Software, correlation with field performance	Medium
System Level Testing No standard tests specific to bifacial systems	Medium

Design Changes

To allow absorption of light from the rear side of a solar module, the opaque backsheet of a conventional solar module is typically replaced with a sheet of glass. To maintain cost, module manufacturers typically reduce the thickness of both the front and rear side glass. The most common cell technology being used for bifacial modules is PERC. The key change in the PERC cell is on the rear side, where an aluminum grid (similar to the silver grid on the front) replaces the screen-printed aluminum layer. Screen printing a grid instead of a layer requires changes to the aluminum paste and to the screen printer, which can impact the interconnection of the cells. These change in the module and cell design can lead to additional risk if not appropriately managed.

Degradation Mechanisms

The glass-glass configuration has the potential to eliminate failure mechanisms specific to the backsheet and, according to some studies, can result in a more reliable module. However, field data associated with glass-glass modules is limited, and the results from long-term field studies are inconsistent. Increased degradation due to a buildup to outgassed acidic species from the encapsulant has been reported in the literature.

System Level Simulation

Conventional solar system simulation tools like PVSyst or SAM are designed for monofacial modules. They have been used for multiple gigawatts of solar projects and their energy generation estimates have been correlated with the historical performance of projects.

Simulation of bifacial solar systems is significantly more complicated than conventional systems. Multiple components of the system design like module tilt, height, row to row spacing, module to module spacing, rear side shading from the racking system, the reflective surface behind the module and others can affect the light incident on the rear side of the module. At this time, bifacial simulation tools and methods have limited field validation history relative to the simulation of mono-facial modules. Therefore, it is critical that the uncertainty of bifacial generation modeling is considered carefully when determining the expected system production and the terms of finance.

System Level Testing

PV systems are typically subjected to capacity testing at the conclusion of the construction process, which often represents a major milestone with respect to the construction contracts and financing contracts. There are both ASTM and IEC standards for the performance of capacity testing. Both methods rely on measured irradiance and weather conditions and the respective output of the system, which is compared to modeled output of the system at similar irradiance and weather conditions. Industry standards have not yet been developed for a similar testing protocol for bifacial systems. Given their reliance on backside irradiance, bifacial systems will require a revised means of capacity and acceptance testing. The testing methods developed by the system constructors should be reviewed in detail to confirm that they appropriately demonstrate the achievement of the expected system performance within an appropriate level of uncertainty.

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

DuraMAT DataHub Year 3 – Integration and Analysis: Development of PV Fleet Data Acquisition and Analysis Pipeline

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[1]National Renewable Energy Laboratory; [2] Lawrence Berkeley National Laboratory; [3] Sandia National Laboratory, [4] SLAC National Accelerator Laboratory

Overview

Year three begins a shift in focus for DuraMAT data operations: We are beginning to move from purely infrastructure development for the data hub and time-series database to more of an acquisition and analysis role. Additional work will continue to improve reliability and access for both systems, but the impetus will focus on utilization.

A first test will be to begin harvesting and analyzing partner PV fleet data to find and identify degradation trends and causes. Data will be anonymized and aggregated together to provide a more concise view across a single site, fleet or multiple fleets. To facilitate this activity, we are building an ancillary cloud-based storage systems and data harvesting pipelines. This will afford participating partners the ability to deliver their fleet performance data quickly and securely.

In this poster, we will describe the existing data hub, the time series database, the new data acquisition and analysis pipeline and how all three tie together.

Current Stats

59	39	34	253
Users	Projects	Datasets	Resources
+ 33%	+ 38%	+ 37%	+ 416%

From 2/2018

DuraMAT Data Hub

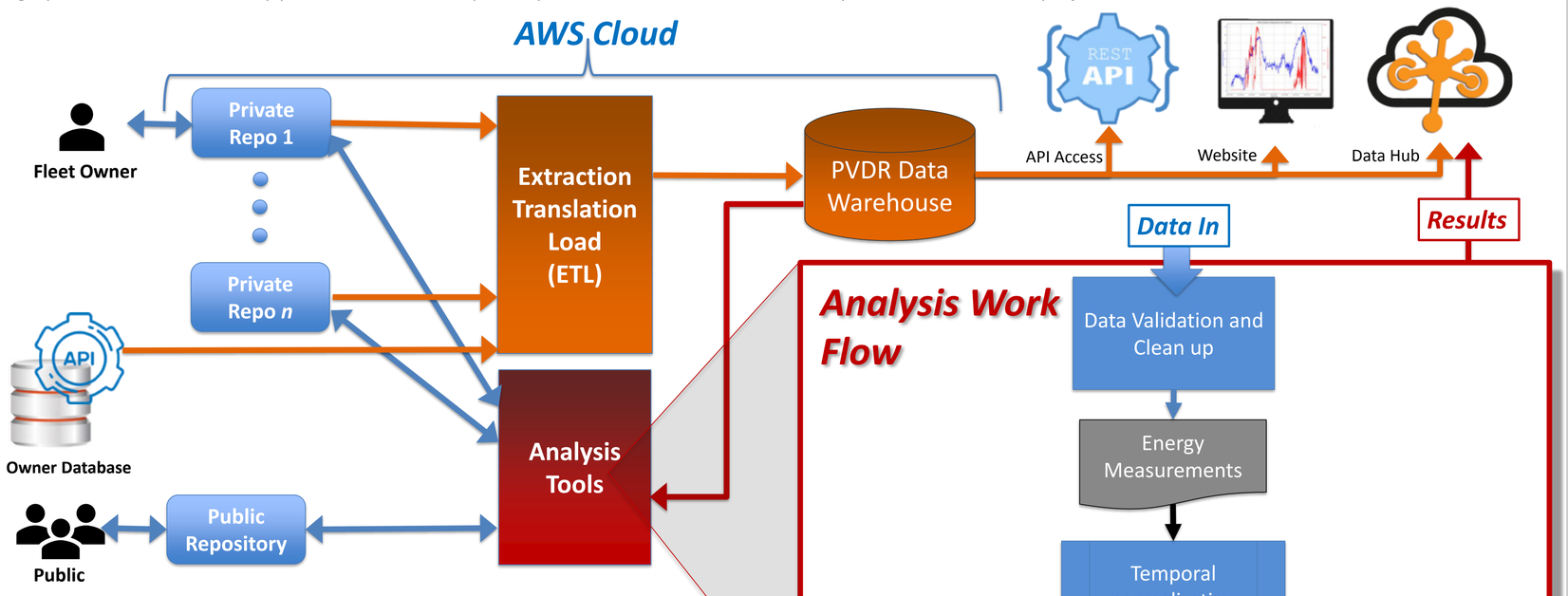
The DuraMAT data hub is built on a highly customized CKAN data sharing framework, tuned to meet our needs. Large sections of the codebase are standardized across all the EMNs, providing a consistent, easy-to-use interface common to any researchers working across the EMNs, but each has their own custom additions for data viewing and retrieval.

The data hub can archive a broad range of data formats and files ranging from experimental results to reports. We have developed a set of user documentation, guidelines, and best practices to inform researchers. The policies will help ensure that data is as contextually complete as possible, containing full sets of data and metadata that will allow others to re-analyze, examine, or reproduce any findings.

The DuraMAT data hub is currently in operation and continues to grow in available resources and registered users. We are currently beginning the process of providing linkages between the data hub and the time series database, along with improving the researcher's experience.

Analysis At Scale – PV Fleets

Solar energy accounts for 2% of the overall electricity production in the United States, exceeding 11% in some states, such as California, Hawaii, Nevada, and Vermont. The rapid expansion of US solar assets demands ongoing accurate assessment of power generation by the US PV plants throughout the years of operation, enabling highly reliable solar electricity production, efficient plant operation, and accurate bankability evaluations for new projects.



Fleet and Site data can be delivered into the system through manual uploads to Amazon Web Services (AWS) Simple Storage Solution (S3) repositories, or through direct harvesting from a fleet database. Once placed in either the repos or harvested, the data can then be funneled into the pipeline for analysis. Any company fleet data is secured and access is restricted to only the analysis team and the customer.

In the early stages we will be running the pipeline as a manual process at all stages. As we gain more information and experience, we will create automated processes to replace the manual operations. The Quality Check points will lend themselves well to the integration of machine learning systems, thereby quickly identifying issues within the data stream or with the results.

Once the analysis for a fleet or site is complete the data is aggregated into the existing model and a report is generated and placed in the data hub for the customer.

Merging data across a single fleet, let alone multiple fleets requires us to prepare and validate the data. It makes the process much easier if there is a standard of deliverable data to be analyzed. This allows us to create templates for the tool-kits, providing a more efficient use of available resources. The following is a list information we would need as part of any provided data from prospective partners (Items in **bold** are required):

Time Series Data

Timestamp: (ISO 8601)
Interval (L, R, or C, Accumulation) or Instantaneous
Irradiance
GHI, DNI, DHI, POA (including tracked with array)
PV Power (AC or DC)
or
PV Energy (AC or DC)

Metadata

Location:
Latitude, Longitude, Time zone, Elevation
System:
Dates or operation: Begin, End or Current
DC and AC capacity
Mounting:
Type:
Fixed
Tracking: number axes, rotation limit, spacing, backtracking, coverage
Azimuth
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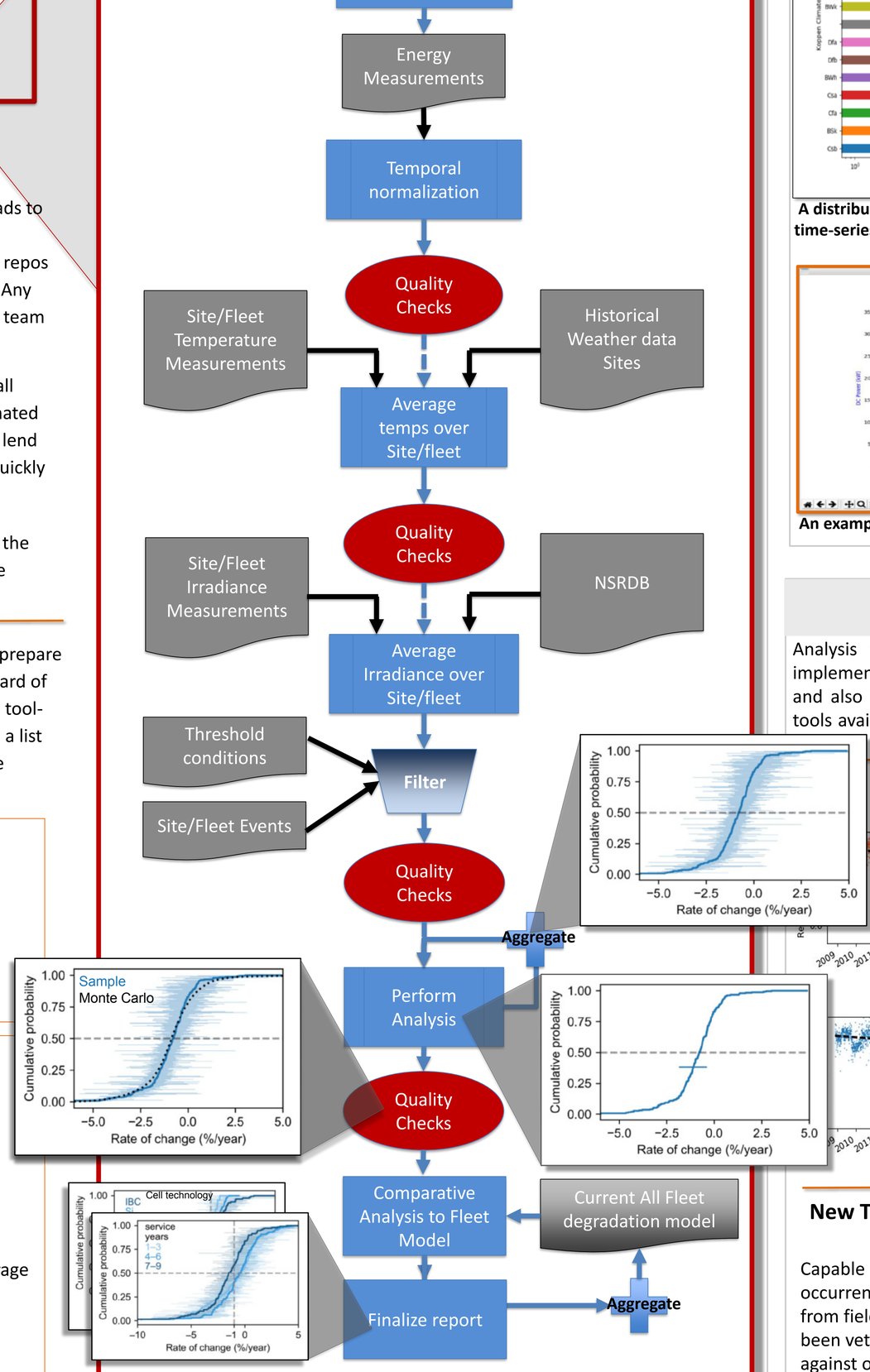
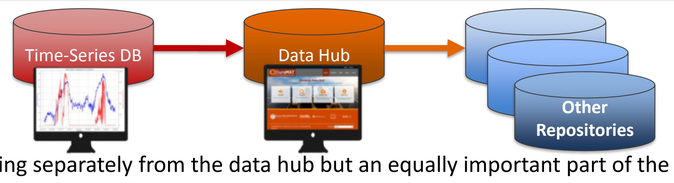
Module: IDs, type
Inverter: IDs, type
Number Subarrays
Documentation

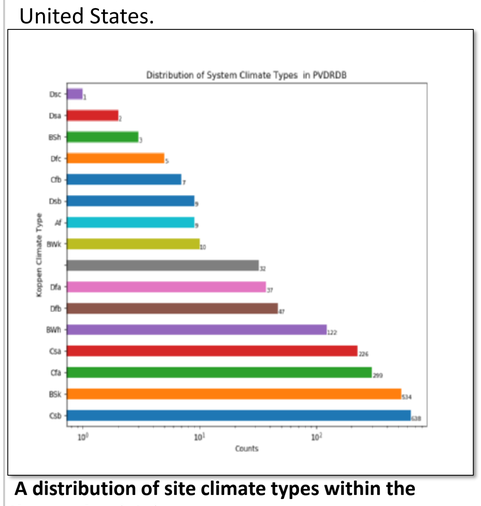


Fleet-Scale Energy-Yield Degradation Analysis Applied to Hundreds of Residential and Nonresidential Photovoltaic Systems. M.G. Deceglie, D.C. Jordan, A. Nag, A. Shinn. C. Deline. IEEE Journal of Photovoltaics (Volume: 9 , Issue: 2 , March 2019) pp.476 - 482

Time-Series Reliability & Durability Database

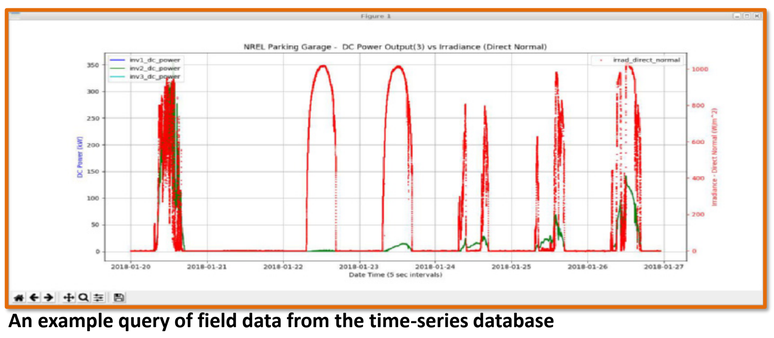


Sitting separately from the data hub but an equally important part of the DuraMAT data infrastructure, is a time-series database for aggregating field performance data. The system is seeded with the archived data from around 2000 PV systems scattered across a variety of locations and climates within the United States.



A distribution of site climate types within the time-series database

This new database system has been re-engineered to take advantage of a federal cloud-based infrastructure now available at NREL. Utilizing utility scale computing allows us to keep cutting edge computing power and re-scalable architecture without the cost of maintaining the systems directly. The cloud infrastructure is fed-ramp certified and accessible by all the national labs, consortium members, partners, and the public.

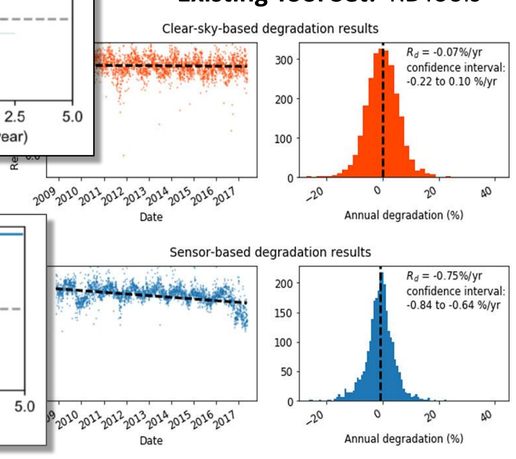


An example query of field data from the time-series database

Analysis Tools

Analysis tools form the bridge between data and understanding. We are implementing new tools for DuraMAT, using the iPython/Jupyter notebook format, and also integrating standard and proven tools into the Data Hub. Many of the tools available on the data hub will provide the crux of software systems that will be supporting the pv fleets analysis

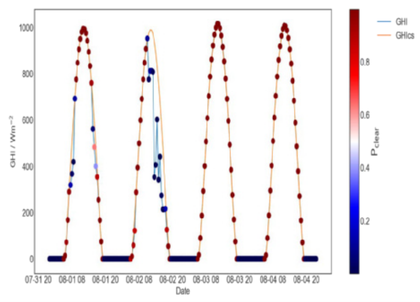
Existing Tool Set: RDTools



A suite of Python based software that can analyze photovoltaic time-series data. The code was developed by merging years of NREL degradation studies along with industry collaborations to identify best practices. The primary focus of the software is to evaluate PV degradation over time. However the toolkit can also be leveraged to evaluate other PV performance issues. Besides a direct download, the toolkit is available via python pip install.

New Tool: Clear Sky Detection

Capable of detecting clear sky occurrence base on performance data from fielded PV systems. The code has been vetted against test data sets and against operational PV arrays. In addition, test data can be acquired via the data hub for validation.



Investigating the degradation kinetics of c-Si and CIGS solar cells under potential induced degradation by various material characterization techniques

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Introduction and Motivation

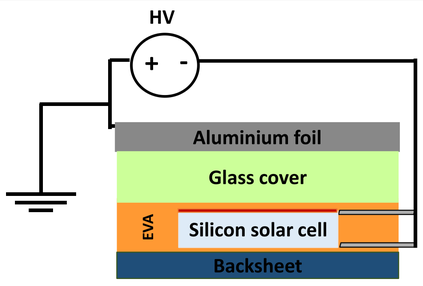
- ✓ Recently, **Potential Induced Degradation (PID)** has appeared as one of the threatening reliability issues.
- ✓ Various research groups and industries have taken extensively participation to explore PID root cause and degradation mechanisms to secure future PV investments[1-3].
- ✓ Generally, migration of Na ions are found to be responsible for PID. However, material degradation aspects to the reduction in electrical performance under PID is less explored.
- ✓ Motivated by this, we have performed PID accelerated tests on commercial c-Si and CIGS solar cells to investigate its material related issues which can lead to a dramatic reduction in electrical performance under field conditions.

Research approach

- ✓ Material aspects of PID treated cells has been explored in detail by Field Emission Scanning Electron Microscope (FESEM), Raman spectroscopy, X-Ray diffraction (XRD), and electro-analytical technique.
- ✓ The degraded cell reveals microstructural defects associated with a blue shift from Raman which signifies that a material experiences compressive strain after PID.
- ✓ In addition, X-ray photoelectron spectroscopy (XPS) and photoluminescence spectroscopy (PL) have been carried out for treated CIGS cells.
- ✓ A very low intense PL peak has been observed in CIGS cell due to the increase in defect density thus results in band-gap deterioration of the material under extreme PID.

Results and Discussion

Multi-crystalline silicon

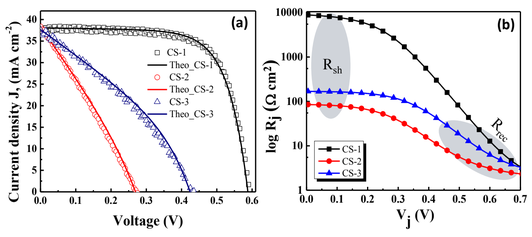


PID test setup

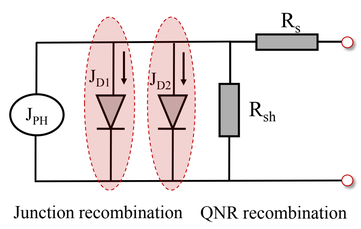
- ✓ PID set up with commercial multi crystalline silicon solar cell
- ✓ 85 °C/ 65 RH%
- ✓ J-V measurements of degraded cells exhibited more than 90% power loss in power output within a very short time under severe field conditions
- ✓ 10^2 change in parallel resistance
- ✓ Two diode model reveals higher recombination in p-n junction and QNR region

Electrical Characterizations

J-V measurements



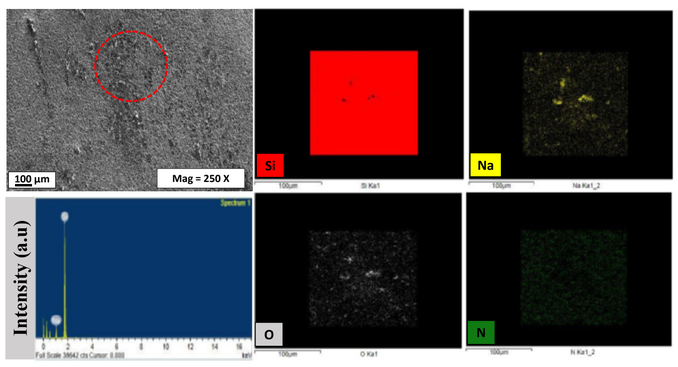
Two-diode model



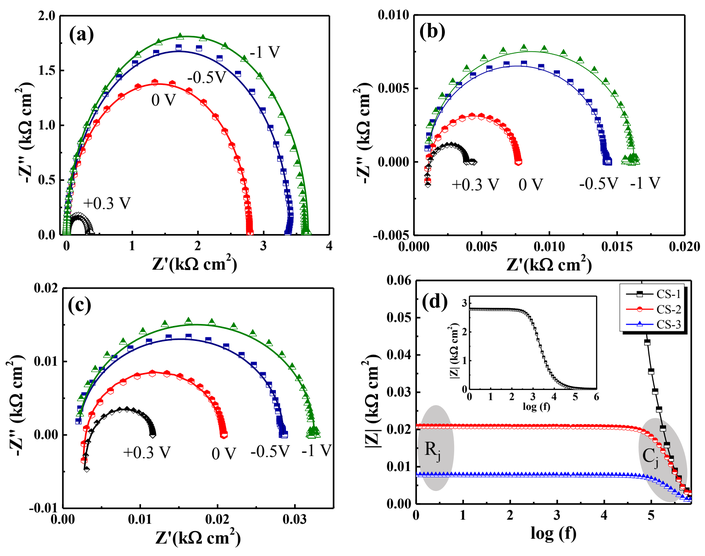
Material Characterizations

FESEM-EDX

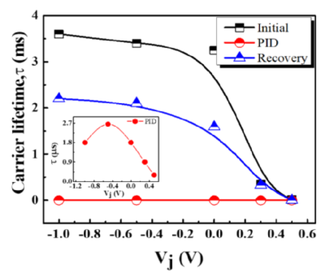
- ✓ PID degraded cell reveals micro-structural deformation on the cell surface
- ✓ EDX elemental mapping of degraded cell reveals presence of higher sodium (Na) impurities
- ✓ Na impurities plays key role in order developing shunting through p-n junction of solar cell[1]



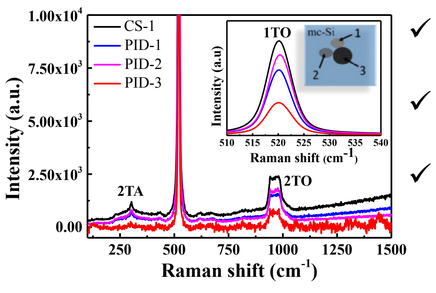
Impedance spectroscopy



- ✓ Change in junction capacitance value of PID treated cells.
- ✓ Parallel resistance decrease for PID treated cell at respective bias compare to initial cells
- ✓ Carrier lifetime decrease

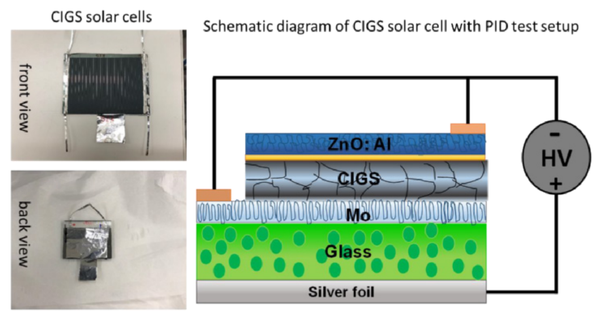


Raman analysis



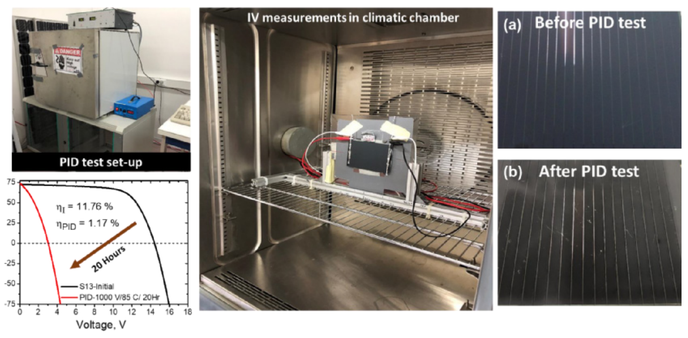
- ✓ Raman analysis reveals low intense 1TO and 2TO peaks for degraded cell compare to initial cell
- ✓ Blue shift for PID degraded cell with micro-structural deformed regions
- ✓ Material experienced compressive strain due to PID under excessive Na impurity incorporation

CIGS

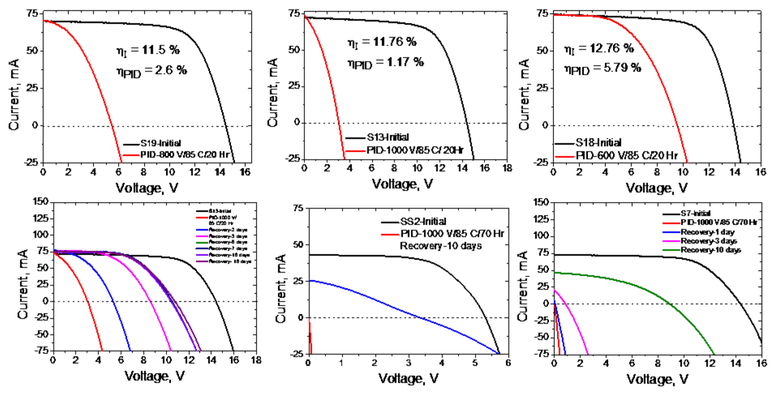


- ✓ PID set-up of commercial CIGS solar cell
- ✓ Climate chamber
- ✓ 85 °C
- ✓ 80 % power loss with in few hours of high voltage exposure time

- ✓ 600 V, 800 V, 1000 V high voltage stress have shown drastic decrement in J-V measurements with in 20 Hr
- ✓ Extremely degraded cells for the longer exposure time
- ✓ Surface modification

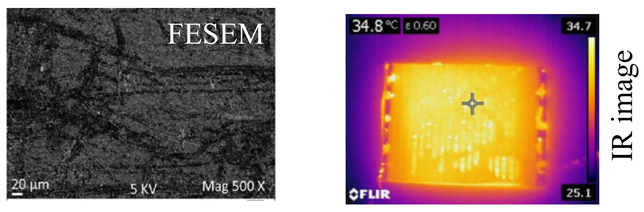


J-V characterization



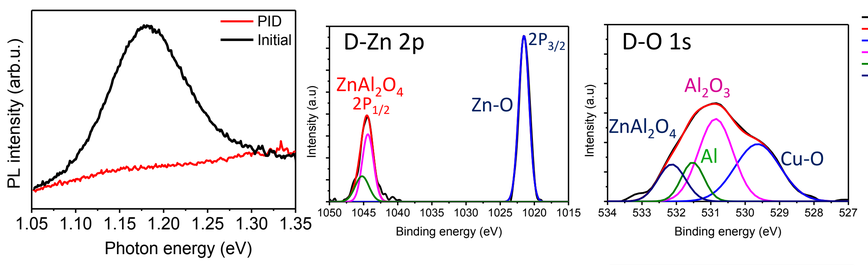
- ✓ PID treated cells exhibited more than 90% power loss in power output within a very short time under severe field condition
- ✓ Moderately degraded cells recovery have been achieved 90 % with reverse polarity

Defected cell

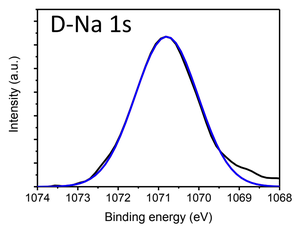


- ✓ IR- thermographic image of degraded cell
- ✓ FESEM analysis reveals micro-trails like structure deformation on cell surface

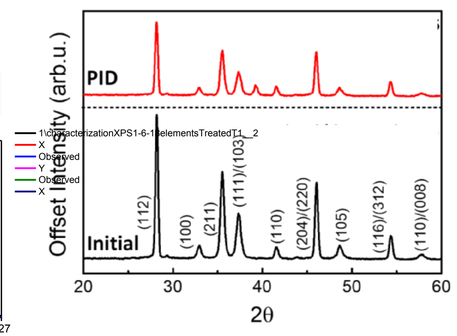
PL and XPS



- ✓ PL intensity for PID degraded cell decrease dramatically
- ✓ Increase in defect density
- ✓ The binding energy at 1172 eV has been acquired which corresponds to Na



XRD



- ✓ XRD analysis reveals intensity variation of peaks after PID compared to initial
- ✓ Extra peak at 37° for PID treated cells corresponds to $MoSe_2$

Conclusion

- ✓ C-Si and CIGS PID treated cells exhibited more than 90% power loss in power output within a very short time under severe field conditions.
- ✓ CIGS cells have shown fast recovery compare to c-Si technology at same parameters may be attributed to different thermal diffusion mechanism owing to Na movement through grain boundaries
- ✓ PID treated cells revealed Micro-structural deformation in both the technologies
- ✓ In both the cases excessive sodium impurity found to be present in defected regions but, the recovery kinetics might be different for both the technologies
- ✓ Raman analysis reveals compressive strain experienced by material under PID stress

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1. V Naumann, D Lausch, A Hähnel, J Bauer, O Breitenstein, A Graff, Solar Energy Materials and Solar Cells 120, 2014, 383-389
2. W. Luo, Y. Khoo, P. Hacke, V. Naumann, D. Lausch, S. Harvey, J. Singh, J. Chai, Y. Wang, A. Aberle and S. Ramakrishna, Energy Environ. Sci.,10, 2017, 43-68.
3. Z. Purohit, B. Tripathi, Deepak Verma, Physical Chemistry Chemical Physics 28, 2018, 19168-19176.

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Product Testing and Compliance for Australian Rooftop PV Market

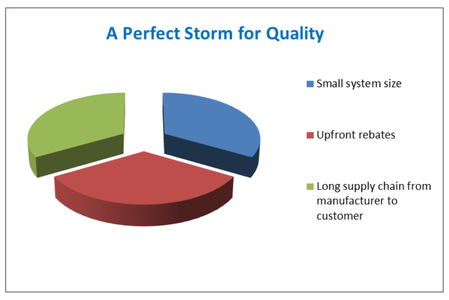
Sandy Pulsford

Clean Energy Council

INTRODUCTION

Clean Energy Council (CEC) is the peak industry body in Australia which operates a listing system for PV modules, inverters and batteries qualified for the rooftop solar market (<100kW). Australia has the world's highest penetration of rooftop PV -

- 2m rooftop systems
- >20% of homes with solar
- 7GW rooftop PV capacity



Quality issues exacerbated by –

- upfront rebates
- split incentives
- long supply chains,
- lack of technical due diligence

Failed modules going for recycling & landfill -

- cheaper to replace whole array than replace a faulty module
- thousands of modules warehoused waiting for recycling programs
- propose data collection program from recycled panels

Backsheet faults reported -

- delamination
- cracking
- water ingress
- low resistance to earth

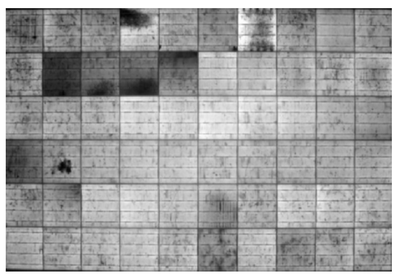
RAISING QUALITY IN THE ROOFTOP PV MARKET

Driven by upfront rebate scheme for solar power up to 100kW, and solar hot water

- has operated since 2000 under the government Renewable Energy Target (RET)
- market price of ~US$28/MWh
- based on deemed CO_2 emission reduction over 15 years – panels have to last!

<100kW segment characterised by -

- domestic and commercial rooftop installs
- large number of manufacturers, mostly supplying distributors selling to retailers,
- retailers employ or contract around 6,000 CEC Accredited Installers who are qualified electrical tradespeople



Quality issues in rooftop market -

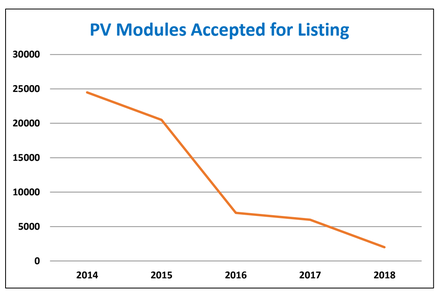
- upfront rebates (rather than feed-in tariffs),
- fragmented supply chain
- disconnect between manufacturer and end-user
- significant sector of market focussed on cheapest price

CEC operates the listing process for products which meet relevant standards and CEC Terms and Conditions covering -

- PV modules & inverters
- lithium-ion batteries recently added
- backed by product testing and compliance investigation
- listing system becomes a de-facto technical due diligence program

Drastic tightening of requirements in response to lower quality products in the market

- certifier must conduct annual factory inspections
- modules certified to 2016 edn IEC 61215, 61730
- Construction Data Form to verify BOM, factories
- datasheet warranty checked for misleading claims
- certifier mark and power tolerances on label
- importers must agree to listing T&Cs
- voluntary serial number verification scheme
- manufacturers down from many hundreds to 60



ENHANCED LISTINGS FOR PV MODULES

Enhanced listings are designed to differentiate PV modules with higher quality or environment-specific standards to help drive quality

- Verification required that all BOM for a model number meets the higher standards

Quality Standards

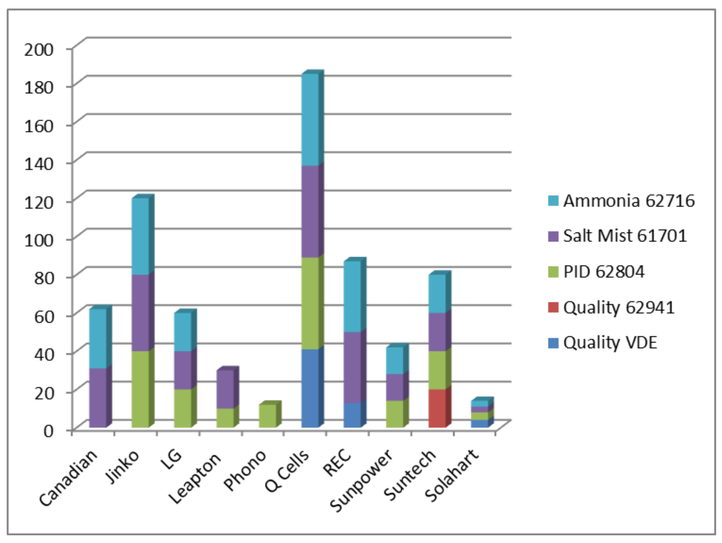
- VDE Quality Tested
- IEC 62941
- PID Resistance
- PVEL PQP

Environmental Standards

- Salt mist corrosion
- Ammonia corrosion
- Cyclonic winds
- Wind blown dust & sand

233 models w Enhanced Listings

- 17% of manufacturers
- >10% of modules

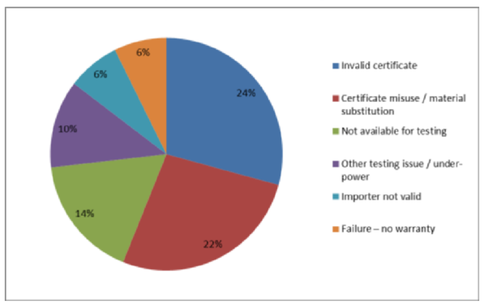


CEC PRODUCT TESTING & COMPLIANCE PROGRAM

PV modules

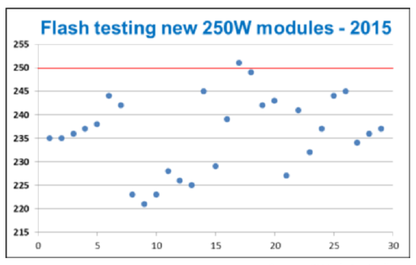
Does the product conform to the certification?

- 50 compliance investigations in 2018
- 78% from internal audits and testing
- 24% certification validity issues
- 22% component substitution or model number issues
- 10% under-powered (improved on 2015 results)
- 18 manufacturers de-listed or suspended
- 380 model numbers affected



22 PV manufacturers compliance tested in last 18m

- testing targeted to low end of market & complaints
- 32% were de-listed
- 32% were suspended
- new test for backsheet compliance
- latest round showed significant improvement
- many reinstated or re-listed after corrective actions



Source: PV Lab Australia

Inverters

12 manufacturers had compliance testing in 2018

- 67% failed to comply with Aus grid protection settings
- 33% failed to supply mandatory demand response
- 75% marking & documentation issues per IEC 62109
- failure to track critical firmware version changes
- 8 manufacturers had inverters de-listed
- 84 model numbers removed
- many reinstated or re-listed after corrective actions

PV MODULE DEGRADATION

Industry reports of delamination, water ingress and backsheet degradation

- evidence of thousands of PV modules going to landfill and recycling in Australia
- rebate scheme subsidises replacement of whole system
- DuPont 2018 Field Survey of PV module defects[1]
- growing problem as new backsheets enter market
- CEC receiving complaints of backsheet cracking, de-lamination & low resistance to earth

Australian rooftop market particularly at risk

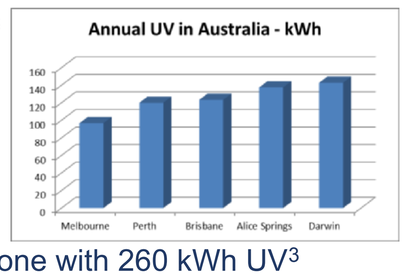
- DuPont found defects double for rooftop installs
- also doubled for higher temperatures
- exacerbated by module selection based on price
- 50% of backsheets tested by CEC are PVDF or PA

Urgent need for new standards which differentiate higher quality backsheets

- IEC 61215 & 61730 appear inadequate for current industry needs
- amendments in draft, but not enough

Accelerated testing protocols

- draft IEC 62309 Extended stress testing of PV modules
- draft IEC 62788-2-1 Polymer backsheets & frontsheets
- draft IEC 63126 PV modules for high temperatures
- Most still have low levels of UV exposure
- Australian capitals have average124kWh UV/yr[2]



Will new tests replicate backsheet defects seen in field?

- Module Accelerated Sequential Testing (MAST) is only one with 260 kWh UV[3]

CONCLUSIONS

CEC Product Integrity Team focused on compliance

- PV modules, inverters and lithium-ion batteries
- logging of all product complaints
- proactive internal audits
- responsive test program
- fast suspensions and de-listings
- investigating more rigorous product standards
- protecting the rooftop solar industry

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1. DuPont, Global PV Reliability 2018 Field Analysis, 2018
2. http://www.approvalsblog.com/short-wave-uv-weathering-tester-for-product-and-component-testing-austest-laboratories-sydney
3. T.J. Trout, Understanding PV module durability through analysis of fielded modules and sequential accelerated testing, PVRW, 2018

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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

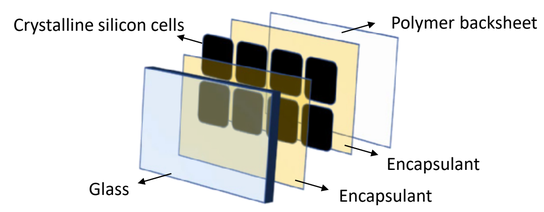
Thermal and Viscoelastic Behavior of Photovoltaic Module Encapsulants

Ashley M. Maes[1], James Y. Hartley[1], Christine C. Roberts[1], Stephanie Moffitt[2]

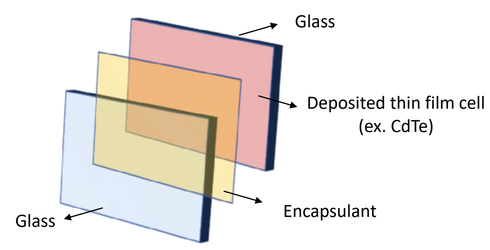
[1]Sandia National Laboratories; [2]SLAC National Accelerator Laboratory

Introduction and Motivation

- This work is part of an ongoing **predictive modeling** effort developing multi-scale thermal-mechanical finite element models to better understand how module deployment environments induce the damaging stresses that lead to module degradation
- The viscoelastic nature of polymer encapsulant is potentially a key factor affecting component stress states
- This poster summarizes the **steps taken to populate a material model** for two encapsulant polymers: poly(ethylene vinyl acetate)(EVA) and a polyolefin elastomer (POE)
    - EVA is the most common encapsulant material used in PV modules
    - We characterized crosslinked samples of a fast-curing commercial EVA
    - Polyolefin films are a common alternative encapsulant with several improved characteristics that are especially valued in thin-film PV modules
    - We characterized commercial POE samples that were heated and pressed to mimic manufacturing lamination conditions



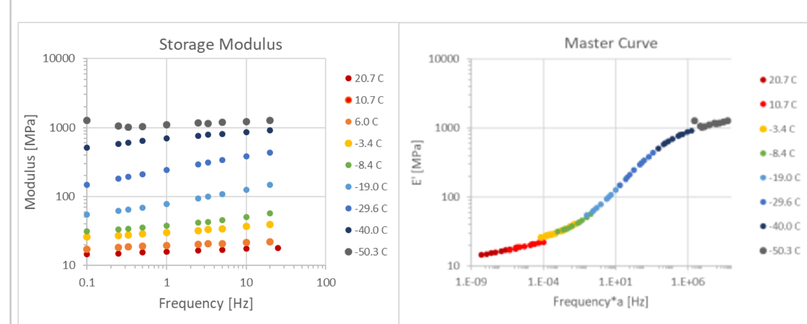
Layers in silicon PV modules



Layers in thin-film PV modules

1: Time-Temperature Superposition

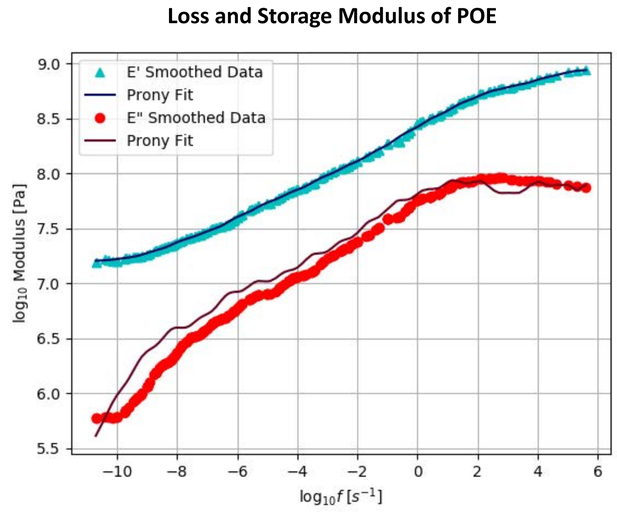
- Isothermal frequency sweeps (0.1 Hz to 10 Hz) were collected with a dynamic mechanical analyzer (DMA) at and above the materials' glass transition regions (EVA: -40°C, POE: -60°C)
- Williams-Landel-Ferry (WLF) equation was used to find shift factors (α_T), with parameters C_1 and C_2 optimized to storage modulus (E') data



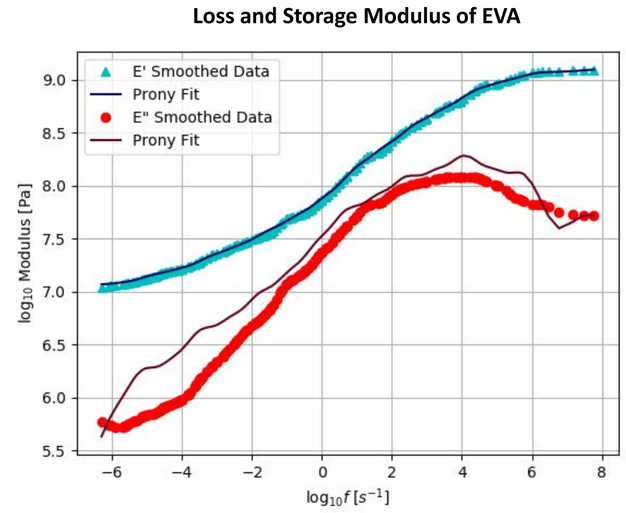
Example of shifted isothermal frequency sweep data - EVA

2: Model of Linear Viscoelastic Behavior

Loss and Storage Modulus of POE

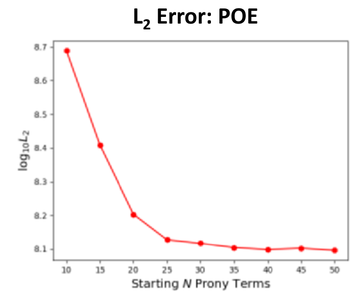


Loss and Storage Modulus of EVA

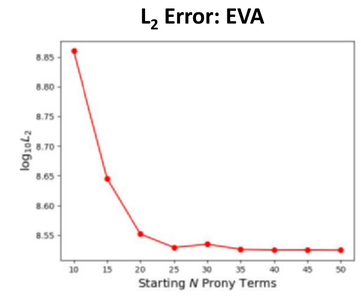


- Master curves of each material consist of shifted DMA data collected on multiple samples and smoothed
- Prony series fits *(lines in plots above)* capture both the elastic and viscous material responses of polymers
    - The number of Prony terms was varied from 10 to 50, with 25 terms selected to minimize L_2 *(right)*

L_2 Error: POE



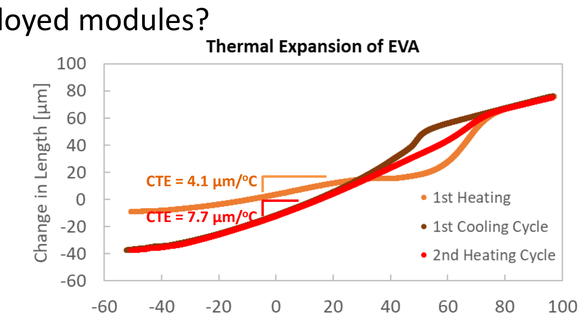
L_2 Error: EVA



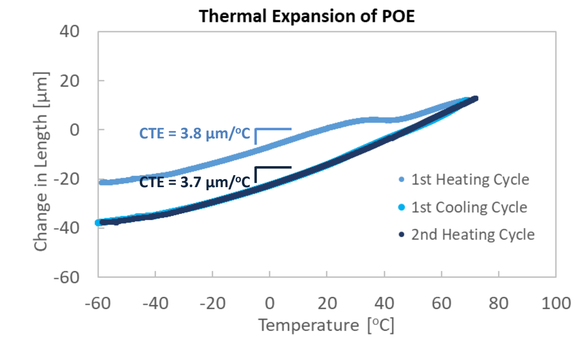
3: Thermal Expansion and Relaxation

- Coefficient of thermal expansion (CTE) was measured using a thermal mechanical analyzer (TMA).
- Significant variation between cycles due to thermal history of the films. Which is the relevant state for deployed modules?

Thermal Expansion of EVA



Thermal Expansion of POE



4: Universal Polymer Model

- Parameters from the data fitting described above will be used to populate Sandia's Universal Polymer Model [DB Adolf, RD Chambers, J. Rheology 2007], including:
    - WLF parameters and reference temperature
    - Linear viscoelastic model Prony terms
    - CTE fit

Material Time Dependencies: Thermal Pressure

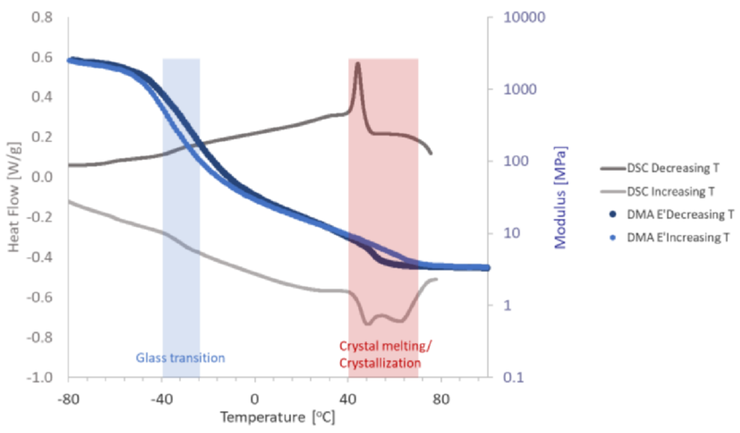
$$N = \left\{\left[T(t)-T_{ref}\right]-\int_0^t ds\, f_1(t^*-s^*)\frac{dT}{ds}(s)\right\}+C_3\left\{I_1(t)_{ref}-\int_0^t ds\, f_1(t^*-s^*)\frac{dI_1}{ds}(s)\right\}$$
$$+C_4\left\{\int_0^t\int_0^t ds\,du\, f(t^*-s^*,t^*-u^*)\frac{d\underline{\underline{\varepsilon}}_{dev}(s)}{ds}:\frac{d\underline{\underline{\varepsilon}}_{dev}(u)}{du}\right\}+C_5(x(t))\left\{\left[x(t)-x_{ref}\right]-\int_0^t ds\, f_1(t^*-s^*)\frac{dx}{ds}(s)\right\}$$

Shear Deformation Matrix Cure

- This model has already been demonstrated with curing kinetics in structural foams [K. Long et al., SAND2018-9096]

5: Polyethylene Crystallization

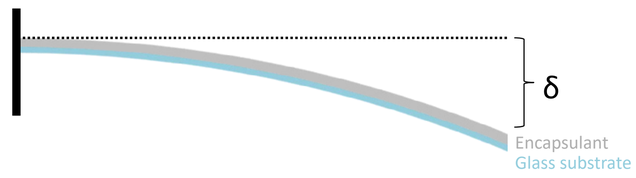
- A key thermal transition not yet captured in the EVA Universal Polymer model is polyethylene crystallization/melting, observed in differential scanning calorimetry (DSC), DMA and TMA
- This transition affects the thermal expansion as well as the viscoelastic behavior of the material and occurs within the operating temperature range of PV modules



Key Thermal Transitions in EVA

6: Model Validation Efforts and Future Work

- Conduct stress-relaxation experiments to increase confidence in viscoelastic model in the low frequency regime
- Validate the constitutive material model using a cantilever deflection technique on encapsulant laminates:



- Additional work will investigate the possibility of adding curing kinetics and crystallization to the material models
- Similar experimental methodologies will be used to characterize samples collected from the fielded module library capability in development at Sandia

SAND2019-1822 C

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Yield Differences of PV Technologies in a Desert Climate

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HAMAD BIN KHALIFA UNIVERSITY

Abstract

PV modules which are less sensitive to temperature (i.e. have lower power temperature coefficient, PTC) are expected to produce more energy in hot environments. Yet a year-long study of 26 PV technologies in Doha, Qatar, found that their daily Specific Yield only weakly correlated with their PTC.

To investigate possible explanations, we selected one multi-Si and one CdTe test system and calculated their energy losses attributable to module temperature, low-light conditions, and W_p discrepancy (difference in W_p values from manufacturers' flash tests and field measurements). We found their PTC in the field differed greatly from their nominal PTC, and differences in W_p discrepancy dominated differences in temperature loss. The results appear to explain the absence of correlation between Specific Yield and nominal PTC.

Fig. 1. The QEERI Outdoor Test Facility is located in Doha, Qatar. Energy yields of 26 test systems were analyzed over one year

Yield vs. Nameplate PTC

Power output and module temperature (T_{mod}) of the 26 test systems, and plane-of-array irradiation (G_{POA}), were recorded every minute for 2017, when the systems were approximately five years old. The data was cumulated and averaged into daily Specific Yield (SY) [Wh/day/W_p] and plotted against the system's nameplate power temperature coefficient (PTC) (Fig 2.) Unexpectedly, there was no observed relation between nameplate PTC and SY of the test systems.

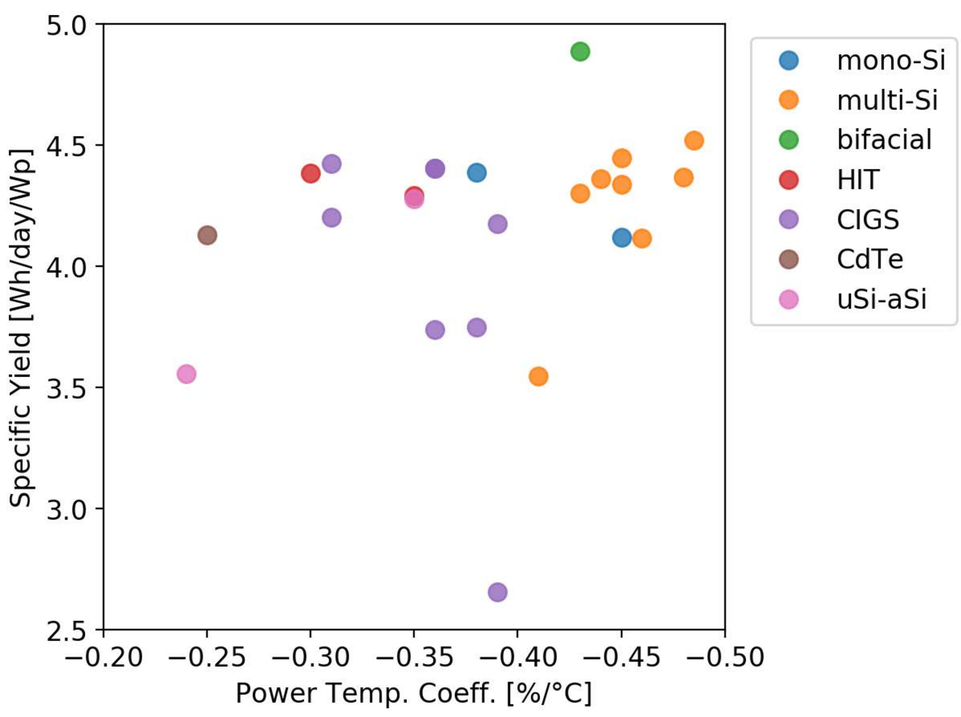


Fig. 2. No correlation was found between PV systems' nameplate PTC and their Specific Yield in field testing. This was also observed within groups of the same PV technology type

Yield Loss Components

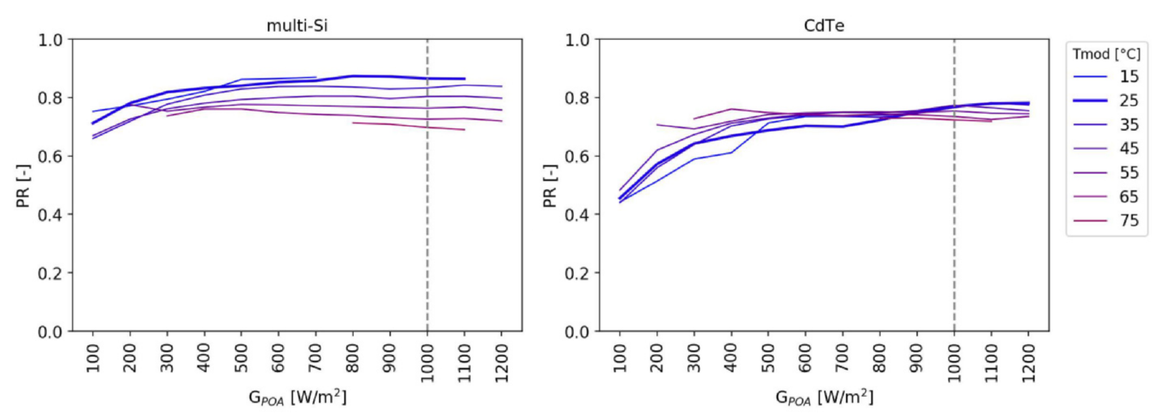
One multi-Si and one CdTe test system which had been cleaned every week (i.e. no soiling losses) were analyzed in detail to determine their energy losses attributable to operating temperature, low light, and W_p discrepancy. First, the year of field data was used to generate "real world" plots of Performance Ratio (PR) vs. T_{mod} & G_{POA} (Fig. 3).

Then, the PR components were extracted for every minute of the year from the PR plots as follows:

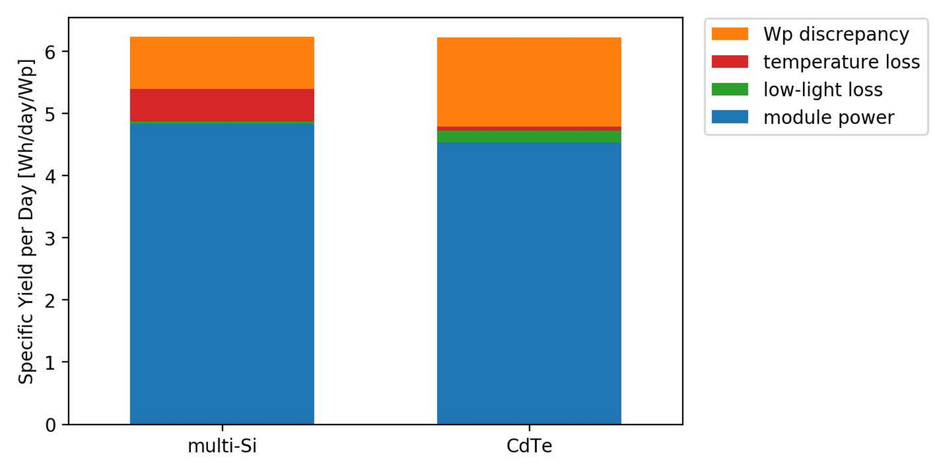
· module power = PR at the operating conditions $\{T_{mod}, G_{POA}\}$
· low-light loss = ΔPR moving to $\{T_{mod}, 1000\ W/m^2\}$
· temperature loss = ΔPR moving to $\{25°C, 1000\ W/m^2\}$
· W_p discrepancy = ΔPR moving to PR=1

The PR components were multiplied by G_{POA} to power components, and cumulated over the years into Specific Yield components (Fig 4.)

It is seen that differences in W_p discrepancy dominated differences in temperature losses between the two systems. Also, field-measured PTC was obtained from the PR charts via the spacing of constant-T_{mod} lines at GPOA=1000 W/m². Field PTC was found to be significantly different from nameplate PTC for both systems. Similar findings have been reported in previous studies [1-3].



↑ Fig. 3. Performance Ratio (PR) vs. irradiation (G_{POA}) and module temperature (T_{mod}) for each system, from one year of field measurements
↓ Fig 4. The PR plots were used to determine loss components at every minute, and cumulated into average daily SY amounts



Conclusions

Nameplate PTC was not a strong predictor of relative Specific Yields of PV systems in Qatar's desert climate. Further analysis suggested this was because W_p and PTC values exhibited by PV systems in the field could differ greatly from their nominal values. And, differences in W_p discrepancy between systems dominated differences in their temperature losses. The results suggest it is important to conduct climate-specific field tests of PV modules, rather than rely on nameplate characteristics, to predict their relative energy yields.

[1] Micheli, D., Alessandrini, S., Radu, R., and Casula, I. Energy Convers. Manag., 80:436–445, 2014
[2] Whitaker, C.M., Townsend, T.U., Wenger, H.J., Iliceto, A., Chimento, G., and Paletta, F. PVSEC 1991, pp. 608–613
[3] Ustun, T.S., Nakamura, Y., Hashimoto, J., and Otani, K. Renew. Energy 136, Dec. 2018

Saving the Lives of PV Modules: Repairing Scratched and Cracked Backsheets

Challenge (Problem)

Global PV is demanding better ways to deal with failing solar modules caused by scratched and cracked solar panel backsheets

Backsheet Repair (Secret Sauce)

Scratched Repair Tape GF-6100

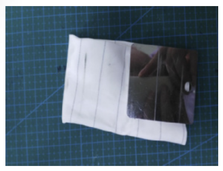
Cracked Repair Tape GF-6265

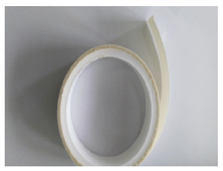
TUV Approved !

Solution (Opportunity)

High performance polymer-based repair tapes to preserve solar module backsheets damaged by improper installation, maintenance, and use of faulty materials **(AAA and PET/E-layer)**

Applying Repair Tape for Scratched





First, cover piece of metal with clean cloth and then move smoothly along tape to prevent bubbles

To ensure best bonding results, distance between scratch and edge of tape should be at least 10mm

Tape can be applied on site with no disassembly required

Company (Cybrid)

Cybrid is an application developer and technology integrator. Company's role is to find and fill needs

Started from a chemistry laboratory in Japan and was incorporated in China at the end of 2008

Well known venture capital firm in China - Legend Capital (Lenovo) - invested in establishing Cybrid

CYBRID 赛伍 胶膜

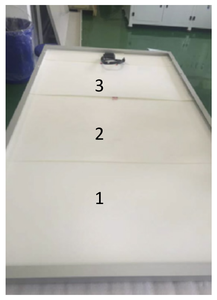
bgbrownell@cybridtechnologies.com

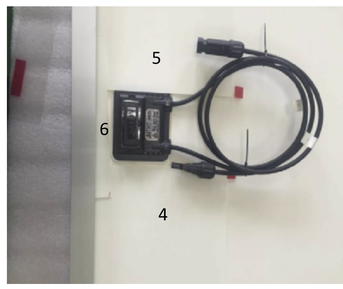
Leading backsheet manufacturer out of in China; world No. 1 in shipments since 2014

Invented f-series backsheets with unique technologies in lamination adhesives and Fluro-skin

Besides backsheets, Cybrid also offers electric conductivity bonding tapes and other polymer materials

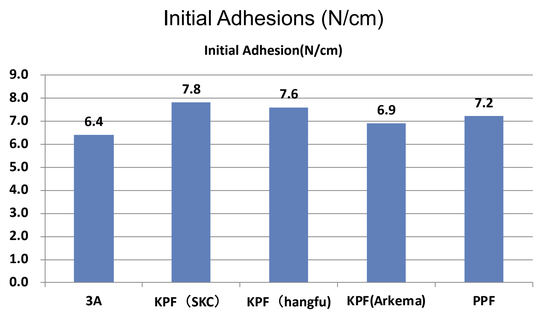
Applying Repair Tape for Cracked





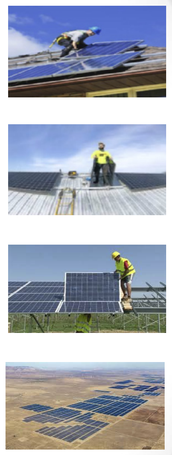
There are 6 repair sheets in total. Pieces 1 ,2, 3 cover the main potion of module (955mm*520mm), while pieces 4, 5 stretch equidistant between the junction box and frame (450mm*200mm), and piece 6 fits above the junction box (20mm~50mm)

Adhesion Testing

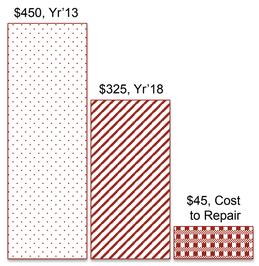


Even after Boiling, PCT48hr, and DH1000 tests, adhesion to different air side of backsheet is still > 4N/cm

Target Markets
Panel Manufacturers
Commercial Installers
Electrical Subcontractors
Installation Subcontractors
Residential Installers
Rooftop Contractors
Solar Developers
Solar EPCs
Utilities



Buy or Fix Analysis



Module and repair prices will vary depending on country

ADVANTAGES to REPAIR
Short out of service period
20% of cost to buy again
Original technology

SAVINGS
Large PV system of 15,000 panels
15,000 X $325 = $4,875,000
15,000 X $45 = $675,000
$4,275,000 in savings !!!

ASSUMPTIONS
Solar module cost $450, 1/3 panel + 1/3 financing + 1/3 install (Base Year 2013)
Significant AAA cracking issues appearing on average after 5-years of use
Total labor ($30) and materials ($15) to repair is $45 per module
Cost to buy, finance and install new solar module is $325 (Base Year 2018)

Better to fix than to buy again

NREL PV Reliability Workshop 2019

(190226-190228) Denver West Sheraton, Lakewood, Colorado

bgbrownell@cybridtechnologies.com +1 (832) 589-0033

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

A Hybrid Hydrophobic-Hydrophilic Coating with Anti-Reflective and Anti-Soiling Properties

QianFeng Xu[1,3], Illya Nayshevsky[1], Daniel Furhang[1], James Newkirk[2], David Miller[2] and Alan M. Lyons[1,3]

[1]City University of New York; [2]National Renewable Energy Laboratory; [3]ARL Designs LLC

DuraMAT Capabilities

1. Data Management & Analytics, DuraMAT Data Hub
2. Predictive Simulation
3. Advanced Characterization & Forensics
4. Module Testing
5. Field Deployment
6. Techno-Economic Analysis

University Goals

- **Problem addressed**: Operation & Maintenance costs due to reflections and soiling
- **Solution**: Multi-functional nano-textured coatings
- **Resource Created**: New coating technology
- **DuraMAT Mission**: Lower LCOE through reduced O&M costs
- **Partnership with NREL provides**: Advanced Characterization (3), Reliability Tests (4), and Field Tests (5)

Accomplishments

- Fabricated anti-reflective coatings on solar glass with 3% gain
- Demonstrated coating abrasion resistance as per EN1096.2
- Observed anti-soiling behavior (45% increase in transmittance) on hydrophobic surfaces due to mobile condensate drops
- Demonstrated self-cleaning behavior in condensation chamber – eliminates need for mechanical cleaning.

Outcomes and Impact

- **Next Step**: Evaluate performance outdoors at RTCs
- **Use**: Coating on the exterior surface of solar cover glass
- **Future Partners**: Panel fabricators & glass manufacturers
- **Implementation**: Coatings for solar glass industry
- **Other Applications**: Sensors and architectural glass

Capability Development

The Challenge

Reflections

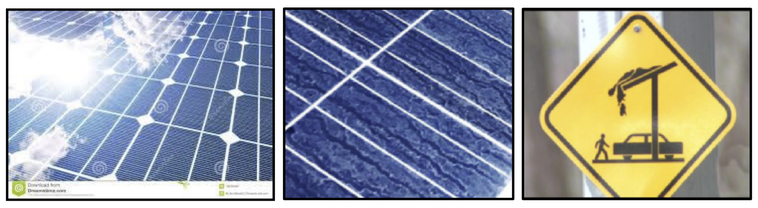
4% of the light energy is reflected off the outer glass surface

Dirt

10 to 50% of the electrical output can be lost to dust. Cleaning required weekly! ***Increases LCOE by 0.6¢/kWh***

Ice

Ice accumulation results in 1-10% lost power. Creates falling hazard in some locations



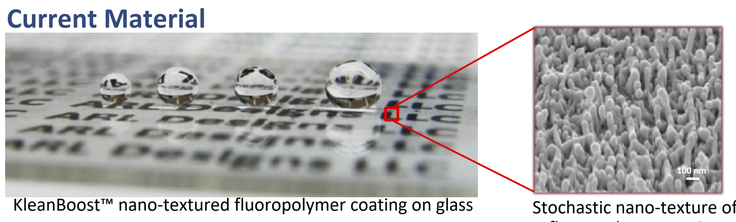
Dubai Test Site 2017

Dust that accumulates on the solar cover glass of a PV module scatters light, thereby reducing energy output and necessitating periodic cleaning.

- Impact in USA on LCOE is estimated to be 1¢/kWh [1];
- Impact in other regions: annual soiling loss may be as high as 50% [2].
- Average annual soiling loss : 5%/year in NREL's current and long-term LCOE input assumptions for the SunShot 2030 targets of 3¢/kWh: [3].

Our Approach: A Multifunctional Coating that Combines Anti-Reflectivity and Anti-Soiling Properties

Current Material

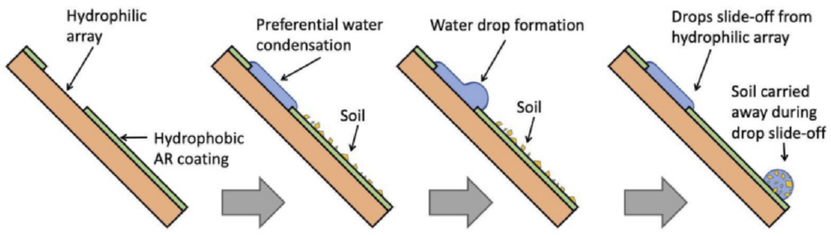


KleanBoost™ nano-textured fluoropolymer coating on glass

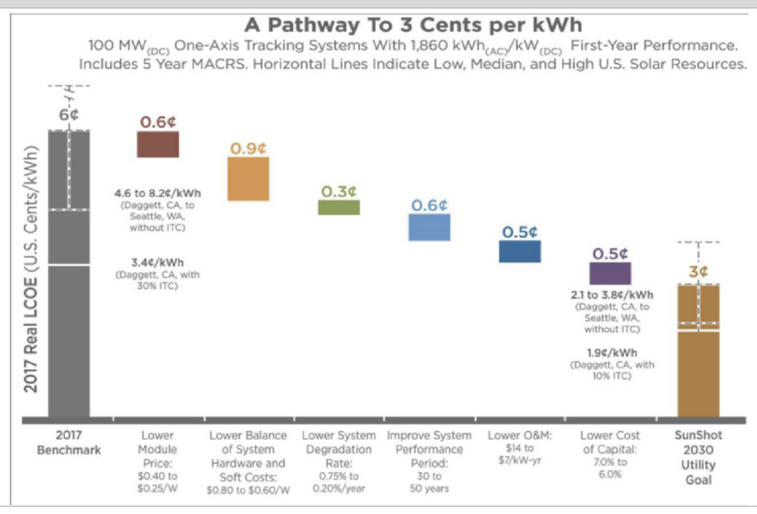
Stochastic nano-texture of fluoropolymer coating

Innovation:

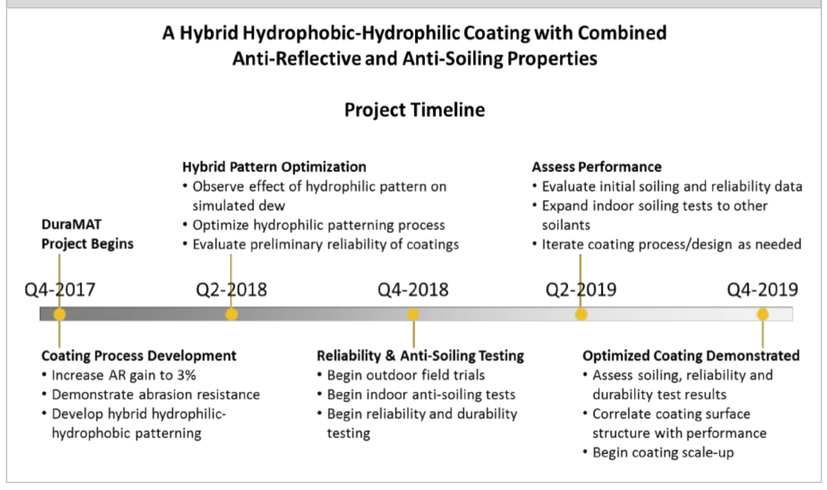
Harvest "free" water from dew to self-clean cover glass



Cost Drivers

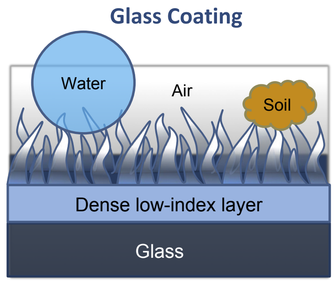


Timeline



Anti-Reflective Properties

Schematic of Cross-Section of Glass Coating

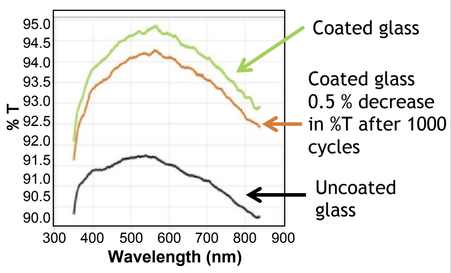


Max %T = 94.9 % at 565 nm
Hydrophobic - CA = 140°

Direct Transmittance Measurements

Anti-Reflectivity Stable to Abrasion

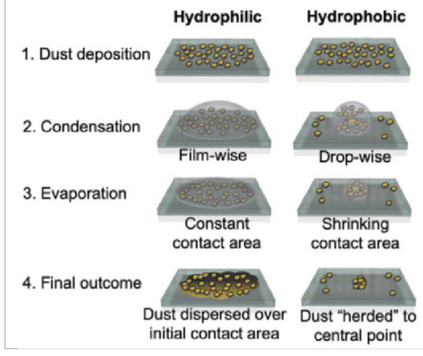
Taber linear felt abrader – EN1096.2



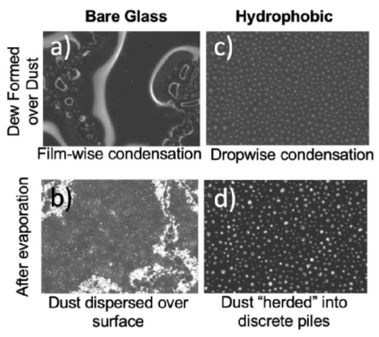
Saint-Gobain Diamant™ Glass

Anti-Soiling Mechanism

Anti-Soiling Mechanism



Experimental Results



Natural Weathering

Cocoa FL RTC

Albuquerque NM RTC

Goal: verify durability of AR/AS coatings in outdoor locations

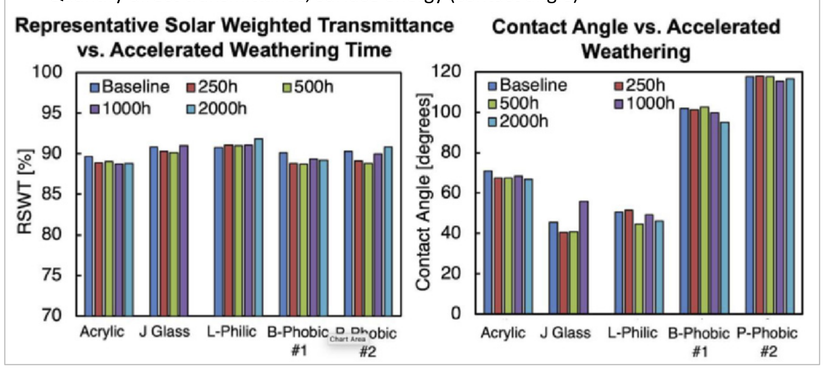
- Examine change in %T over 1 year exposure to natural soiling and weather (including dew)
- Identify likelihood of degradation occurring via factors that may not be examined in PV safety & qualification tests.
- Weather in challenging locations (DOE RTC's in Albuquerque, NM and Cocoa, FL.
- Direct transmittance and visual appearance will be monitored every other month.

Artificial Weathering

Goal: verify UV durability of polymer based AR/AS coatings

Weather to IEC 62788-7-2 A3 test condition:

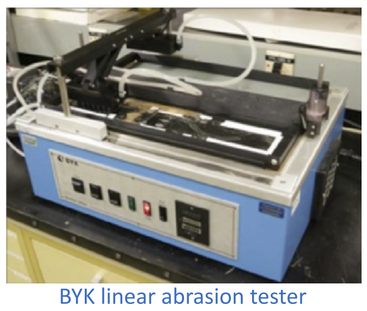
- Xe lamp at 0.8 $W \cdot m^{-2} \cdot nm^{-1}$ at 340 nm; 65 °C chamber temperature; 20% chamber RH.
- 4000h (6m) test.
- Xe lamps give high fidelity replication of the terrestrial solar spectrum, compliant with spectral requirements of the recent ASTM D7869 standard.
- Quantify direct transmittance, surface energy (contact angle)



Abrasion Testing

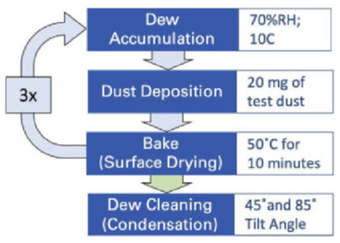
Goal: verify abrasion durability of AR/AS coatings

- Slurry & dry linear brush testing will be performed on coated specimens. Compare to float glass & PMMA references.
- ASTM D2486 (Nylon 6,6) brush.
- ISO 12103 Arizona Test Dust (A3 coarse)
- Method similar to DIN 53778-2.
- 0, 100, 1k, 2.5k and 5k cycles.
- Quantify direct transmittance, surface energy (contact angle).



BYK linear abrasion tester

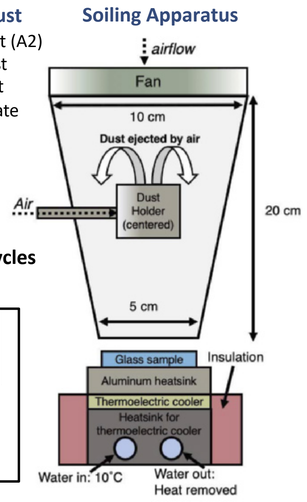
Effect of Dust Type on Self-Cleaning



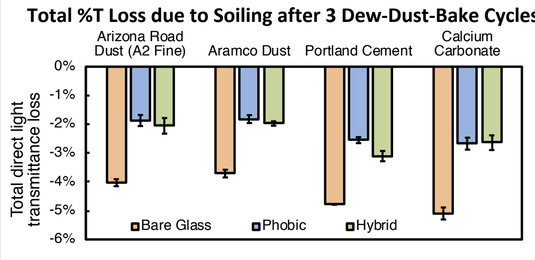
Standard Test Dust

1) Arizona Test Dust (A2)
2) Aramco Test Dust
3) Portland Cement
4) Calcium Carbonate

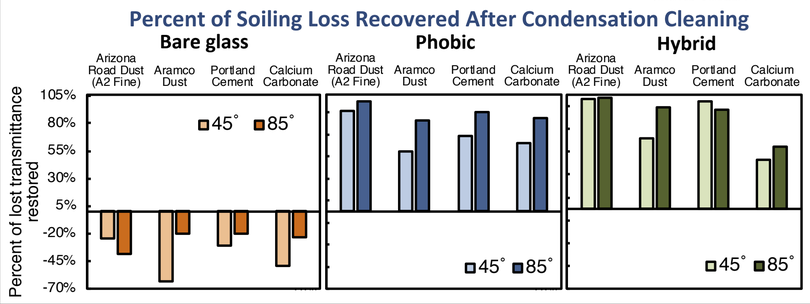
Soiling Apparatus



Total %T Loss due to Soiling after 3 Dew-Dust-Bake Cycles

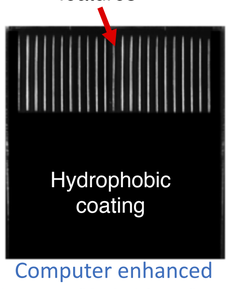


Percent of Soiling Loss Recovered After Condensation Cleaning



Optimization of Hydrophilic Features

Array of hydrophilic features



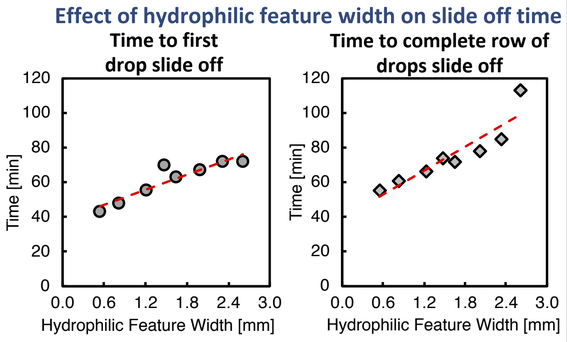
Computer enhanced image of hybrid surface

Channel Width: 0.5 mm
Channel Height: 20 mm
Channel Pitch: 2 mm

Goal: Optimize design of hydrophilic features to maximize condensation rate

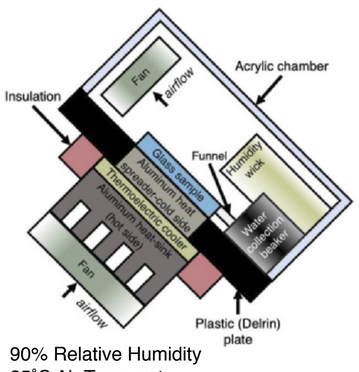
- Optimize geometry of the hydrophilic features
  - Hydrophilic feature width, height and pitch
- Minimize time for drops slide off the surface
- Maximize cleaning efficacy

Effect of hydrophilic feature width on slide off time



Hybrid Surface Cleaning Efficacy

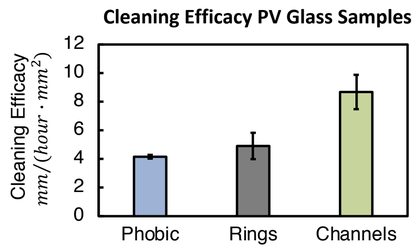
Condensation Chamber



90% Relative Humidity
25°C Air Temperature
10°C Glass Temperature

Experimental Results

Cleaning Efficacy PV Glass Samples

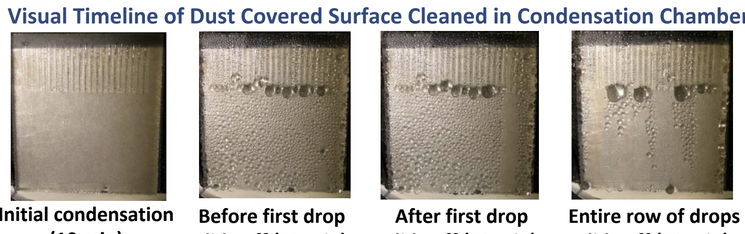


Cleaning Efficacy =

$$\frac{\text{total width of cleaned paths } \left(\sum_{r=1}^{n} w_n\right),\ mm}{(\text{time},\ hour)\ (\text{active area},\ mm^2)}$$

where: w = width of path cleaned by a drop

Visual Timeline of Dust Covered Surface Cleaned in Condensation Chamber



Initial condensation (10 min) | Before first drop slide off (52 min) | After first drop slide off (53 min) | Entire row of drops slide off (70 min)

[1] Simpson, L.; Muller, M.; Deceglie, M.; Miller, D.; Moutinho, H., The Modeling of the Effects of Soiling, Its Mechanisms, and the Corresponding Abrasion, PV Module Reliability Workshop, 2016. NREL/PR-5K00-66822.
[2] Qasem, H. Modeling dust for optimization, long term analysis, Soiling Effect of PV Modules Workshop, Dubai, UAE, 7 April, 2016.
[3]Woodhouse, M. et. al., On the Path to SunShot: The Role of Advancements in Solar Photovoltaic Efficiency, Reliability, and Costs. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-65872.

Albedo Data for Bifacial PV Systems

Bill Marion
National Renewable Energy Laboratory, Golden, CO

Introduction

At the September 2018 Bifacial PV Workshop in Lakewood, CO, a better understanding of albedo values and characteristics was identified as a key need by both the PV and financial communities to better estimate performance and to reduce risk of bifacial PV systems. To meet this need, the U.S. Department of Energy (DOE) has initiated work with the National Renewable Energy Laboratory (NREL) to provide the following:

- A multi-year database of measured and quality-assessed albedo values with temporal resolution of one hour or less for numerous locations and types of ground surfaces.
- Site metadata for each location (pictures, instruments and calibration history, soil and vegetation types, etc.)
- Site albedo statistics for each location (diurnal profiles, monthly and annual means, interannual variability)
- Analysis of the spectral mismatch for bifacial PV modules of the ground-reflected radiation for anticipated deployment surfaces (using both measured and modeled spectral albedo data)
- Comparisons of the measured albedos with available satellite-derived MODIS albedo products to validate the MODIS albedo products for estimating bifacial PV system performance

The albedo data base will include data from the SURFRAD and Ameriflux measurement networks. *We are also asking the PV industry to provide their albedo measurements and take part in a cooperative effort to create an expansive and accurate database of albedo values.*

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.

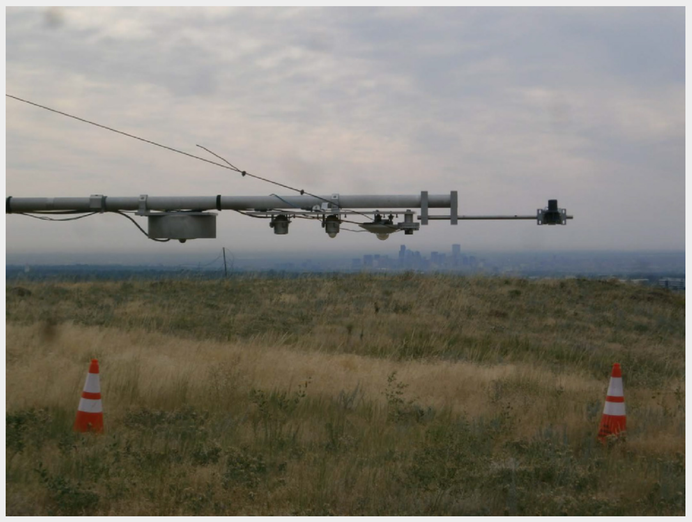


Fig 1. Albedo measurements at NREL's Solar Radiation Research Laboratory.

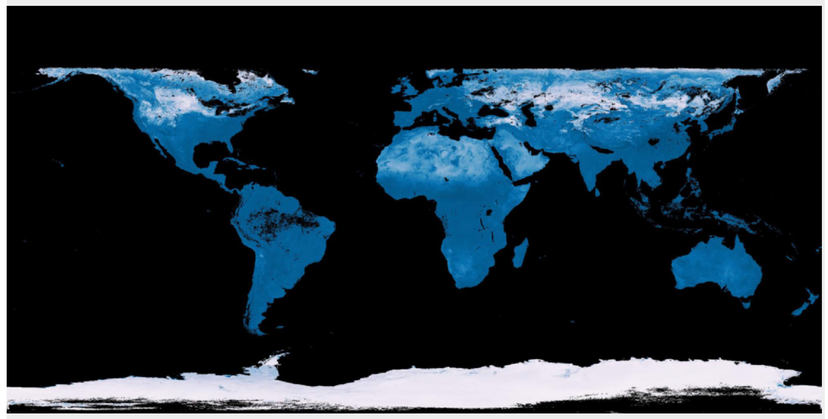


Fig 2. NASA's Earth Observations albedo map for December 2016.

Albedo is an essential parameter for determining the earth's energy balance and climate change; consequently, NASA makes available albedo products using Moderate Resolution Imaging Spectroradiometer (MODIS) data from sensors onboard Terra and Aqua satellites. Ground reflection is measured from a changing satellite viewpoint over several days. Persistent cloudiness preventing the satellites from viewing the ground may result in "no data" (shown as black in Fig. 2 for parts of South America).

Albedo Characteristics

The albedo of a surface is not a constant. There is an angular dependence that typically increases the albedo as the sun's zenith angle increases. This imparts diurnal, seasonal, and latitude variations. Most surfaces do not reflect all wavelengths of light equally; consequently, as the spectral content of the radiation received by the ground surface varies throughout the day, variations in albedo may occur. Additionally, the spectral characteristics of the surface may also change with season, such as green grass becoming brown in the fall.

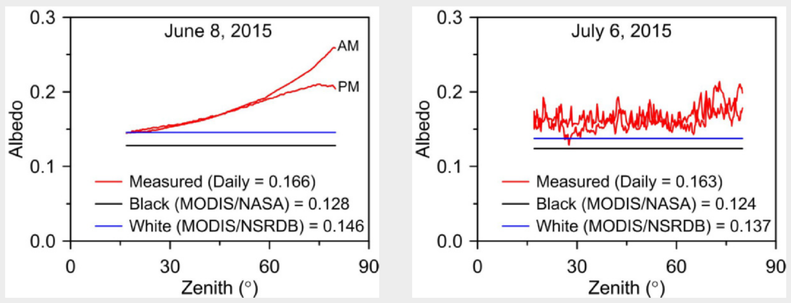


Fig 3. Albedo versus sun zenith angle for a sunny day (June 8) and a cloudy day (July 6). The cloudy day measurements show a smaller variation in albedo because the angular distribution of the radiation from the diffuse sky is more constant. The sunny day shows larger variations in measured albedo with maximum values occurring at larger sun zenith angles (near sunrise and sunset). Satellite derived daily albedo values are also shown. "Black-sky" is the derived albedo in the absence of a diffuse component and for solar noon. "White-sky" is the derived albedo in the absence of a direct component (cloudy skies).

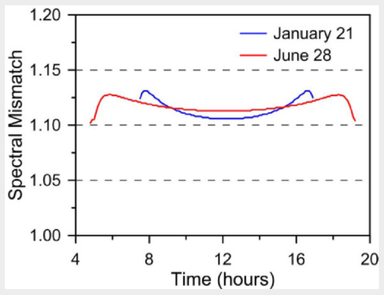


Fig 4. Albedo spectral mismatch for x-Si cells for clear skies and using SMARTS modeled ground-reflected spectral irradiance and spectral reflectance data for "Dry Long Grass". Mismatch values greater than one indicate PV module output is greater than indicated by albedo measured with broadband pyranometers.

How to Participate

We are asking the PV industry to provide their albedo measurements and take part in a cooperative effort to create an expansive and accurate data base of albedo values. If you have albedo data to contribute or for more information, please contact Bill Marion (bill.marion@nrel.gov or 303-384-6793).

Albedometer data using either pyranometers or reference cells are sought. Additional meteorological data for quality assessment and general PV performance modeling would also be very useful if available. This includes parameters such as direct normal and diffuse horizontal irradiance, ambient dry bulb temperature, relative humidity, wind speed and direction, snowfall, and rainfall (wet soils have lower albedo).

Metadata

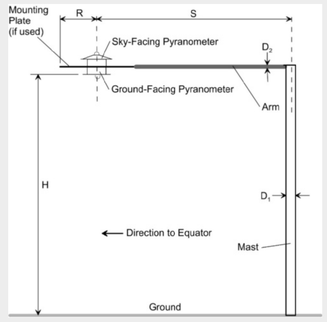
Information about your albedo data and its collection will be needed (to the extent possible) for the following areas:

Location of Measurements
- City, state, country
- Latitude, longitude, elevation

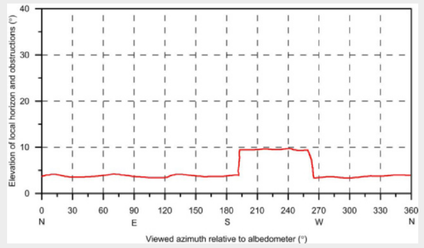
Ground Surface
- Vegetation and soil types

Albedometer Instruments
- Sky-facing, manufacturer and model
- Ground-facing, manufacturer and model

Albedometer Installation Dimensions
- Using reference dimensions to right



Shading Obstructions Viewed by Albedometer
- Sketched on diagram, if any



Maintenance
- Instrument cleaning and calibration frequency

Images
- Albedometer installation and the supporting structure
- Horizontal views from the albedometer for the four cardinal directions (N, E, S, and W).
- Ground surface. If the ground surface is vegetation, date-stamped images depicting seasonal changes.

Products

NREL will quality assess the albedo data and use a common data file format (hourly or less temporal resolution). Albedo summary statistics will be determined for each location (diurnal profiles, monthly and annual means, interannual variability). The albedo data files, the summary statistics, and the site metadata will be available from the DuraMAT website (https://www.duramat.org/).

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2019 PV Reliability Workshop
Lakewood, CO
February 26-28, 2019
NREL/PO-5K00-73375

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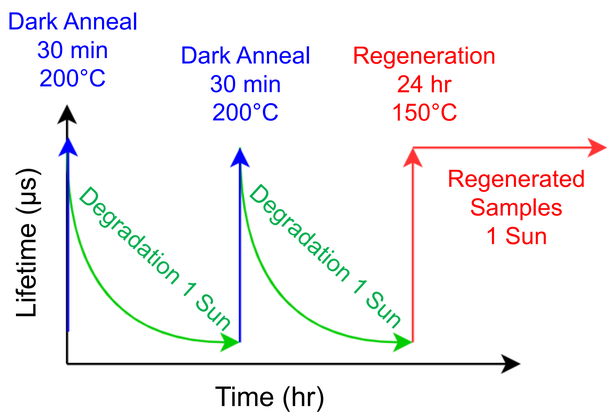
Surface Passivation and Fast Firing effect on Light Induced Degradation and Regeneration of *p*-type Crystalline Silicon Solar Cells

Abigail Meyer, Sumit Agarwal - Colorado School of Mines;

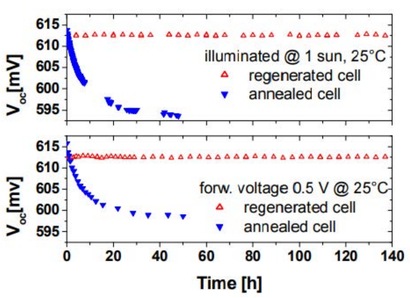
Vincenzo LaSalvia, William Nemeth, Matthew Page, David Young, and Paul Stradins - National Renewable Energy Laboratory

abigailmeyer@mymail.mines.edu

Current understanding of light-induced degradation (LID)



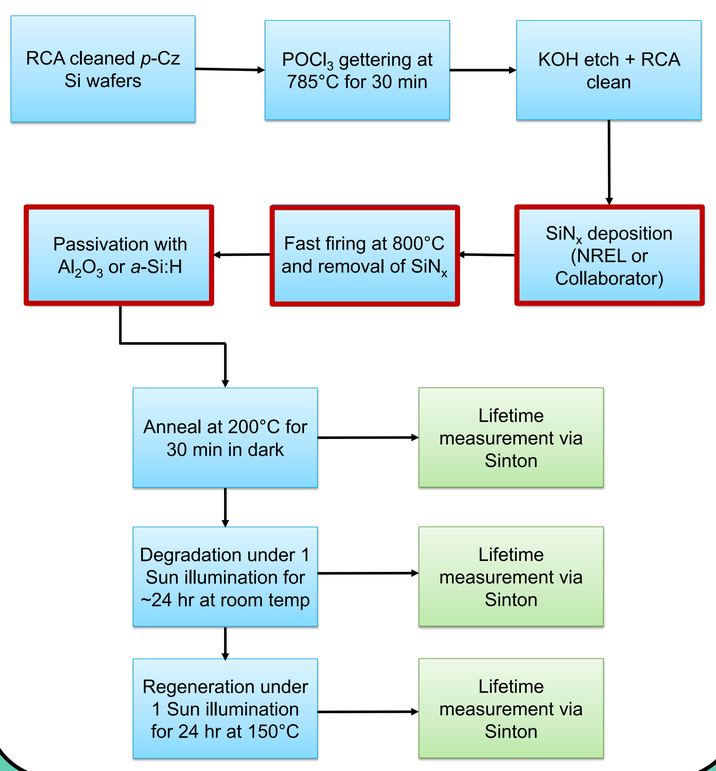
Mitigation of LID is well known,[1] but mechanisms are not well understood



Hydrogen has been hypothesized to be vital to the regeneration process, but no structural or chemical/bonding evidence has confirmed this.

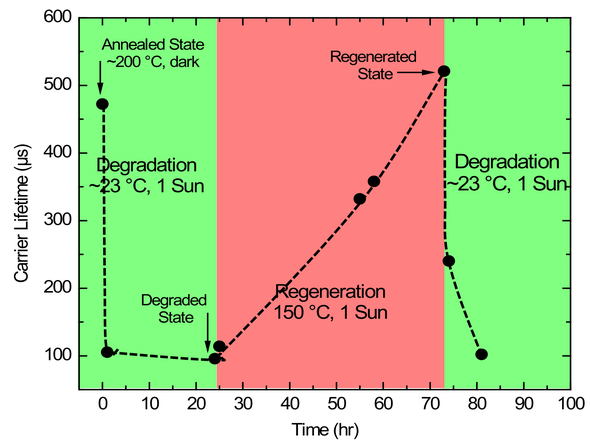
[1] Herguth *et al., Proc. of the 32nd IEEE PVSC (4th WCPEC)*, 2006.

Experimental process flow for investigation of regeneration



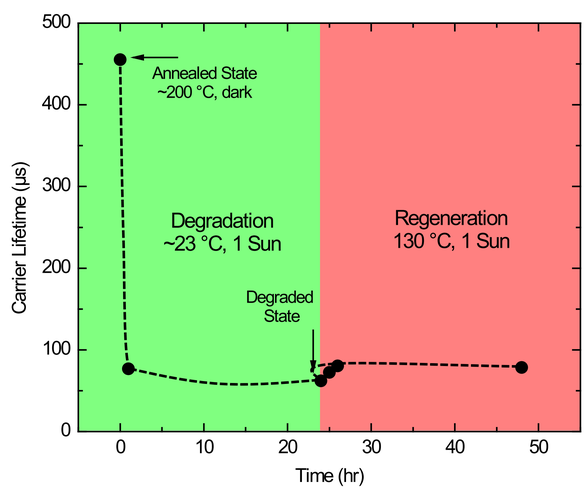
Effect of Fast Firing and Passivation Scheme on Regeneration

No Fast Firing and Al_2O_3 Passivation



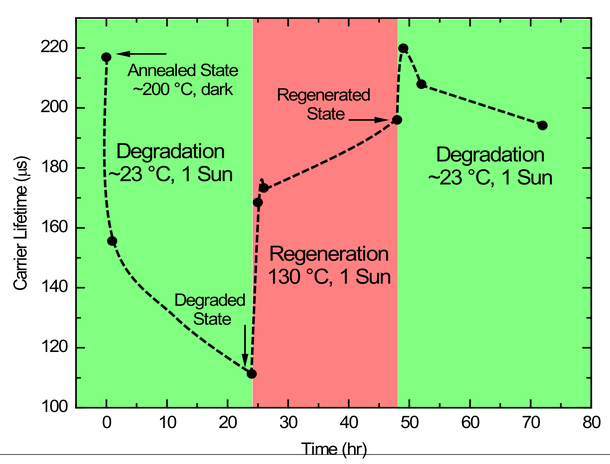
Metastable regeneration obtained

Fast Firing and Al_2O_3 Passivation



Negligible regeneration

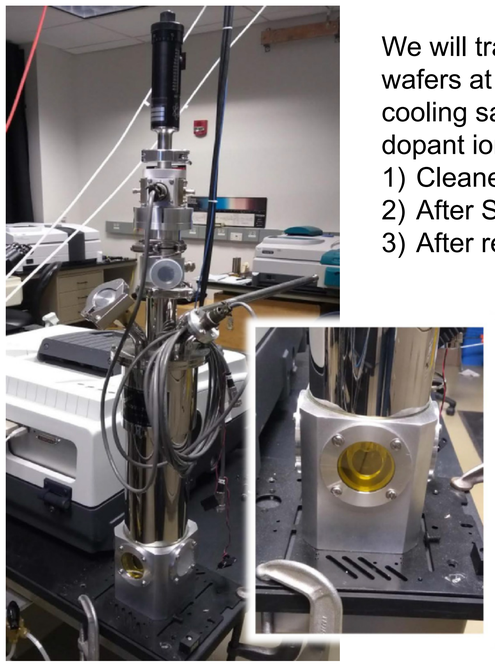
Fast Firing and *a*-Si:H Passivation



Stable regeneration achieved with *a*-Si:H passivation

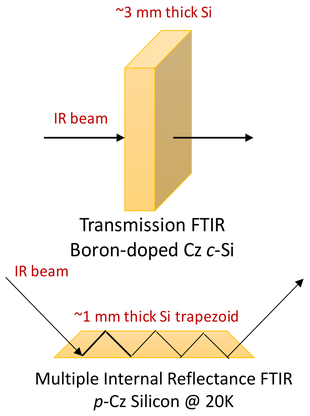
Hypothesized that Al_2O_3 activation anneal at 400 °C erases the precursor for regeneration to occur

Future Work: Identifying vibrational modes of LID boron-oxygen defects using cryogenic FTIR

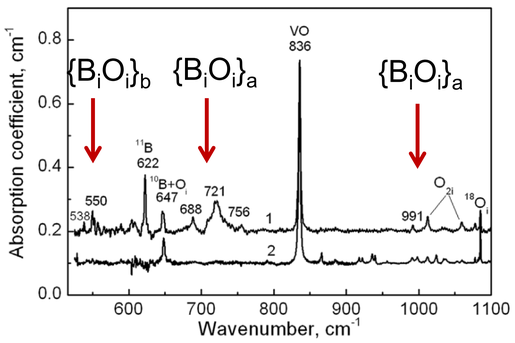


We will track hydrogen within the wafers at three stages of LID by cooling samples to freeze out dopant ionization.

1) Cleaned SDR wafers
2) After SiN_x firing and strip
3) After regeneration



Murin *et al.* identified local vibrational modes for B-O complexes at 550, 721, and 991 cm^{-1} [2]



We can detect B-O and B-H modes which are currently hypothesized to be related to LID

[2] Murin *et al., Phys. Status Solidi A.* **213**, 2850-2854, (2016)

Conclusions

- Using *p*Cz wafers we have shown that LID can be reversed with a fast firing and regeneration step.
  - ✓ Plasma deposited *a*-Si:H provides stable regeneration compared to Al_2O_3 followed by FGA at 400 °C
  - ✓ We hypothesize low temperature deposition of *a*-Si:H prevents hydrogen effusion from the bulk compared to Al_2O_3 passivated samples.
- Chemical nature of B-O and B-O-H defects will be studied using ESR and FTIR.
  - ✓ Hydrogen will be tracked at three stages throughout LID to determine the role of firing and hydrogen during regeneration.

We acknowledge Dr. Axel Herguth and Dr. Brett Hallam for SiN_x deposition and firing samples for this work.

Funding for this work was provided by US DOE EERE contract SETP DE-EE0008171 and under Contract No. DE-AC36-08GO28308 for the PVRD-2 project.

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Degradation Comparison of UV-cut and UV-pass Encapsulants

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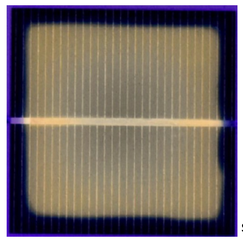
Introduction

- Two common degradation modes in field-aged modules: Encapsulant browning and delamination
- Caused by UV light, elevated temperatures, and humidity

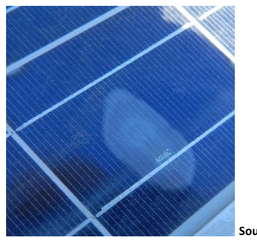
Encapsulant Browning



Source: PRL

- Late-onset degradation mode in PV modules
- Chromophore formation decreases transmission
- Durability issue detected by UV fluorescence (UVF) imaging

Delamination

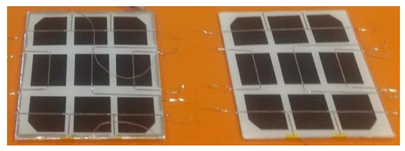


Source: NREL

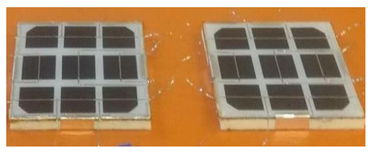
- Adhesion loss between encapsulant and other layers
- Optical decoupling decreases transmission
- Reliability issue leading to other degradation modes

Experimental Setup

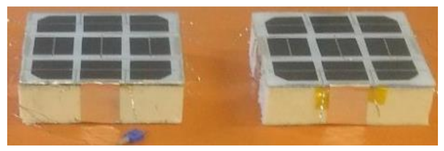
- Six mini-modules, three each with UV cut and UV pass EVA, were exposed to accelerated UV light
- Al tape on the backsheet prevents diffusion through the backsheet
- Each cells is 5.2 cm x 5.2 cm
- Samples were characterized intermittently with UVF imaging, light IV (solar simulator), reflectance, and Yellowness Index (YI) measurements



No insulation



0.5” insulation



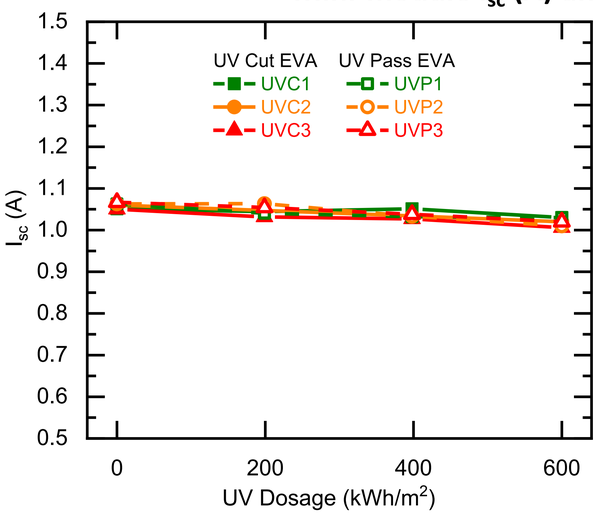
2” insulation

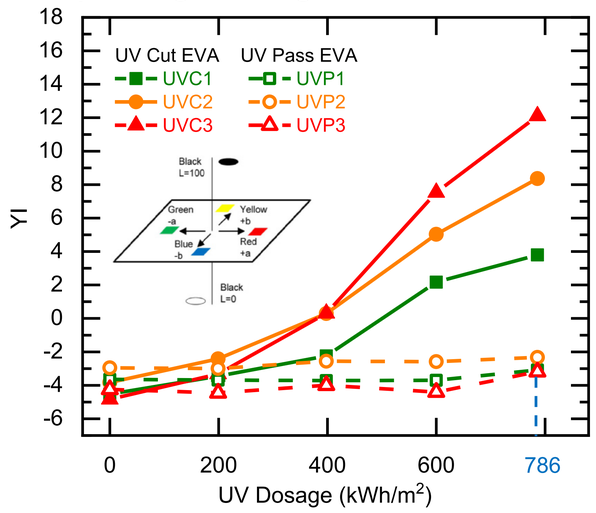
Results and Discussion

- Solar gain from UV lights combined with insulation enabled maintaining multiple mini-module temperatures

Temperature (°C)	UVC1	UVC2	UVC3	UVP1	UVP2	UVP3
	60.9	66.2	72.5	60.5	66.5	69.9

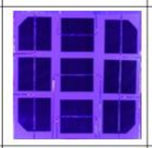
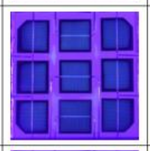
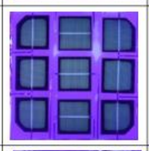
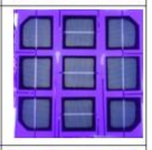
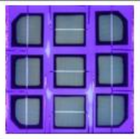
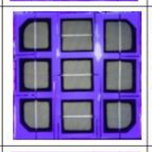
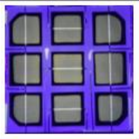
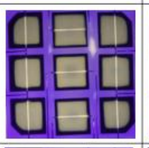
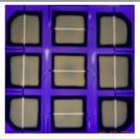
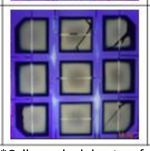
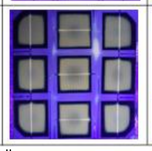
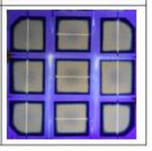
Mini-module I_{sc} (A) and corresponding YI change



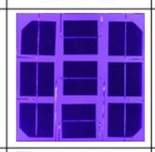
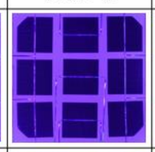
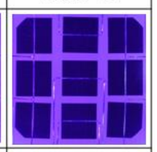
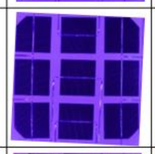
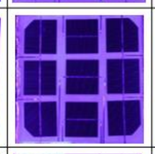
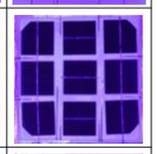
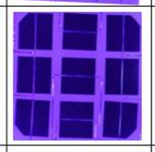
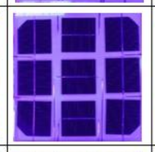
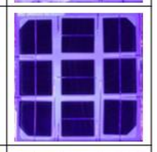
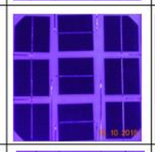
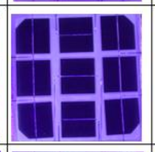
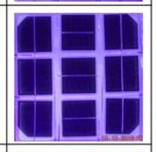
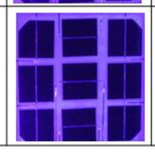
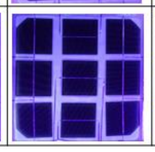
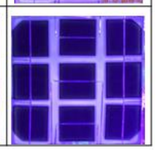


- I_{sc} drop measured is within measurement uncertainty
- YI shows an increase indicating a temperature based change in the UVC mini-modules

Detecting the encapsulant browning and delamination through UVF imaging

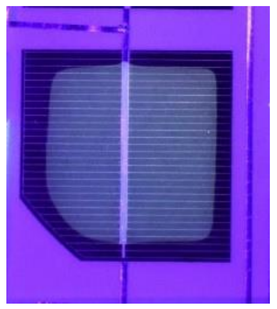
Coupons	UVC 1	UVC 2	UVC 3
Temperature	60.9°C	66.2°C	72.5°C
0 kWh/m²			
200 kWh/m²			
400 kWh/m²			
600 kWh/m²			
786 kWh/m²			

*Cells cracked due to a fall

Coupons	UVP 1	UVP 2	UVP 3
Temperature	60.5°C	66.5°C	69.9°C
0 kWh/m²			
200 kWh/m²			
400 kWh/m²			
600 kWh/m²			
786 kWh/m²			

- The browning seen in UVC samples increases with UV dosage and mini-module temperatures
- This is supported by YI measurements
- The UVP mini-modules have undergone no visible browning

UV-T exposure – 200 kWh/m²



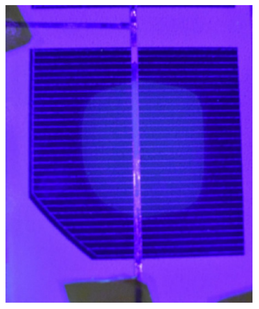
UVC 3
T: 78.4°C
RH: 0%

UVP 3
T: 77.9°C
RH: 0%

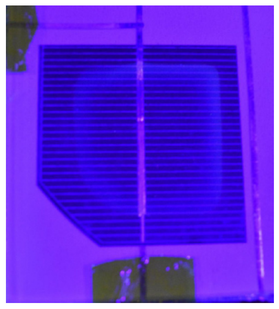
Al tape on the backsheet

Al tape on the backsheet: No oxygen photobleaching

UV-T-RH exposure – 186 kWh/m²



RH-UV Cut EVA 3
T: 63.1°C
RH: 28.9%



RH-UV Pass 3
T: 67.1°C
RH: 28.9%

No Al tape on the backsheet

No Al tape on the backsheet: Photobleaching

Conclusions

- YI measurements differentiates degradation modes despite the similar I_{sc} drop in both sets
- UVF imaging >> YI > Isc drop to detect browning
- UVC mini-modules undergo encapsulant browning, a durability issue whose course can be predicted
- UVP mini-modules undergo little to no encapsulant browning and delamination
- Delamination is a reliability issue whose course and intensity cannot be predicted and can lead to other degradation modes such as corrosion

Arizona State University

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

Direct Imaging of Stress in Crystalline Silicon Modules

Imaging Deflection and Stress in Next Generation PV Modules

Xiaodong Meng, Mariana Bertoni

Ira A. Fulton Schools of Engineering, Arizona State University, Tempe AZ, 85287

DuraMAT Capabilities

1. Data Management & Analytics, DuraMAT Data Hub
2. **Predictive Simulation**
3. **Advanced Characterization & Forensics**
4. **Module Testing**
5. Field Deployment
6. Techno-Economic Analysis

University Goals

- Understand the origin of cracking and control crack formation by selecting best materials
- Several types of encapsulants (e.g., silicone, EVA, POE, IO); stress induced and failure mechanisms may be different
- Stress evolution through aging unknown
- Standard IEC tests have different impact in different encapsulants

Accomplishments

- Upgraded tool to map 6" solar minimodules and replace plate for CMOS camera to increase throughput
- Imaged the effect of materials and connections on deflection
- Created framework to correlate to electrical performance
- Preliminary evaluation of stress vs. probability of failure
- Preliminary evaluation of accelerated testing on deflection

Outcomes and Impact

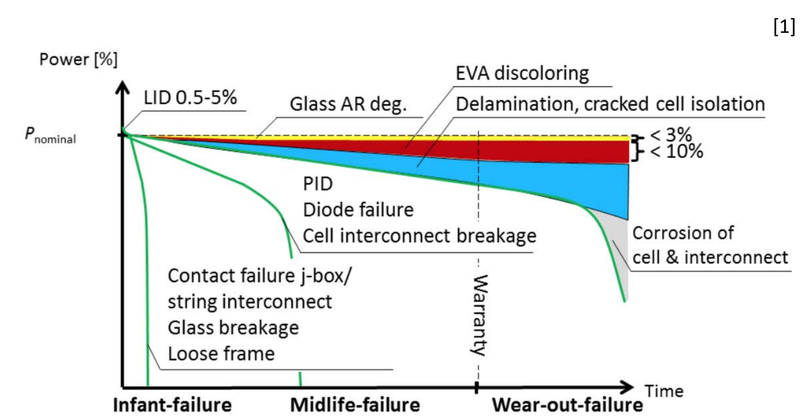
- Outcomes will include stress mapping before and after accelerated testing protocols, physical models of stress evolution, and materials recommendations
- Close collaboration with supply chain ensures that project remains relevant to PV industry
- Ensuring best material selection to minimize cracking and module lifetimes of 40 years

Capability Development

- Cell cracking accounts for a high percentage of the power loses in the midlife-failure and wear-out-failure regimes.
- Cracking also increases the sensitivity of system performance to shading.
- Most cracks originate during the stringing or from the intrinsic mismatch of thermo-mechanical properties between the wiring and the silicon during the soldering process.
- We argue that the process of module assembly today is optimized from the point of view of the inactive materials (e.g. encapsulant cross-linking) offering no insights into the solar cell status.

✓ Image modules with a range of encapsulants, backsheets and tabbing materials combinations
✓ Image after accelerated testing
✓ Correlate maps and module performance
✓ Physical models of the failure mechanisms
✓ Materials and Processes recommendations for module fabrication

Cost Drivers



Setup

X-ray Topography

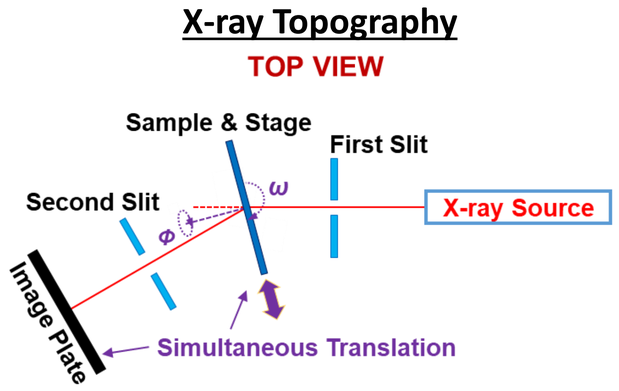
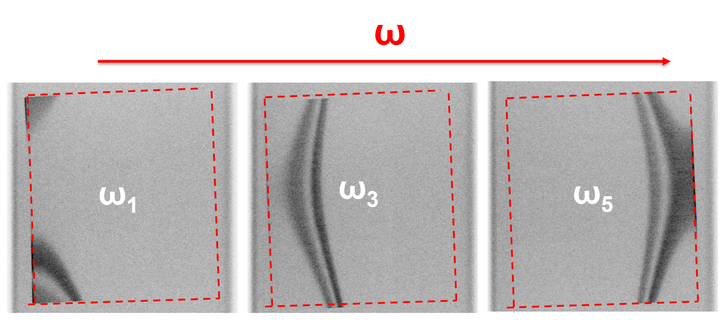
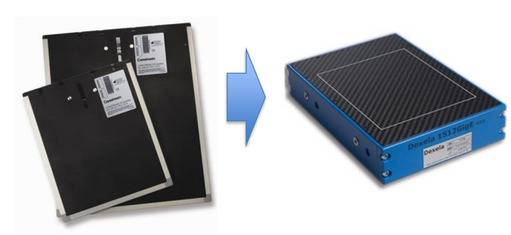


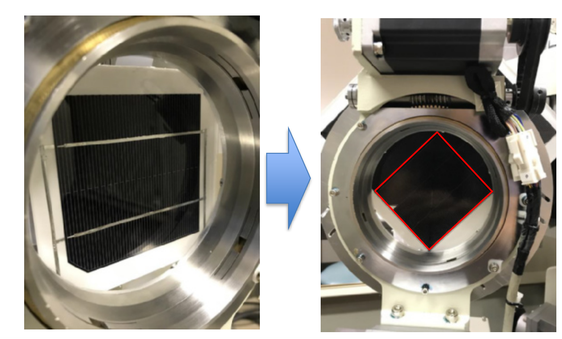
Image Acquisition



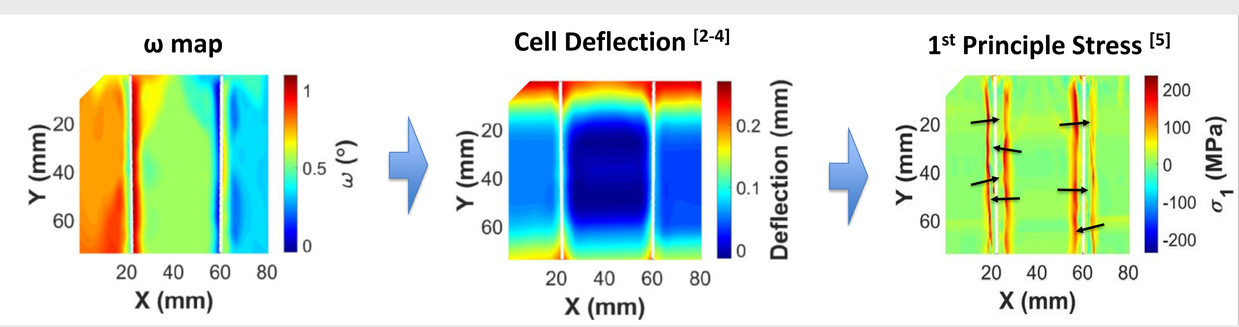
Detector Upgrade, 5x faster



Holder Upgrade, 6'' capability

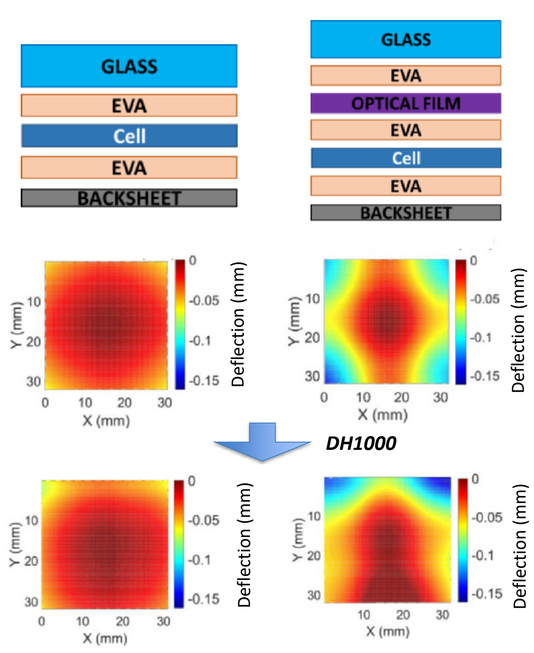


Data Processing

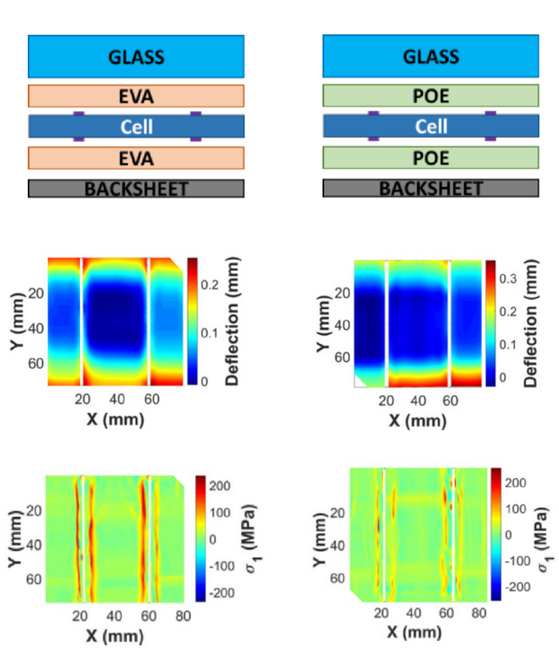


Reliability Testing & Material

Effect of DH1000

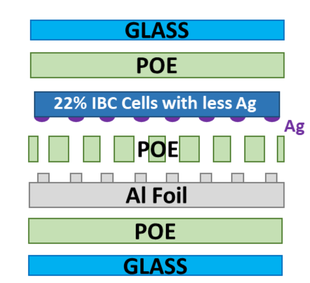


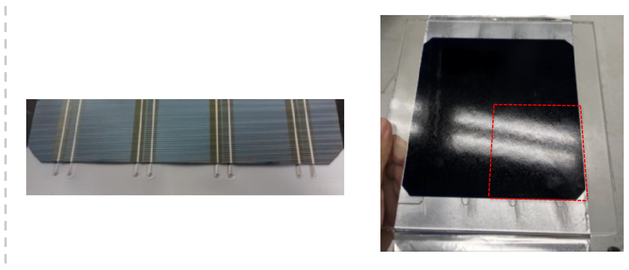
Effect of Encapsulant

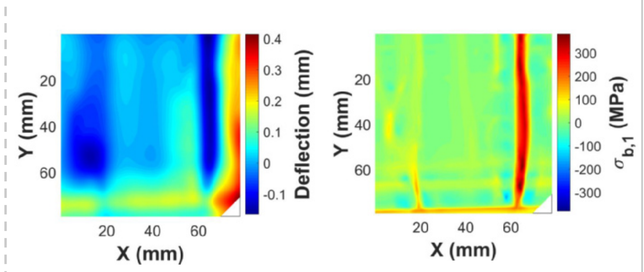


6'' Next Generation Modules

Case 2: Flex-Circuits







Reference

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[2] X. Meng, M. Stuckelberger, L. Ding, B. West, A. Jeffries, and M. Bertoni, "Quantitative mapping of deflection and stress on encapsulated silicon solar cells," *IEEE J. Photovoltaics*, vol. 8, no. 1, pp. 189–195, 2018.
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[5] X. Meng, R. Meier, M. Stuckelberger, A. Jeffries, S. Bernardini, M. Bertoni, "Bending Stress Analysis of Encapsulated Silicon Solar Cells", in *2018 World Conference on Photovoltaic Energy Conversion (WCPEC-7)*, 2018, In Press.

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Analysis of the acetic acid generation in the PV modules

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Eco Solutions Company of Panasonic Group
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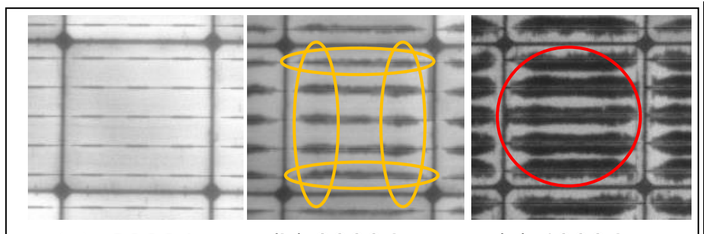
Motivation

Most of the PV modules have been produced using ethylene-vinyl acetate (EVA) encapsulants. As shown in Figs. 1 and 2, the power (P_{max}) of the modules with EVA/EVA/water-permeable-back-sheet structure sharply degrades after damp-heat(DH) test over than 3000 hours(h). It is known that the degradation is caused by the corrosion of the silver (Ag) grid and solder connection on the cell where the acetic acid concentration is high[1, 2].

Since the power loss by the degradation is critical to the power decay of PV systems, the mechanisms of the acetic acid generation is important. To clarify the mechanism of acetic acid generation, the acetic acid concentration is calculated by diffusion equation and hydrolysis reaction.



(a) 2000 h (b) 3000 h (c) 4000 h

Figure 1. EL image of module B after DH test.

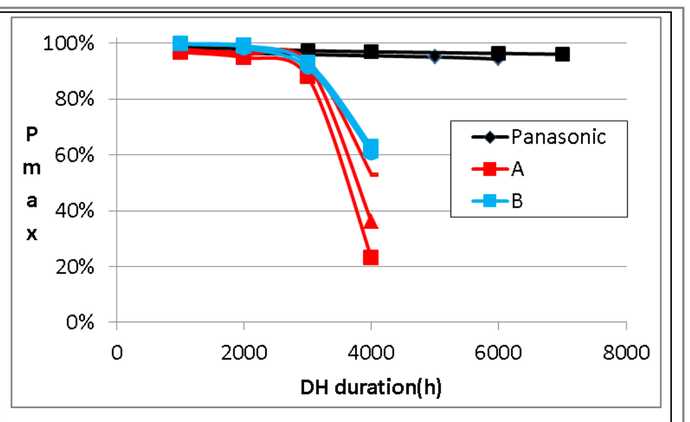


Figure. 2. Power decay as a function of DH duration.

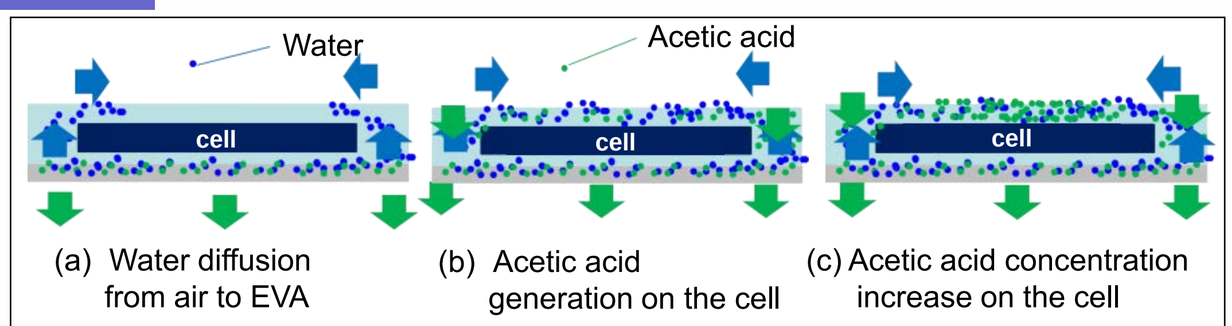
Calculation of water diffusion and acetic acid generation

Figure 3 shows the schematic diagram of water diffusion and acetic acid generation. Firstly, water diffuses from air to the EVA which is between glass and cell. Then the EVA is degraded by hydrolysis reaction. Since the acetic acid generated in EVA between cell and glass takes long time to diffuse to air, the acetic acid concentration (C_A) increases with time(t) there.

Mapping of water concentration (C_W) and C_A are calculated by two dimensional diffusion equation(Eq) (1). Since water diffusion from air to EVA is much faster than that in the EVA on the cell, the C_W of saturation water content of EVA is assumed as a boundary condition on the cell edge. On the other hand, the acetic acid diffusion from EVA to air is much faster than that on the cell. Therefore, the C_A of zero is also assumed as a boundary condition on the cell edge. The area dependence of the diffusion coefficient is considered since the interconnector works as diffusion barrier.

As shown in Eq. (2), the hydrolysis reaction is caused by water and acid catalyst. Since acetic acid is weak acid, the hydroxyl ion (H^+) concentration ($[H^+]$) comes near Eq. (3). Therefore, the increased C_A and decreased C_W by hydrolysis are shown as eq. (4).

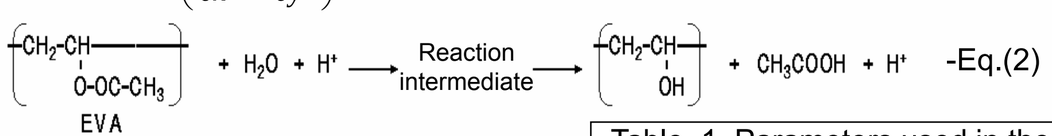
Using Eqs. (1) and (4), the micro changes of C_W and C_A after micro time (Δt) are shown as Eqs. (5) and (6). The parameters used in the calculation are shown in Table. 1. Concentration is described by weight ppm.



(a) Water diffusion from air to EVA (b) Acetic acid generation on the cell (c) Acetic acid concentration increase on the cell

Fig. 3. Schematic diagram of water diffusion and acetic acid generation.

$$\Delta C_D = \Delta t D\left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2}\right) \quad \text{-Eq.(1)}$$



-Eq.(2)

$$[H^+]^2 = C_a \cdot K_a \quad \text{-Eq.(3)}$$

$$\Delta C_{AH} = -\frac{60}{18}\Delta C_{WH} = a\Delta t \cdot C_W \cdot C_A^{1/2} \quad \text{-Eq.(4)}$$

$$C_W(t+\Delta t) = C_W(t) + \Delta C_{WD} + \Delta C_{WH} \quad \text{-Eq.(5)}$$

$$C_A(t+\Delta t) = C_A(t) + \Delta C_{AD} + \Delta C_{AH} \quad \text{-Eq.(6)}$$

Table. 1. Parameters used in the calculation

Water diffusion coefficient (mm^2/h)	edge	6.25
	center	0.625
Acetic acid diffusion coefficient(mm^2/h)	edge	6.25
	center	0
Acetic acid generation($/ppm^{1/2}/h$)		2.53×10^{-5}

Results and discussions

Figure 4 shows the mapping of the C_W and C_A after DH test. Since water diffusion from cell edge to cell center takes over than 1000 h, the C_A before 1000 h is very low. However, the C_A after 1000 hrs is non-linearly increased. This is caused by acetic acid working as the catalyst of hydrolysis reaction. The increase of the C_A causes the increase of the generation rate of the C_A. Therefore, the C_A increases with square of time (t) where water is sufficiently supplied. This sharp increase of C_A causes the sharp drop of P_{max} as a function of t. In the DH test, the degradation began at 3000 h at a part of the place between edge and center on the cell and almost all area on the cell were degraded at 4000 h. As shown in Fig. 5, the C_A in area 2 before 3000 h and that in area 1 at 4000 h are around 2000 ppm. Therefore, C_A of 2000 ppm is found to be the threshold concentration of the degradation mode.

It should be noted that the C_A is nearly proportional to the square of time. Since the 25 years correspond to illuminated duration of 30000-60000 h, which is one order of magnitude longer than DH test. Since the water content in outdoor is one order of magnitude lower than DH test, the generation speed during DH test should be one order of magnitude higher than that in outdoor for sufficient acceleration test. It is suspicious that the generation speed at illuminated module is one order of higher than that at 85°C. The DH test up to 2000 h might not be sufficient for this degradation mode.

Recently, the outdoor modules degraded by acetic acid are reported by ISES[1]. Although the modules are exposed at hot-humid area of China, the degradation rate reach around 25% after 18 years. We should take notice of the degradation rate after DH 3000 h if the PV system is used for long term in hot-humid area.

On the other hand, our panels are free from this degradation mode. Our panels can be used with higher reliability at hot-humid area.

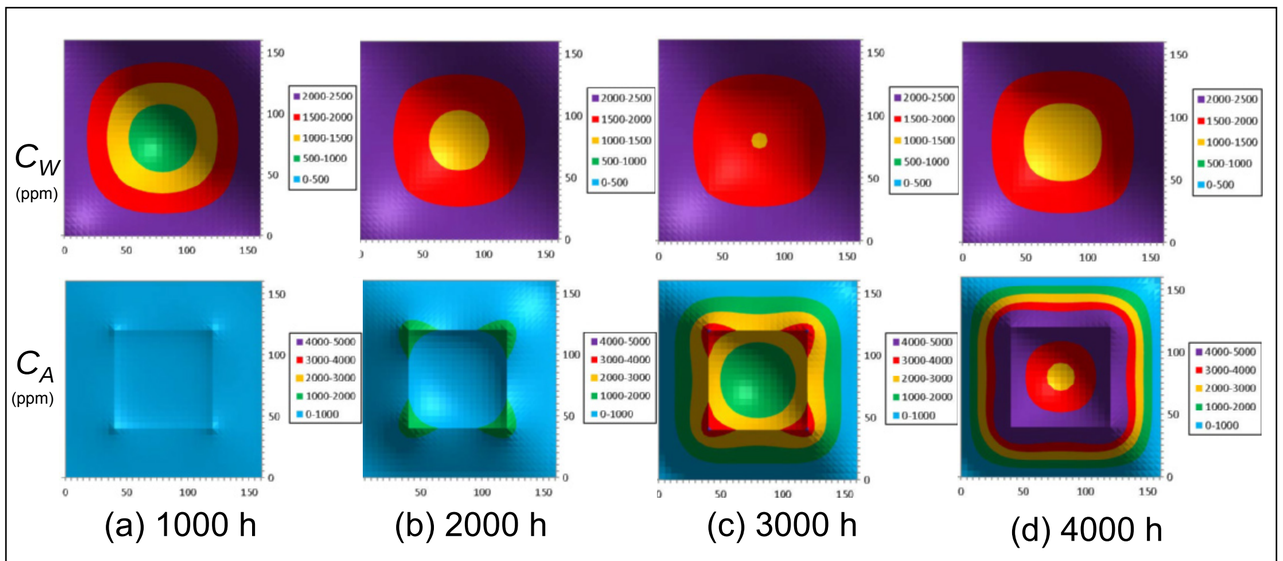
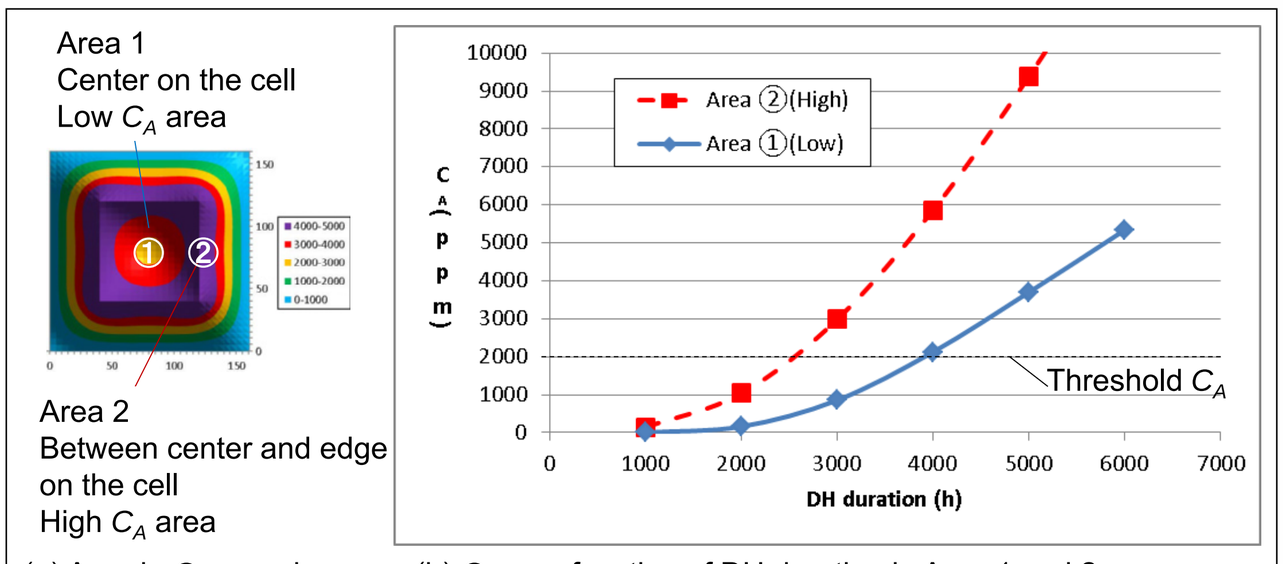


Figure 4. Mappings of water and acetic acid concentrations (C_W and C_A) after DH test.



(a) Area in C_A mapping (b) C_A as a function of DH duration in Area 1 and 2.

Figure 5. C_A during DH test at low and high areas.

[1] Huili Han , Xian Dong, Haiwen Lai , Huan Yan, Kai Zhang, Jiangfeng Liu, Pierre J. Verlinden , Zongcun Liang , and Hui Shen, IEEE JOURNAL OF PHOTOVOLTAICS, VOL. 8, NO. 3, MAY 2018
[2] Y. Ino et al. "Effect of soldering on the module degradation along bus bar in DH test and PCT for crystalline Si PV modules", in Proc. WCPEC-7, (2018).

Conclusions

Since water diffusion from air to EVA between glass and cell takes over than 1000 h in DH test, DH test for 1000 h is not sufficient for durability evaluation of the acetic-acid degradation. It should be noted that the acetic acid concentration is nearly proportional to the square of time where water is sufficiently supplied. Both facts indicate that the longer DH test is required for EVA/EVA/water-permeable-back-sheet structure. Since our panels are free from this degradation mode, our panels can be used with higher reliability at hot-humid area.

Regional Test Centers
Differentiating PV Quality

WattGlass
Glass Coatings Perfected

Field Installations of a High-Performance Antireflective Coating for Solar Modules

Robert A. Fleming[1], Aaron Sahm[2], John R. Sherwin[3], Bruce H. King[4], and Corey S. Thompson[1]

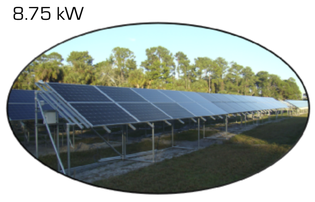
[1]WattGlass, Inc.; [2]University of Nevada – Las Vegas; [3]Florida Solar Energy Center; [4]Sandia National Laboratories

Field Installations at DOE Regional Test Centers

Southern Nevada Water Authority
Las Vegas, NV
9.45 kW

Sandia National Laboratory
Albuquerque, NM
9.45 kW

Florida Solar Energy Center
Cocoa, FL
8.75 kW



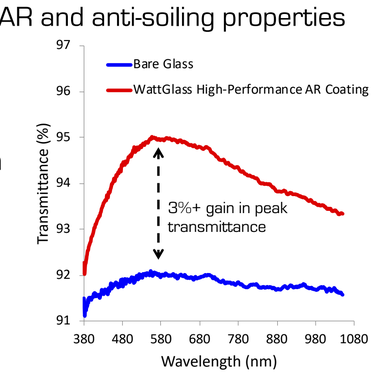
WattGlass has partnered with the DOE Regional Test Center (RTC) Program to conduct field testing of PV modules packaged with WattGlass' high-performance AR coating

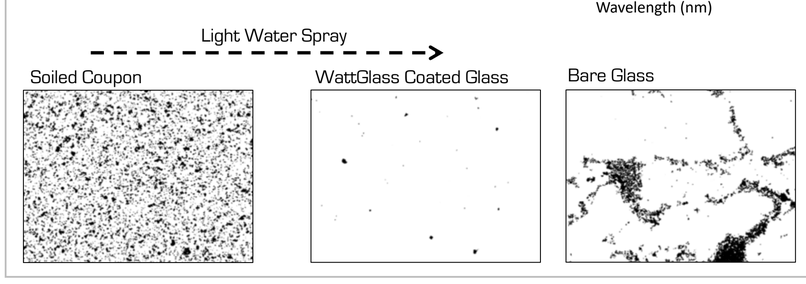
- Three locations with different climates
  - Cocoa, FL (Humid Subtropical)
  - Albuquerque, NM (Cold Semi-Arid)
  - Las Vegas, NV (Hot Desert)
- 30 modules installed at each test site
  - 15 experimental modules packaged with the WattGlass AR coating
  - 15 control modules packaged with either bare glass or with competing AR coatings utilized by two Tier 1 solar module manufacturers
  - Same bill of materials used for experimental and control modules

WattGlass High-Performance AR Coating

WattGlass has developed a high-performance multifunctional coating for solar PV modules with AR and anti-soiling properties

- Fabricated from an aqueous nanoparticle solution with proprietary binder
- Greater than 3% improvement in solar-weighted transmittance
- Resistant to particulate soiling
  - Superhydrophilic surface chemistry that reduces adhesion of dust and dirt



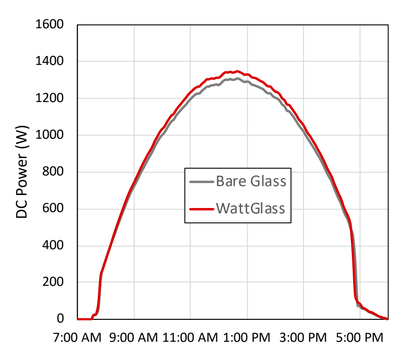


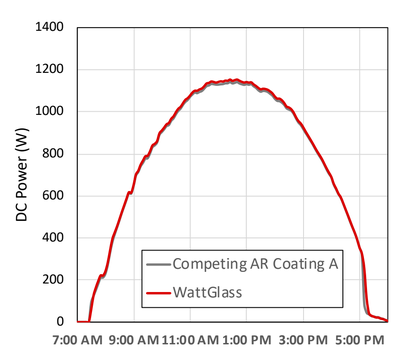
System Design

- Three module manufacturers
  - D2 Solar (San Jose, CA): WattGlass and Bare Glass
  - Two Tier 1 Module Manufacturers: WattGlass and Competing AR Coatings A and B
- Fixed tilt installations with 6 independent strings (experimental and control modules × 3 manufacturers)
- Fronius Primo 3.8-1 string inverters with independent MPPTs (2 strings per inverter)
- Integrated DC current/voltage monitoring on Fronius inverters, transitioning to a standalone data monitoring system (completed at Albuquerque, installation at Cocoa and Las Vegas expected soon)

Improved Power Output

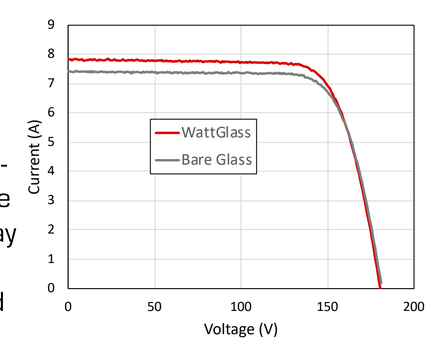
- DC power output comparison for WattGlass modules compared to bare glass and compared to modules from Manufacturer A
- Data collected on a clear day at the Florida RTC location in early February 2019
- Greater than 3% increase in peak power output compared to bare glass; greater than 1% increase in peak power output compared to competing AR coating A
- Results correlate well with flash test data obtained during module manufacturing

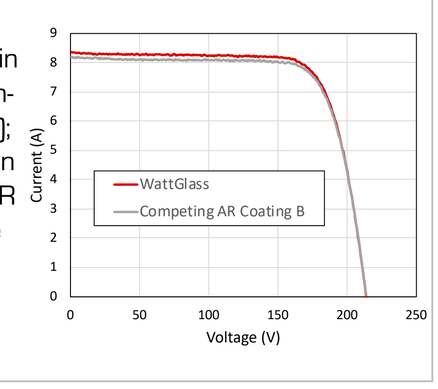




On-Site I-V Measurements

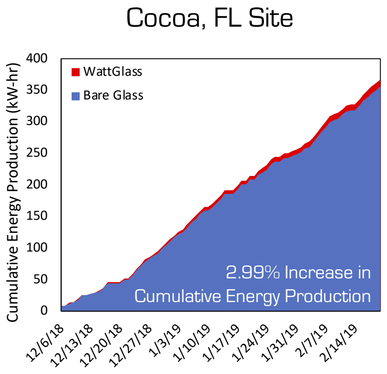
- String-level current-voltage curves measured with a Daystar DS-100C mobile curve tracer
- Curves measured during mid-morning sun conditions at the Florida RTC site on a clear day in December 2018
- In-plane irradiance monitored with a hand-held Si cell pyranometer
- Greater than 5.5% increase in I_{sc} compared to bare glass (in-plane irradiance 850 W/m^2); greater than 2.2% increase in I_{sc} compared to competing AR coating B (in-plane irradiance 920 W/m^2)

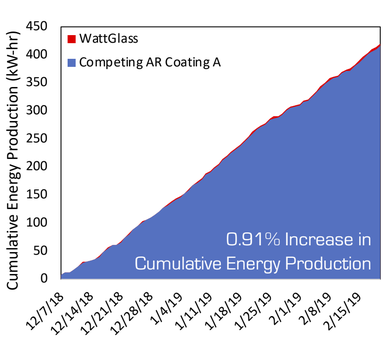


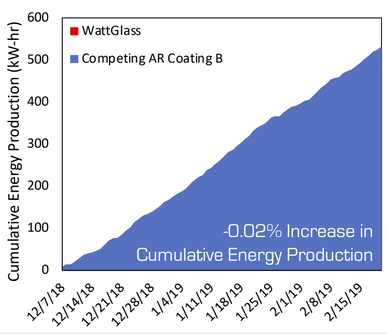


Cumulative Site Energy Production

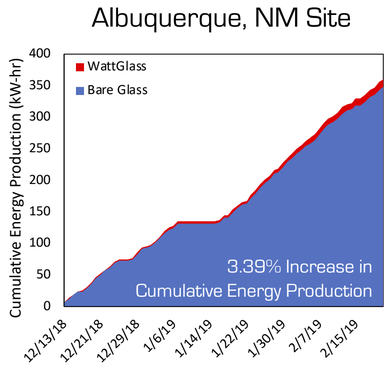
Cocoa, FL Site

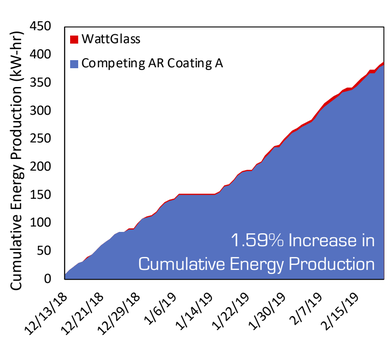


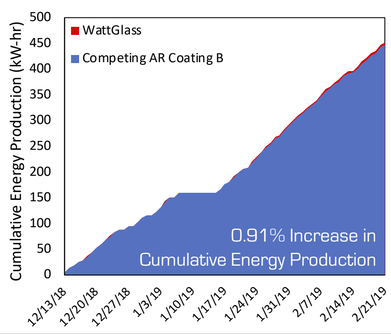




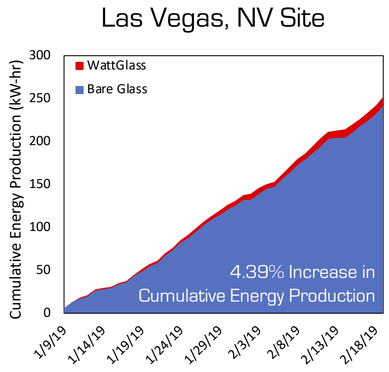
Albuquerque, NM Site

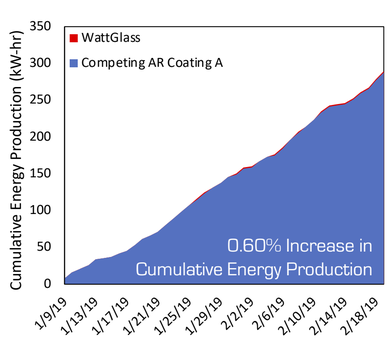


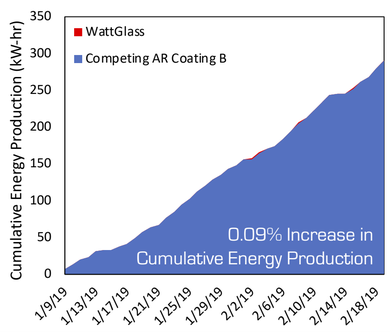




Las Vegas, NV Site







- Preliminary cumulative DC energy data accumulated over 2-3 months
- Across all sites, average increase in cumulative energy production is:
  - 3.59% compared to bare glass
  - 1.03% compared to Competing AR Coating A
  - 0.33% compared to Competing AR Coating B
- Currently no way to de-couple the AR performance from the improvements due to anti-soiling; working to quantify this in the future
- High humidity may be a factor in Florida
- Tentative plans to increase capacity at existing test sites and establish additional installations in other locations (e.g., the American heartland and western China)

Conclusions

- Field installations in three different regional climates have been installed to compare the energy output improvement of PV modules packaged with WattGlass' high-performance antireflective coating to other commercial AR coatings and bare glass
- DC power output measurements and on-site I-V curve measurements show increases in peak power output and I_{sc} in excess of 3% and 5.5%, respectively, compared to bare glass, while increases of 1% and 2.2% are obtained compared to competing AR coatings
- Preliminary cumulative DC energy data, accumulated over 2-3 months, shows a 2.99% - 4.39% increase in energy production compared to bare glass, depending on location
- Compared to competing AR coatings, energy output increases of up to 1.59% (Competing AR Coating A) and 0.91% (Competing AR Coating B) are demonstrated
- These results position WattGlass as a strong competitor in the AR coatings market, with a high-performance, cost-effective, water-based drop-in solution for AR coatings for solar PV modules

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FSEC
SOUTHERN NEVADA WATER AUTHORITY
D2 solar

Status of IEC 63163 Consumer Product Specification

Authors: Paul F. Robusto, Bill J.J. Liu and Venkata Bheemreddy

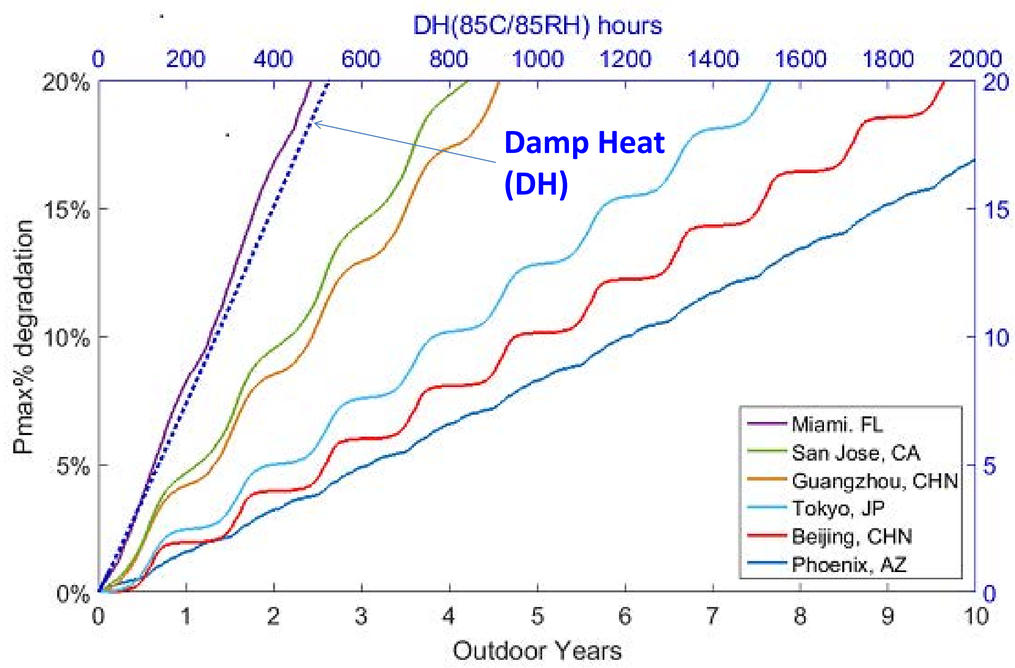
Introduction

- Currently there is no standard for Consumer Products and these products are being shipped without certification. IEC 63163 is an approved new work item for Terrestrial PV modules for consumer applications for design qualification and type approval. The specification has three categories: mobile, portable and attached. For portable applications, the product is expected to last 2 to 3 years so products can have lower cost components.
- For these portable applications, we have fabricated CIGS modules with an experimental lower cost front barrier which has a higher water vapor transmission rate (WVTR) in E-2 g/m^2/d range.
- Using data from accelerated reliability testing conducted at a range of temperature and humidity conditions, we previously developed a reliability model [1,2] that has enabled us to predict module performance in various locations.
- Based on the model prediction and by plotting the damp heat degradation versus lifetime we can determine a power degradation specification for the damp heat testing and we can use this value in the IEC 63163 specification.

Proposed Environmental Qualification Tests Category 1, 2 and 3

Category 1	Category 2	Category 3	
Mobile	**Portable**	**Attached**	**Potential Applications**
PC/Smart phone/Battery Charging/ Biking GPS Locator	Emergency Power Hiking/Camping	Stationary Applications	Potential Markets
Low (1 year)	Medium (2-3 yrs.)	High (5 years)	Expected Usage
Low	Medium	High	UV Exposure
Medium	High	Low	Mechanical Durability
N	N	15 kWh/m2	UV Pre-Conditioning
N	30 kWh/m2	60 kWh/m2	Outdoor Exposure Test
TC 20	TC 25	TC 200	Temperature Cycling (-40C to 85C)
HF 2	HF 4	HF 10	Humidity Freeze
100 hrs	300 hrs	1000 hrs	Damp Heat (85C/85%)
20%	15%	10%	Maximum power degradation

Model Field Life Estimate for Miami vs. Damp Heat Performance

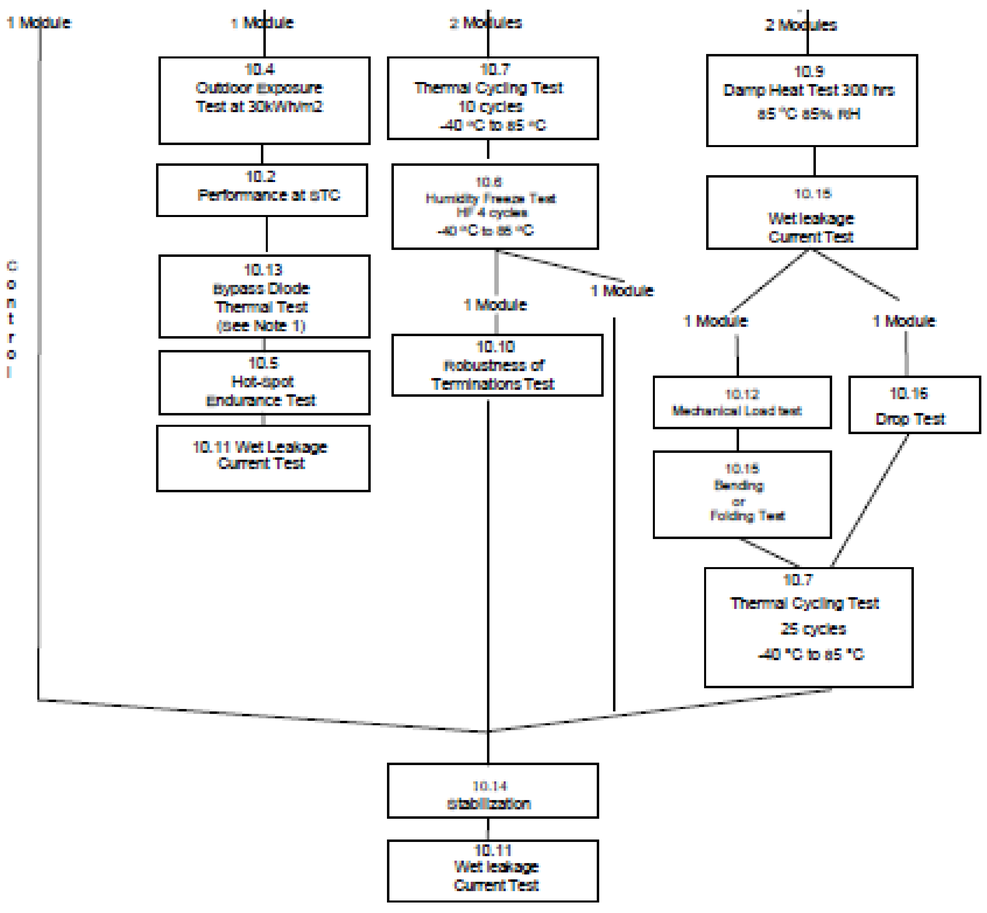


For Miami, for 2 years outdoors a 15% power degradation is equivalent to exposing the module to Damp Heat (85C, 85%RH) for 400 hours and 3 years outdoors for San Jose.

Purpose of IEC 63163

- The purpose of the test sequence is to determine if the module is capable of withstanding outdoor exposure for different use time durations. Mobile and attached applications have a lower mechanical durability than portable applications. Portable has a high mechanical durability since it is prone to mechanical damage due to increased handling.
- For the purposes of designing this standard Category 1 (Mobile) "low" lifetime was though of for one year, Category 2 (Portable) "medium" use of 2-3 years, and Category 3 (Attached) "high" use of 5 years.

Category 2: Qualification Test Sequence (Portable Products) Damp Heat sequence has Bending/Folding Test and Drop Followed by TC 25



Testing Status/Plans

- Performed testing on Sunpower Flexible Si, Canadian Solar Glass Si, Miasole Flexible CIGS, Hanergy eMobike CIGS modules
- Plan to test other Hanergy CIGS modules used for Backpack; Bike; Folding Cloth Charger.
- We are in the Testing mode.
- We have testing support – NREL, UL, RETC and JET
- We need modules so we can have products that pass or fail
- Need more manufacturer's to participate
- Need samples for testing especially silicon and amorphous silicon

References

[1]Venkata Bheemreddy, Bill J. J. Liu, Andrew Wills and C. Paola Murcia], "Life Prediction Model Development for Flexible Photovoltaic Modules using Accelerated Damp Heat Testing" WCPEC-7, Waikoloa, HI, June 10-15, 2018,.

[2] Bill J.J. Liu and Venkata Bheemreddy "Establishing a Moisture-induced Degradation Model of Flexible PV Modules for Field Life Estimation", 2018 NREL Photovoltaic Reliability Workshop, Lakewood, CO, Feb.27-Mar. 1, 2018.

Activities, Capabilities, and Services Provided by the NREL Cell and Module Performance Group

Allan Anderberg, Daniel Friedman, Dean Levi, Chuck Mack, Tom Moriarty, Paul Ndione, Carl Osterwald, Larry Ottoson, Steve Rummel, Tao Song, Rafell Williams
National Renewable Energy Laboratory

Introduction: What We Provide

- Timely accurate cell and module performance calibrations
- Available to anyone; rapid turnaround; convenient website request form
- Calibration of module IV under outdoor and simulator light
- Oversee cell and module records charts
- Advance state-of-the-art measurements

Calibration Services Offered

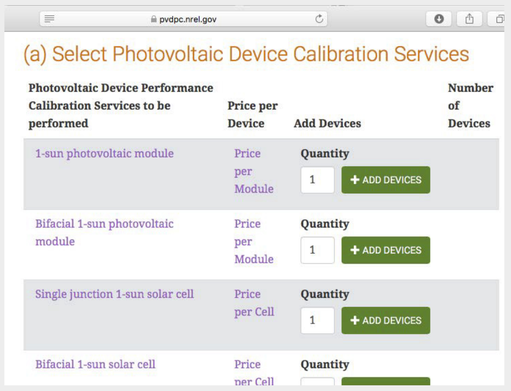
Cells
- Cell current vs. voltage
  - Single- and multijunction; 1-sun and concentrator
- Spectral responsivity
- Linearity of I_{SC} vs irradiance (0—2 suns)
  - Standards require reference cells to be linear over range of operation

Modules
- Current vs. voltage – flash and continuous simulators
- Current vs. voltage – outdoors
- Accredited to ISO 17025 standards for secondary module calibrations

Primary Reference Cells
- Accredited to ISO 17025 standards for primary and secondary reference cell calibrations

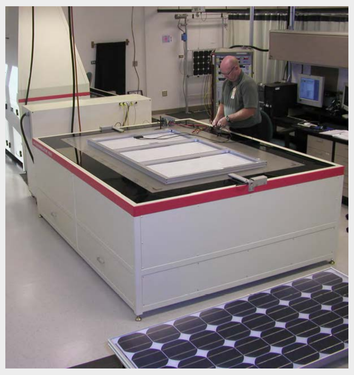
Online Calibration Services Request

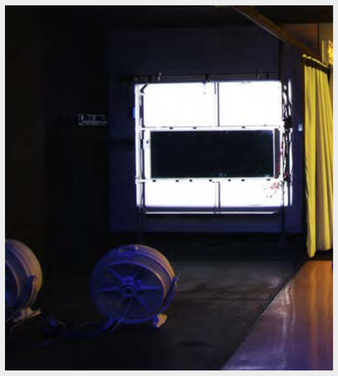
- Quick and simple
- Pay with credit card or technical services agreement
- Fast turnaround



Indoor Module Testing

- Spire flash simulator
- Large-area continuous simulator
- Custom mesh reduces spatial nonuniformity to ±1.5%





Outdoor Module Testing

- Spatial sunlight-illumination nonuniformity is essentially zero
- Irradiance measured using a c-Si primary reference cell
- Spectrum measured using an ASD FieldSpec3 spectroradiometer

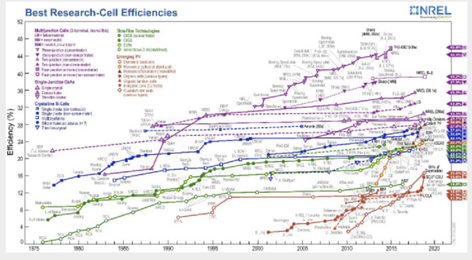
ISO 17025 Accreditation

- Lowest reported P_{max} uncertainty for this size module for any accredited calibration laboratory

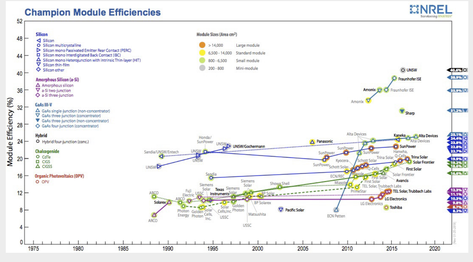
Parameter/Equipment	Range[4]	CMC[2, 3, 5] (±)	Comments
Photovoltaic Reference Modules –			ASTM E1036, IEC 60904-1 (sec. 4) with:
DC Voltage	(2 to 290) V	0.4 %	Agilent 34401
DC Current	(0.1 to 15) A	0.8 %	Agilent 34401, precision resistor
Power	(1 to 800) W	1.1 %	Agilent 34401
Area	(20 × 20) cm to (140 × 210) cm	0.2 %	Tape measure
Broadband Outdoor Radiometer Calibration –			

Cell and Module Record Eff Charts

- NREL CMP maintains these charts
- Valuable tool for PV stakeholders

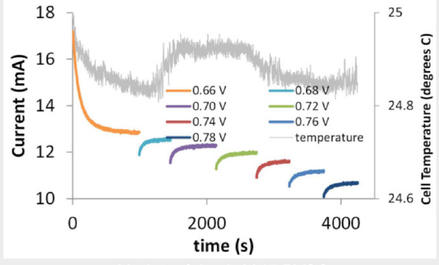


- Module chart is new
- Module size indicated on chart



Measuring Slowly-Responding Cells

- Perovskites and some other cells may respond slowly to bias voltage changes
- Sweeping the entire IV curve slowly is not an option
- Solution: Determine the IV curve piece by piece:
  - Fix voltage
  - Measure current vs. time until stable
  - Change voltage, repeat

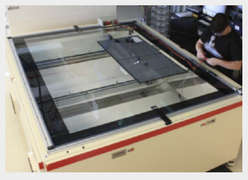


Moriarty & Levi, 2017 PVSC

Lowering Module Calib. Uncertainty

- Flash gives V_{OC}
- Outdoors with high spatial uniformity gives I_{SC}
- Indoor continuous gives final IV curve, with no sweep-rate artifacts

Spire flash simulator



T= 25°C
Minimal heating during flash
→ Gives V_{OC} (Irr) at 25°C

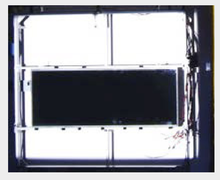
V_{OC} 25°C →

Outdoor test bed

~0.2% Spatial Nonuniformity
→ Gives I_{SC} at 25°C

I_{SC} 25°C →

Continuous simulator



Use I_{SC} to set simulator intensity
No ref. cell → no spectral error, no nonuniformity error
→ Gives J(V) at correct V_{OC} and I_{SC}, at 25°C

- → ±1.1% uncertainty in P_{max}: lowest of any accredited lab

Levi *et al.*, 2017 PVSC

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2019 PV Reliability Workshop
Lakewood, CO
26–28 February, 2019
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Development of a Rotating Brush Abrasion Method

(as part of IEC 62788-7-3 PV Abrasion Standard)

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(3) Colorado School of Mines, Golden CO, 80401, USA, (*) Lin.Simpson@nrel.gov, 303-384-6625

I. Introduction

Background and Motivation

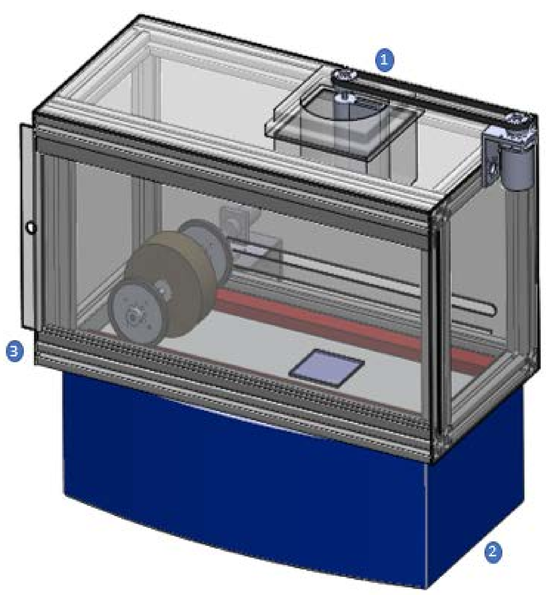
Natural soiling reduces PV energy output, increasing levelized cost of electricity. Mitigation often includes dry brush cleaning.

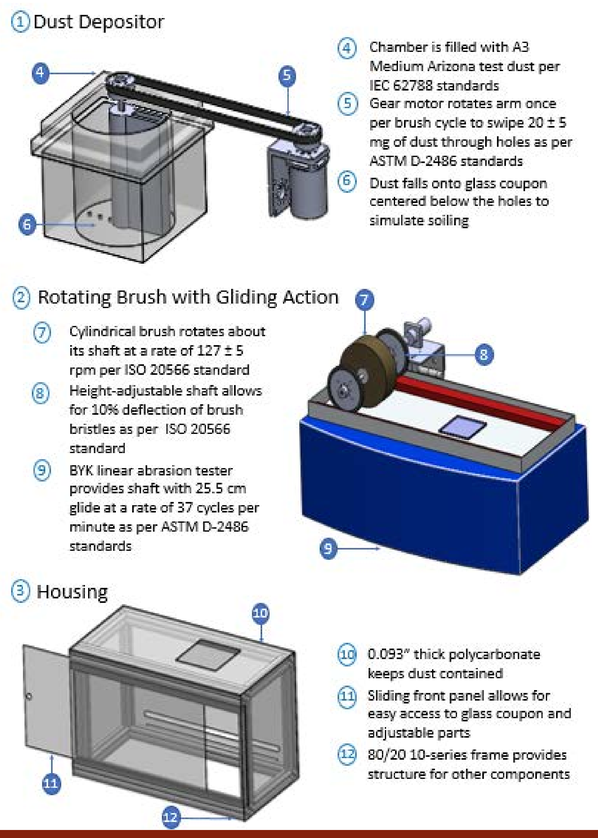
Images of Ecoppia's robotic cleaning system

Research Goals

- *Develop rotating brush test procedure*
  - *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





III. Results

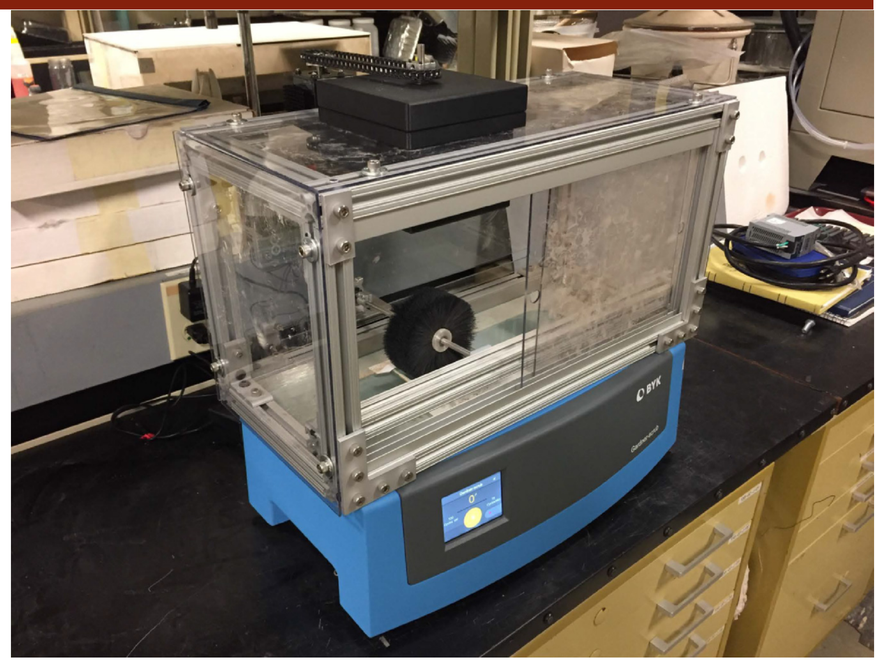
Leverage test equipment and standards, including:

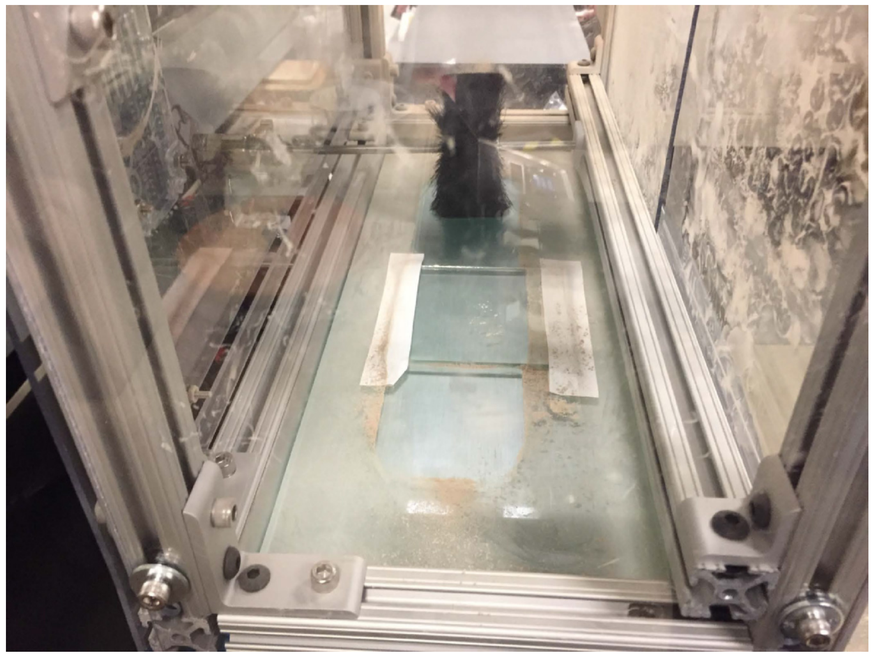
- *Modified commercial BYK "linear brush test" system (for linear actuation)*
- *ISO 20566 Laboratory-Scale Car Wash International Standard*
- *ISO 12103 Arizona Test Dust*
- *ASTM D 2486-06 Standard Test Methods for Scrub Resistance of Wall Paints*

Table of proposed rotating brush test parameters based on other procedures

Feature	Criteria		Standard
Dust/dry abrasive	Material:	A3 (med) AZ test dust	ISO 12103
	Flow rate:	20 ± 5 mg/cycle	IEC 62788
Brush	RPM:	157 ± 5 rpm	ISO 20566
	Bristle Deflection:	10% deflection	ISO 20566
	Bristle material:	Nylon 6,12	IEC 62788
	Bristle length:	3.8 cm	IEC 62789
	Bristle diameter:	0.23 ± 0.03 mm	IEC 62790
	Bristle profile:	round bristles, untapered	IEC 62791
	Bristle count:	158 ± 6 tips/tuft	IEC 62792
	Bristle tuft pattern:	staggered	IEC 62793
	Length:	3.5 cm	ASTM D-2486
	Stroke length:	25.5 cm	ASTM D-2486
	Stroke rate:	37 cycles/minute	ASTM D-2487

Please provide your feedback on what other parameters may be important and what the specific parameters should be.





Pictures of initial rotating brush test system with automated dust deposition.

Initial Findings:

- *Consequences of bristle deflection need to be resolved.*
  - *Brush rpm changes with load and thus bristle deflection.*
  - *Must account for this issue in defining test parameters.*
- *Brush speed varies based on direction of linear movement. Not sure if this will impact the test.*
- *Rotation in car wash test is too fast*
  - *Brush V_t at 160 rpm ~ 84 cm·s^{-1}*
- *BYK linear limit of 37 cycles per minute (34.5 cm·s^{-1}) is too fast*
  - *Reducing speed will increase time to reach desired number of cycles*
- *Dust dispensed adequately: sufficient fall time between cycles; no airborne interaction with brush*
- *Eliminate step at sample edge to improve uniformity, increase bristle lifetime*

IV. Conclusions and Future Pursuits

Conclusion

- *Designed, constructed and tested prototype of an inexpensive rotating brush system.*
- *Initial results demonstrate that the system can provide appropriate control of critical parameters.*
  - *Deposits relatively reproducible amounts of dust with each brush pass, linear and rotating speeds fairly constant.*

Future Plans

- *Must determine long term durability of test system to provide tens of thousands of reproducible cycles.*
- *Need to systematically determine that each test parameter is in appropriate range.*
- *Characterize/quantify glass/coating degradation per number of cycles and dust loading.*
- *Validate rotating abrasion test relative to fielded coupon samples and veteran modules.*

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.

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.

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

Multi-Scale Multi-Physics Modeling for PV Reliability

James Hartley[1], Ashley Maes[1], Joshua Stein[1], Scott Roberts[1], Laura Schelhas[2], Nick Bosco[3]

[1]Sandia National Laboratories; [2]SLAC National Accelerator Laboratory; [3]National Renewable Energy Laboratory

DuraMAT Capabilities

1. **Data Management & Analytics, DuraMAT Data Hub**
2. **Predictive Simulation**
3. **Advanced Characterization & Forensics**
4. **Module Testing**
5. **Field Deployment**
6. **Techno-Economic Analysis**

Modeling Capability Goals

- A suite of simulation tools and workflows and a community of experts, used to generate data to expand the durability test space and help interpret and enrich existing test/experimental data
- Partnered with **Data Analytics**, **Advanced Characterization & Forensics**, and **Module Testing** capability areas

Accomplishments

- Developed full-scale module mechanical models for c-Si glass-backsheet and glass-glass thin film architectures, and validated against experimental loaded deflection data
- Collected data for EVA and Polyolefin encapsulants necessary to populate constitutive models; computational implementation in progress

Outcomes and Impact

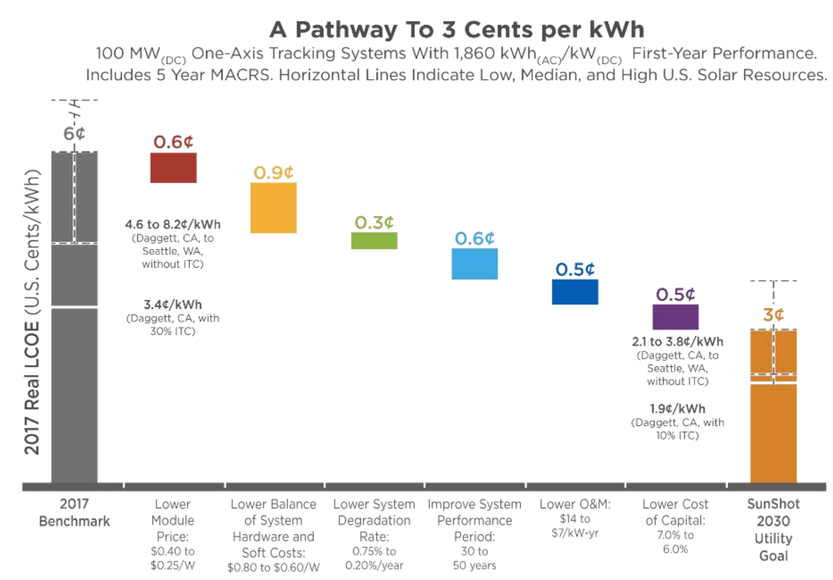
- Predictive models enable smarter service life predictions and accelerated test specification
- Informs best practices for material choice and module design, and aids interpretation and identification of new degradation mechanisms
- Reduces costs by optimizing all phases of module deployment: design, testing, production, service life

Capability Development

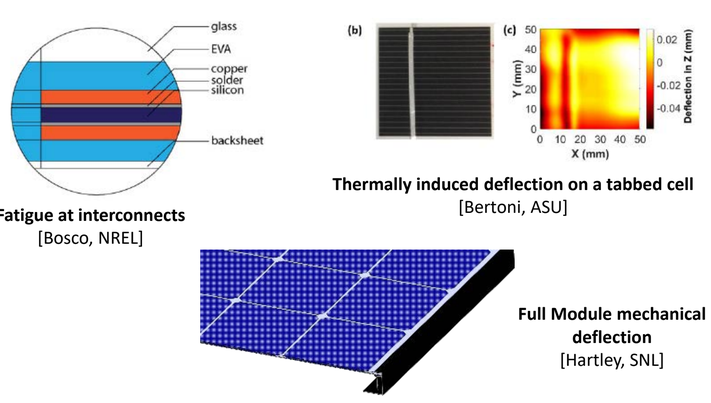
Failures in deployed photovoltaic modules occur by complex physical mechanisms

- **Motivation:** A predictive model is needed to better understand how module deployment environments induce the damaging thermal-mechanical stresses leading to module degradation, via delamination, cell fracture, and solder bond fatigue- among other mechanisms.
- **Capability vision:** A module-scale modeling capability capturing key degradation physics at the length- and time- scales of interest, tightly coupled with experimental material and module characterization efforts to receive information for model validation while enriching interpretation of measurement results. The final validated and informed capability would enable accurate lifetime predictions, efficient accelerated test specification, and optimized module material selection and design for durability.
- **Current development efforts and accomplishments:** Full-scale module mechanical models developed and validated against experimental deflection data, for c-Si, glass-backsheet and thin-film glass-glass module architectures. Data to populate viscoelastic encapsulant constitutive models collected. Next steps include computational implementation of encapsulant viscoelasticity, and an application case to correlate full module scale modeling insights against mini-module experiments.

Cost Drivers



Multi-Scale Modeling Capabilities



Fatigue at interconnects [Bosco, NREL]

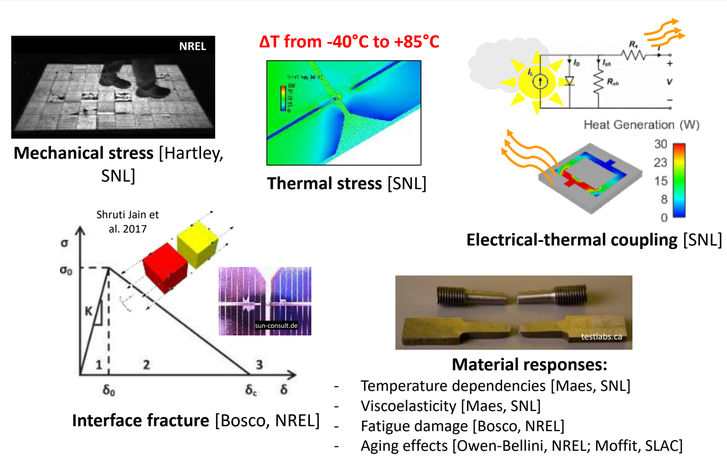
Thermally induced deflection on a tabbed cell [Bertoni, ASU]

Full Module mechanical deflection [Hartley, SNL]

Modeling capabilities to predict stressors at various scales of a PV module: from interconnects to cells to full modules

- Multiple scales enable efficient resolution of specific degradation mechanisms. For example:
  - Propagation of full module deflections to stress at specific cell and interconnect positions; to inform detailed, location-specific solder fatigue prediction

Multi-Physics Modeling Development



Mechanical stress [Hartley, SNL]

Thermal stress [SNL]

Electrical-thermal coupling [SNL]

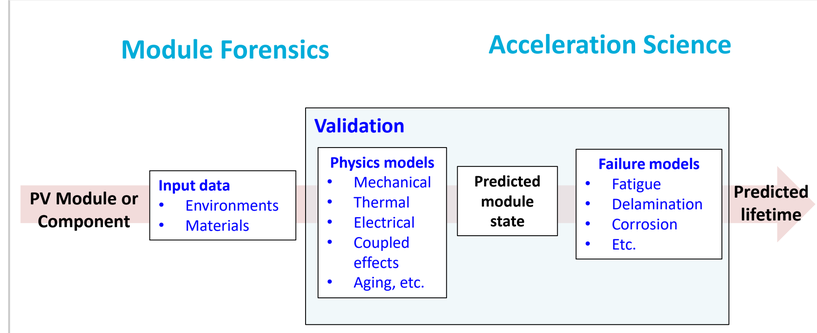
Interface fracture [Bosco, NREL]

Material responses:
- Temperature dependencies [Maes, SNL]
- Viscoelasticity [Maes, SNL]
- Fatigue damage [Bosco, NREL]
- Aging effects [Owen-Bellini, NREL; Moffit, SLAC]

Development of physics models for degradation related phenomena

- Degradation physics being implemented include mechanical, thermal, and electrical effects, as well as failure models for material fatigue and interface fracture
- Detailed material response including viscoelasticity and aging are also considered physics of interest

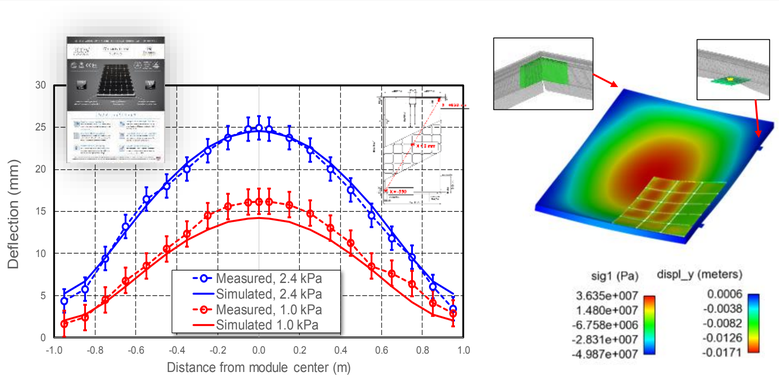
Capability Roadmap



Capability end goal is to accurately predict lifetime for any PV module or component, leveraging module forensics, acceleration science, and data resource capabilities

- Required inputs to generate a lifetime prediction include environmental exposure data and physics models to understand module state, then failure criteria models
- Module forensics, acceleration science, and data resource capabilities provide supporting information for model development, including model validation evidence

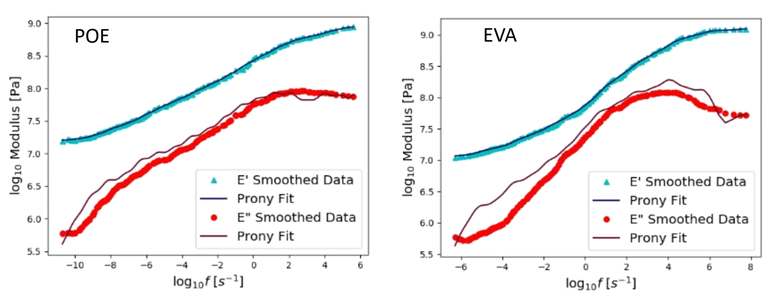
A Module Scale Mechanical Model



Simulated vs. Measured Deflection under load across module diagonal for a c-Si module, with model construction details

- A commercially available module was translated to a finite element model and validated against experimentally collected deflection vs. load data, under IEC61215 pressure loads
- Detailed parameter sensitivity analyses are being performed to develop an understanding of key influential design parameters
- Parallel analyses for a thin-film glass-glass module architecture are also underway

Material Models for Encapsulants

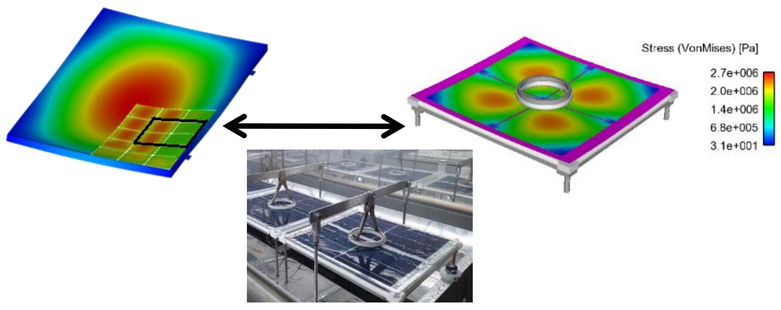


Master curve data and Prony series fit of a commercial polyolefin elastomer (POE) *(left)* and commercial poly(ethylene-co-vinyl acetate) (EVA), fully crosslinked (*right*).

Prony series fits of master curve data capture both the elastic and viscous material responses of polymer encapsulants

- Mechanical and thermal characterization was conducted on two common commercial encapsulants
- Parameters from the WLF time-temperature shift, fitting of coefficient of thermal expansion (CTE) data, and the above Prony series fits will be combined in Sandia's Universal Polymer Model for direct use in cell-scale and module-scale finite element models

Capability Development Next Steps



"Correlation of advanced accelerated stress testing procedures with field data through advanced characterization and data analytics" PI: M. Owen Bellini

A high-fidelity mini-module model provides a testbed for advanced material models and allows comparisons with full module models

- A model application case exists to assess mini-module (commonly used in accelerated testing) representativeness against full module behavior
- Mini-module finite element model will be a useful testbed for implementing new physics capabilities, including but not limited to viscoelastic material models, solder fatigue models, and cohesive zone models for encapsulant delamination

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Reduction and Climate-Specific Evaluation of Module Operating Temperatures using Thermally Conductive Backsheets

Ashwini Pavgi[1], Jaewon Oh[1,*], George Kelly[2], Govindasamy Tamizhmani[1]

[1]Arizona State University Photovoltaic Reliability Laboratory (ASU-PRL), Mesa, Arizona, USA [2]Sunset Technology, Mount Airy, MD 21771, USA

Introduction

- Reducing PV module operating temperature leads to an improvement of the module performance as well as lifetime.
- Various active and passive approaches to cool the modules were effective for specific environmental conditions. The influence of various weather parameters can be utilized to lower the module temperature using site-specific thermally conductive packaging materials.
- The focus is to compare performance of modules with Tedlar-Polyester-Tedlar (TPT) and thermally conductive backsheets (TCB) exposed in different climatic conditions for more than one year.
- Several one-cell PV modules were fabricated using two different TCBs (TCB_A and TCB_B) and their backsheet temperatures compared with conventional TPT under 3 site and 2 climatic conditions: hot and dry, temperate climatic conditions.

Experimental Setup

Site	AZ-1 site	AZ-2 site	NC site
Weather condition	Hot and dry (low wind speed)	Hot and dry (high wind speed)	Temperate

- **Glass/Polymer Modules** (8" x 11" one-cell modules)
  - Glass/EVA/Cell/EVA/Backsheet
  - 156mm x 156 mm monocrystalline Si cells
  - TPT: Tedlar-PET-Tedlar
  - TCB_A: PVDF-PET-EVA
  - TCB_B: PA-Aluminum-PET-PA
- **Identical module installation and data acquisition system**
  - 45° fixed tilt, south-facing open rack system.
  - Irradiance, wind speed, wind direction, module and ambient temperature recorded.

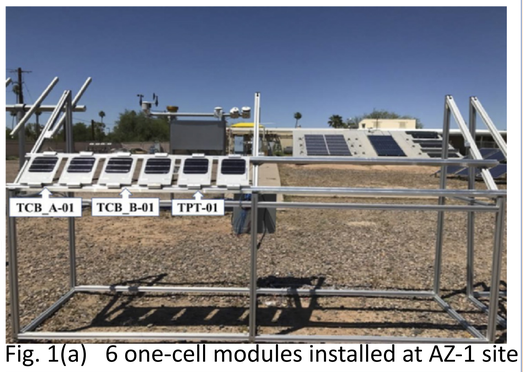

Fig. 1(a) 6 one-cell modules installed at AZ-1 site

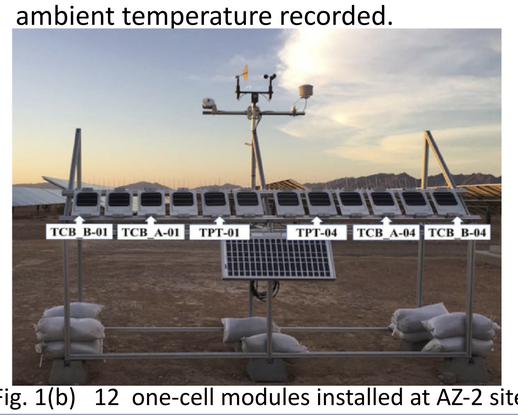

Fig. 1(b) 12 one-cell modules installed at AZ-2 site

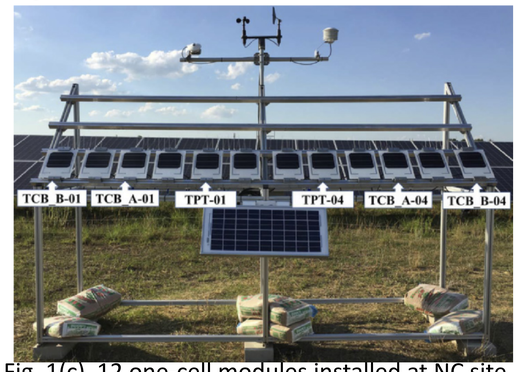

Fig. 1(c) 12 one-cell modules installed at NC site

Results and Discussion

1. Module Temperature Seasonal Trends

Fall season	Winter season	Spring season	Summer season
September 21st- December 20th	December 21st- March 20th	March 21st- June 20th	June 21st- September 20th

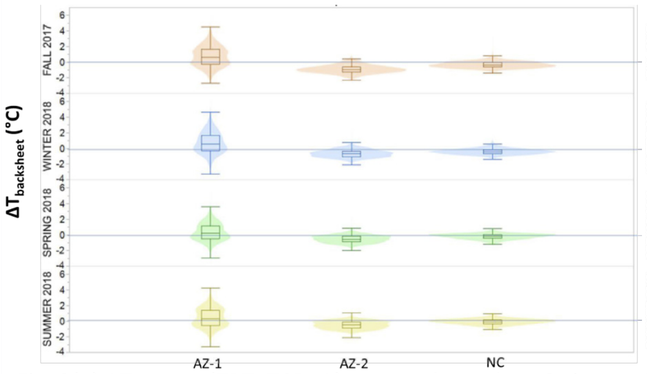

Fig. 2(a) $\Delta T_{backsheet}$ (TPT−TCB_A) seasonal trends at 3 sites

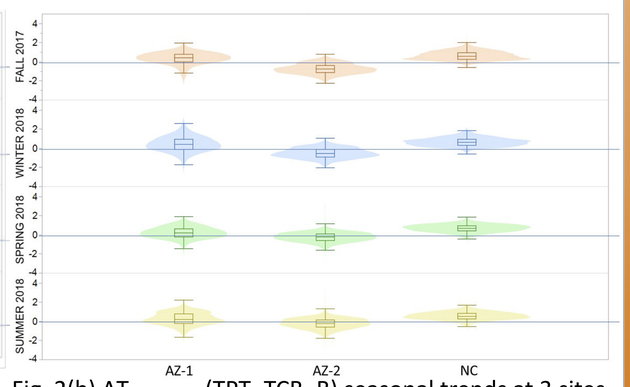

Fig. 2(b) $\Delta T_{backsheet}$ (TPT−TCB_B) seasonal trends at 3 sites

- The median $\Delta T_{backsheet}$ values between TPT and TCB_A are greater than 0.5 °C at AZ-1 site.
- $\Delta T_{backsheet}$ values as high as 5 °C observed.

- The median $\Delta T_{backsheet}$ between TPT and TCB_B are at least 0.7 °C at NC site throughout the year.
- $\Delta T_{backsheet}$ values as high as 2.4 °C observed.

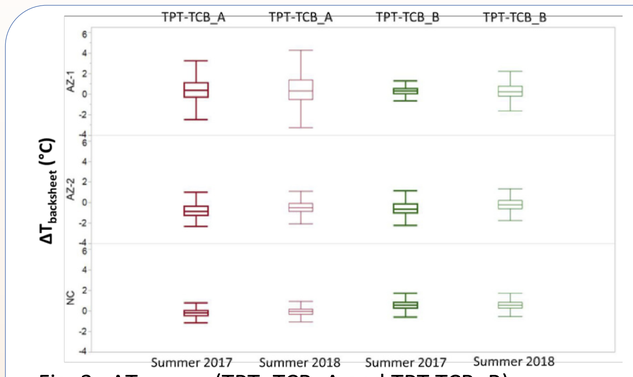

Fig. 3 $\Delta T_{backsheet}$ (TPT−TCB_A and TPT-TCB_B) comparison between Summer 2017 and 2018 at 3 sites

- Since both the backsheets operate at lower temperatures in Summer, the trends are compared over 2 years.
- The median $\Delta T_{backsheet}$ value is slightly higher at AZ-2 and NC site in year 2 but $\Delta T_{backsheet}$ values at AZ-1 site have similar trends over the two years exposure.
- The $\Delta T_{backsheet}$ (TPT-TCB_B) quartile range is higher by 0.5 °C in Summer 2018 as compared to Summer 2017 at AZ-2 site.

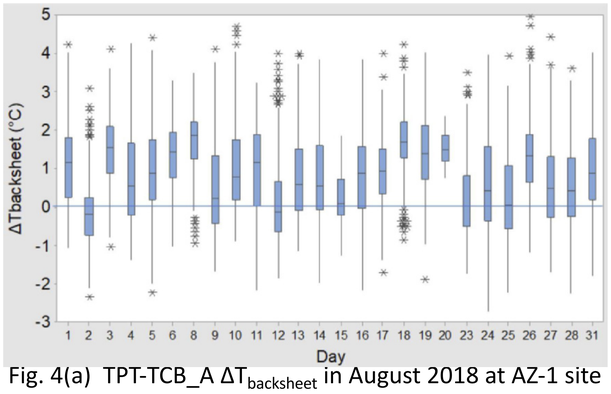

Fig. 4(a) TPT-TCB_A $\Delta T_{backsheet}$ in August 2018 at AZ-1 site

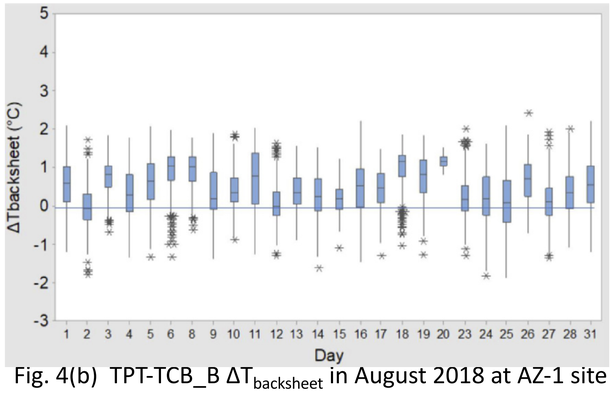

Fig. 4(b) TPT-TCB_B $\Delta T_{backsheet}$ in August 2018 at AZ-1 site

- In Summer, both TCB_A and TCB_B operates at lower temperatures than TPT at AZ-1 site and therefore chosen for comparison.
- The median of the maximum ΔT for TCB_A is 3.97 °C and for TCB_B is 1.86°C.

2. Weather and Climate Dependence

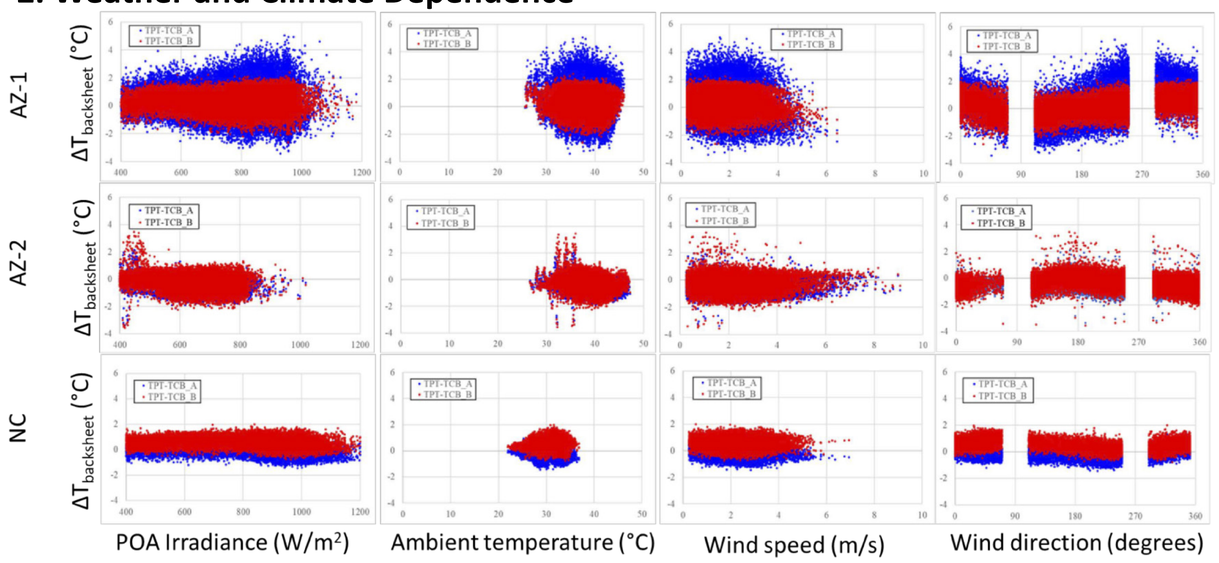

Fig. 5 Weather trends at 3 different sites: POA Irradiance, ambient temperature, wind speed and wind direction

- **AZ-1 site:** $\Delta T_{backsheet}$ (TPT- TCB_A) is higher than (TPT- TCB_B). $\Delta T_{backsheet}$ (TPT-TCB_A) is higher with higher ambient temperatures and wind blowing from west direction.
- **AZ-2 site:** (TPT- TCB_A) and (TPT-TCB_B) have similar trends with respect to meteorological data.
- **NC site:** $\Delta T_{backsheet}$ (TPT- TCB_B) are higher than (TPT- TCB_A). $\Delta T_{backsheet}$ (TPT-TCB_B) is higher with ambient temperatures between 25 and 35 °C and wind blowing from east direction.

Conclusions

- The weather and climate dependence on $\Delta T_{backsheet}$ values validate two different trends of TCB_A and TCB_B seen at AZ-1 and NC sites.
- TCB_A operates at a lower temperature at AZ-1 site experiencing hot climates but on the other hand, TCB_B operates at a lower temperature under temperate climatic conditions.
- The hot climatic conditions with higher wind speeds (> 7 m/s) pertinent to AZ-2 site did not lead to any reduction of operating temperatures using any of TCB_A and TCB_B backsheets.

Arizona State University

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Simulating the Spread Spectrum Time Domain Reflectometry Responses of Photovoltaic Cells to Detect and Locate Faults

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[1] Department of Electrical and Computer Engineering, University of Utah, UT 84112

[2] Department Electrical and Computer Engineering, University of Florida, FL 32611

Motivation

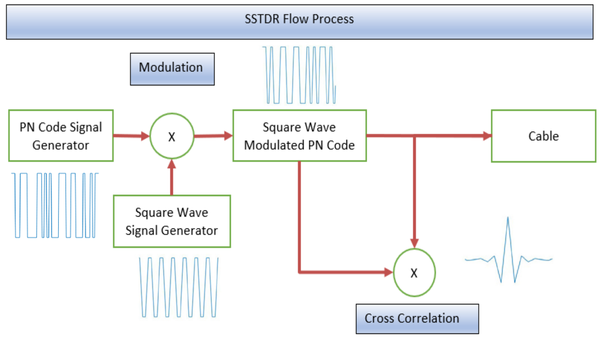
- **Detecting and Locating Faults in Photovoltaics**
  - Research has shown success using Spread Spectrum Time Domain Reflectometry (SSTDR) to detect
    - Open faults (i.e., broken wires)
    - Shorts (i.e., connections between wires)
  - Yet, there has not been successful research in identifying faults in more complex systems.
  - The long-term goal of this project is to use SSTDR to detect and locate faults in photovoltaic (PV) panels
- **Predicting reflections in PV cells**
  - Solar panels are an aggregation of solar cells.
  - Our goals are to :
    - Inspect reflection behavior of PV cells
    - Identify faults in PV cells
    - Extend to solar panels
    - Simulate SSTDR through solar cells

Background

- **What is an SSTDR signal?**
  - When a signal propagates through a transmission line, it will reflect energy at any impedance mismatch
  - Data is characterized by reflection coefficients

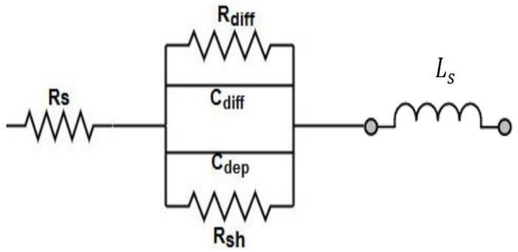
$$\rho(\omega) = \frac{V_{\text{reflected}}(\omega)}{V_{\text{incident}}(\omega)} = \frac{Z_L(\omega) - Z_0(\omega)}{Z_L(\omega) + Z_0(\omega)}$$

  - The SSTDR system flow is shown in the diagram below
  - The location of a fault is determined from the maximum of the cross-correlated data



Methodology

- **We test our system with solar cells**
- **Model of Solar cell**



- **Estimate SSTDR response through solar cells**
  - First solve estimated frequency response

$$X(\omega) = S(\omega)\Gamma(\omega)$$

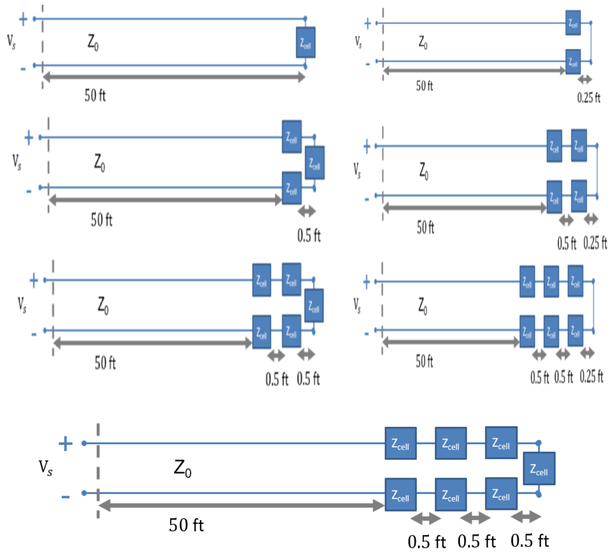
  - $\Gamma(\omega) = \frac{NZ_{cell}(\omega) - Z_0(\omega)}{Z_0(\omega) + NZ_{cell}(\omega)}$ N ~ Number of cells

    Zcell ~overall impedance
- **Adding effect of transmission lines**
  - Reflection Coefficient is modified

$$\rho(\omega) = \frac{V_{\text{reflected}}(\omega)}{V_{\text{incident}}(\omega)} = \frac{Z_1(\omega) - Z_0(\omega) + 2Z_i}{Z_0(\omega) + Z_1(\omega) + 2Z_i}$$

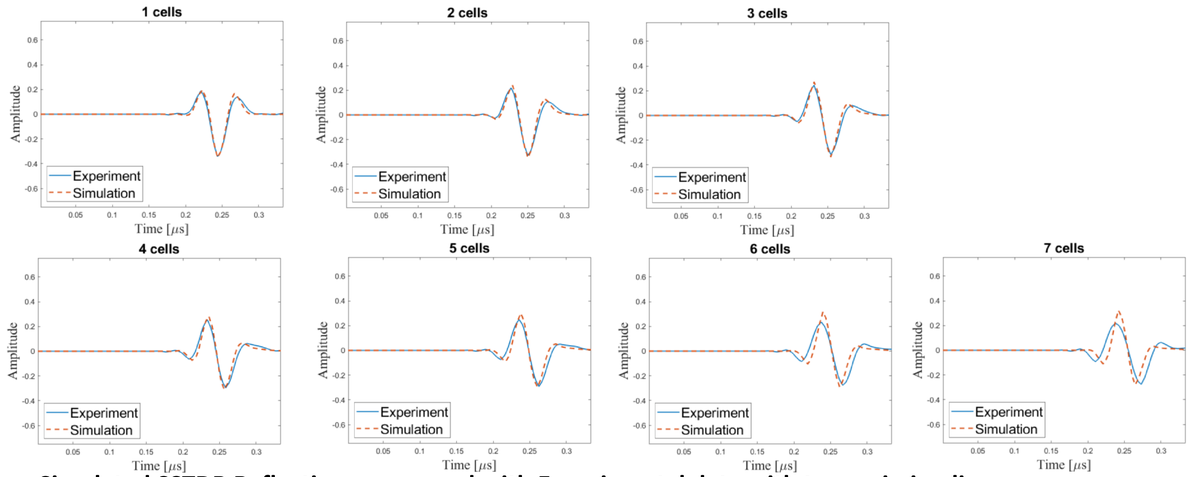
Experimental Setup

- **The physical setup of PV cells with transmission lines**

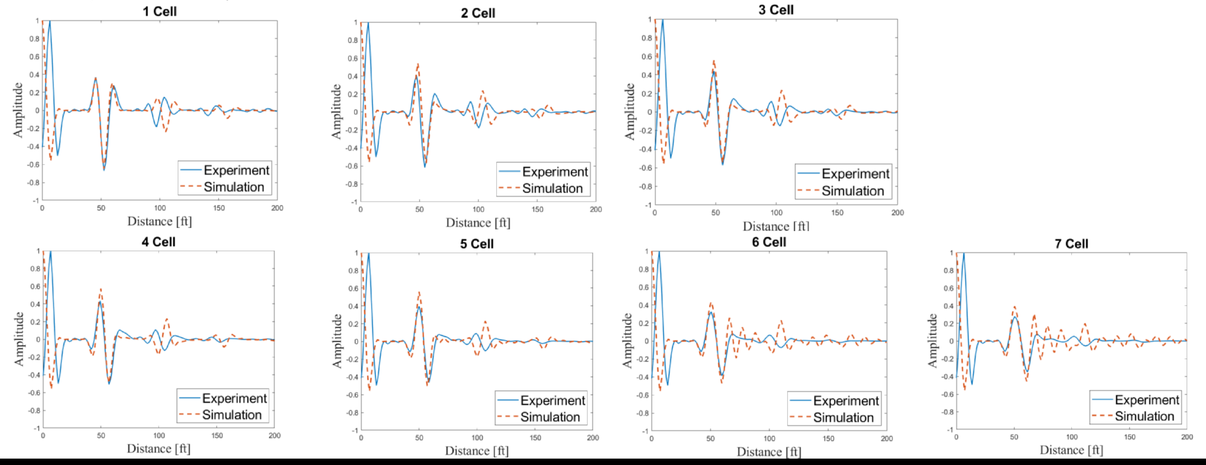


Results

- **Simulated SSTDR Reflections compared with Experimental data without transmission lines.**
  - (Solid Line is Experimental Data & Dashed Line is the Simulated data for n cells)



- **Simulated SSTDR Reflections compared with Experimental data with transmission lines.**
  - (Solid Line is Experimental Data & Dashed Line is the Simulated data for n cells)



Conclusions

- **We created a Simulation framework that can:**
  - integrate transmission lines and solar cells
  - predict reflection and transmission of high frequency EM waves across the cells
- **Simulations through solar cells that match experiments have been demonstrated successfully**

Acknowledgements

This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under Solar Energy Technologies Office (SETO) Agreement Number DE-EE0008169 in collaboration with Livewire Innovation and the National Renewable Energy Laboratory.

References

[1] S, P., Furse, C. and Gunther, J. (2005). Analysis of spread spectrum time domain reflectometry for wire fault location. *IEEE Sens. J.*, 5(6), pp.1469-1478.

[2] J. A. Tropp and A. C. Gilbert (2007), Signal Recovery from Random Measurements Via Orthogonal Matching Pursuit, in *IEEE Trans. Inf. Theory*, vol. 53, no. 12, pp. 4655-4666.

[3] Ching-Wen Hsue and Te-Wen Pan (1997). Reconstruction of nonuniform transmission lines from time-domain reflectometry. *IEEE Transactions on Microwave Theory and Techniques*, 45(1), pp.32-38.

[4] Ulaby, Fawwaz T., and Umberto Ravaioli. *Fundamentals of Applied Electromagnetics*. Pearson, 2015.

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

Techniques to study failure mechanisms in electronically conductive adhesive interconnects

Arizona State University (ASU)

B. Hartweg[1], K. Fisher[1], M. Branch[1], N. Chawla[1], and Z. Holman[1]

[1]Arizona State University

DuraMAT Capabilities

1. Data Management & Analytics, DuraMAT Data Hub
2. **Predictive Simulation**
3. **Advanced Characterization & Forensics**
4. **Module Testing**
5. Field Deployment
6. Techno-Economic Analysis

University Goals

- Failure mechanism(s) of ECA interconnects not known
- Several flavors of ECA materials (e.g., silicone- vs. epoxy-based); failure mechanisms of each may be different
- Standard IEC tests may or may not be appropriate to accelerate ECA failure
- **Our approach: ECA and module materials set → materials measurements and FEA model → accelerated tests**

Accomplishments

- 7 ECAs with a variety of properties obtained
- Properties as a function of processing conditions evaluated
- Fabrication sequence for making mini-module test structures for tabbed and shingled geometries developed
- Evaluation of x-ray tomography as a failure analysis technique for these test structures begun

Outcomes and Impact

- Outcomes will include preferred accelerated testing protocols, accelerated testing of select ECA materials, and recommendations for subsequent field testing
- Close collaboration with Dupont, Eurotron, Coveme, and CelLink ensures that project remains relevant to PV industry
- Several GW capacity online using ECA; this project has the potential to ensure that those modules last for 40 years

Capability Development

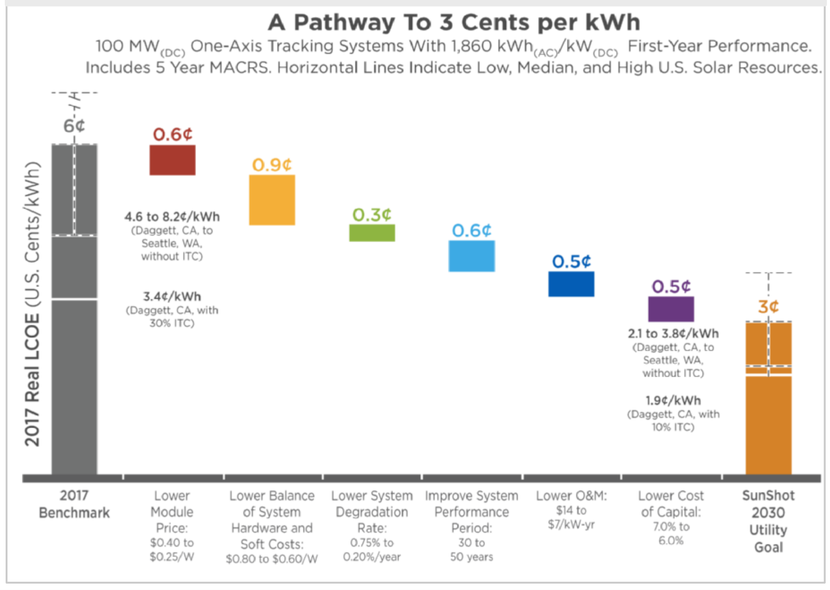
Two module designs are gaining traction in the market today that employ electrically conductive adhesive (ECA) interconnects instead of established tabbing technologies:

1. modules with conductive back sheets (CBS) that string together back-contacted silicon cells with a patterned metal foil,
2. modules with shingled cells that increase packing density by overlapping the cell edges

CBS modules have very low cell-to-module losses and the potential to nearly eliminate silver usage or copper plating in IBC modules, and shingled modules increase efficiency by eliminating wasted space.

- ✓ Physical models of the failure mechanisms of ECA interconnects in silicon PV modules
- ✓ Accelerated testing procedures for these interconnects
- ✓ Tested modules with a range of interconnect materials combinations
- ✓ Identify and characterize common failure mechanisms in ECA interconnects

Cost Drivers



Timeline

Q1-2018 — Project begins

Q3-2018 — Obtain materials and characterize
- Define systems to study
- Obtain materials
- Measure properties and determine process conditions

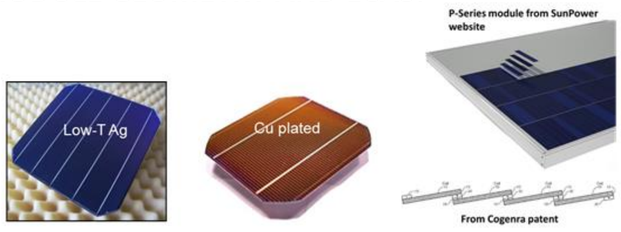
Q4-2018 — DOE: test failure mechanisms

Develop analytical techniques
- Determine useful techniques to characterize failure mechanisms
- Begin industrial collaboration
- Preliminary testing on failed in-house fabricated modules

Q2-2019 — DOE: module design for field tests

Q4-2019 — Industrial Sample Analysis
- Study failed ECA interconnects from industrial partner
- Characterize common failure mechanisms

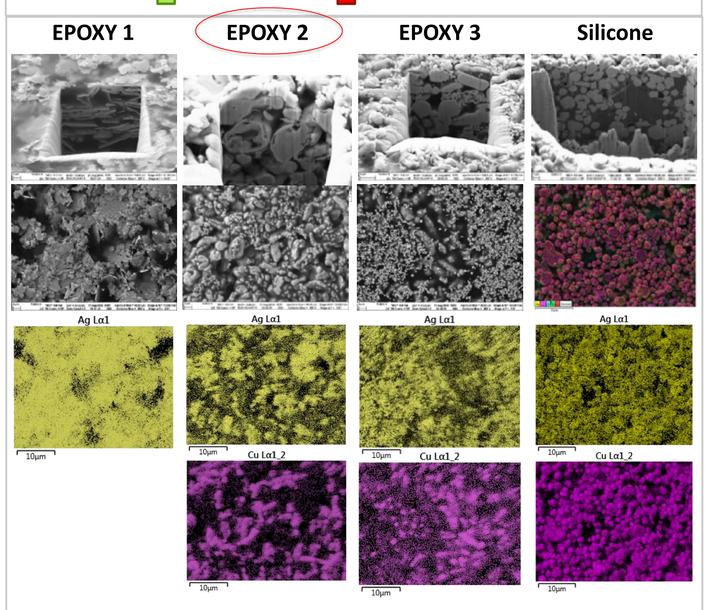
MODULE GEOMETRY AND ECAS:



SHJs with ribbons — Shingled

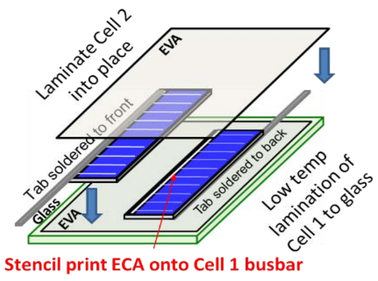
Paste	Filler	Metal %	ρ (mΩcm)	G @ 25°C (MPa)	T_g(°C)
EPOXY 1	Ag flakes	25-50	100		50-60
EPOXY 2	Ag & Cu flakes	60-100	0.4	1720	Onset: 55-90 Tandelta: 16
EPOXY 3	Ag & Cu flakes	70-100	0.5	160	Tandelta: -10
EPOXY 4	Ag & Cu flakes	70-90	0.32	212	Onset: -10 Tandelta: 16
EPOXY 5	Ag & Cu flakes	~ 80	0.3	80	Onset: -30 Tandelta: -15
EPOXY 6	Ag & Cu flakes	~ 80	0.2	170	Onset: -20 Tandelta: 0
SILICONE	Ag & Cu particles	83-88	0.18	Low	
ACRYLATE	Ag flakes	99-100	2.5	650	-30

Have In-House — Not In-House (yet)



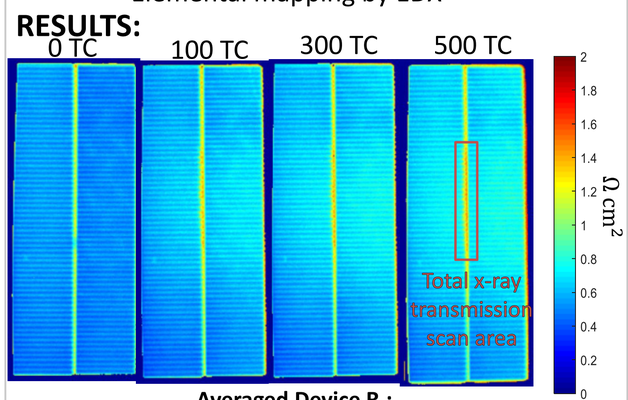
EXPERIMENTAL METHOD:

Shingled mini-module fabrication



- Thermocycle (TC) (-40°C to 85°C) samples until failure is demonstrated
- **Failure monitoring:**
  - I-V and Suns Voc
  - Electroluminescence
  - Series resistance mapping [1]
- **Failed sample analysis:**
  - X-ray transmission
  - X-ray tomography
  - Cross-sectional SEM
  - Elemental mapping by EDX

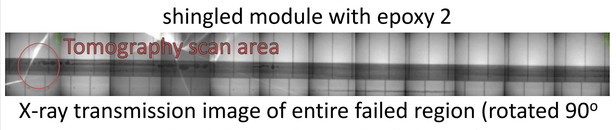
RESULTS:



Averaged Device R_s:

0.55 Ω cm² 0.63 Ω cm² 0.66 Ω cm² 0.71 Ω cm²

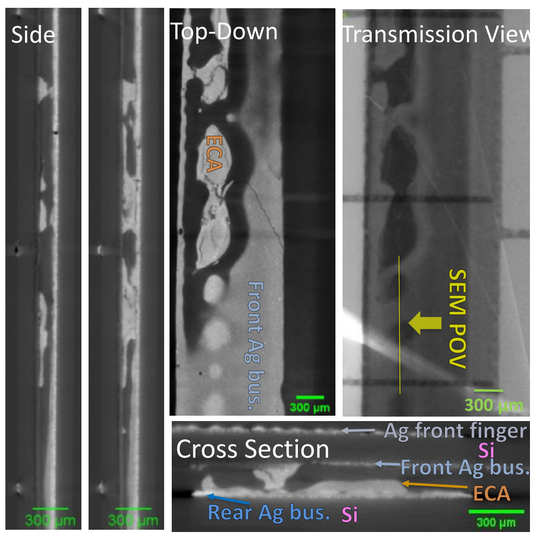
Series resistance maps throughout thermocycling of shingled module with epoxy 2



X-ray transmission image of entire failed region (rotated 90° to the right relative to the R_s image)

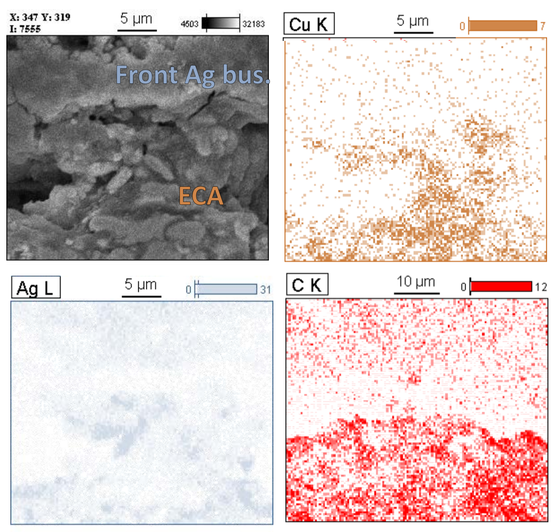
RESULTS:

X Ray Tomography



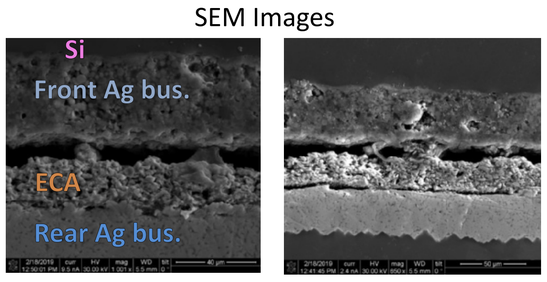
SEM/EDX Imaging

Well Contacted Area

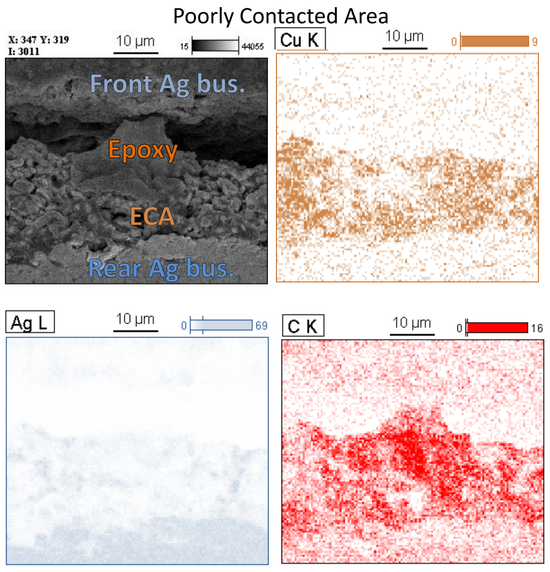


- SEM samples are cut out of sample and polished after X-ray tomography scans

SEM Images



Poorly Contacted Area



CONCLUSIONS AND FUTURE WORK:

- X-ray tomography, SEM, and EDX are useful techniques to understand the movement of ECA throughout thermocycling
- X-ray transmission scans provide a non-destructive method to study relative ECA location before and after thermocycling
- Further work needs to be done to find an adequate method to analyze chemical changes in the ECA

REFERENCE:

[1] J. Haunschild, et al. *Phys. Status Solidi RRL.* 3. No. 7-8, 227-229 (2009).

ACKNOWLEDGEMENTS:

This work was supported by the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308 with Alliance for Sustainable Energy, LLC, the Manager and Operator of the National Renewable Energy Laboratory (NREL). NREL is a national laboratory of the DOE, Office of Energy Efficiency and Renewable Energy. Funding provided as part of the Durable Modules Consortium (DuraMAT).

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Re-Evaluating Solar Panel Mechanical Durability Testing: Case Study of Commercial Modules

Eric J. Schneller[1,2], Hubert Seigneur[2], Jason Lincoln[2], Joseph Walters[2], Andrew Gabor[3]

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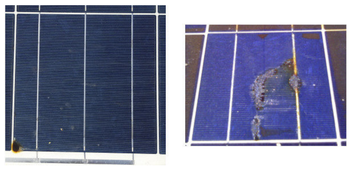
[2]Florida Solar Energy Center, University of Central Florida, Cocoa, FL USA
[3]Brightspot Automation, Westford, MA, USA

UCF

Introduction

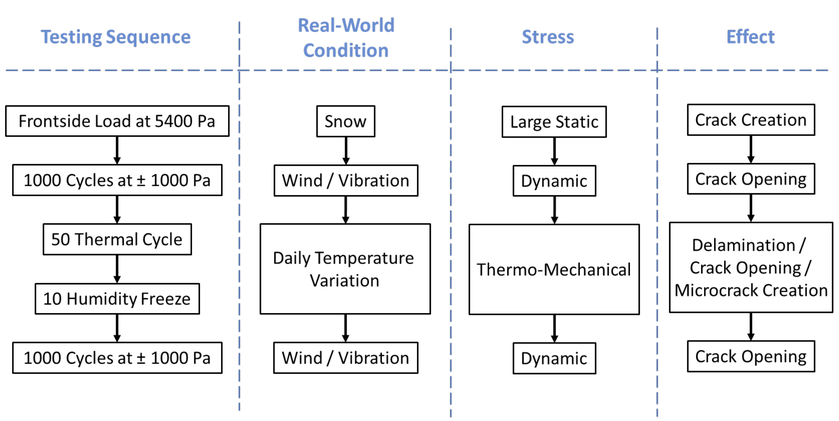
- PV modules experience a wide range of mechanical stressors over their lifetime that may cause cell cracking (e.g. shipping, installation, snow, wind, thermal cycling)
- Cell cracks pose a risk to long term performance
  - Increase in **series resistance**
  - **Shunting** from cracks can lead to reduced low light performance
  - Increase in "dead area" leading to **current mismatch**
  - Potential for **hot spot** generation
  - Severe hot spots are a potential **fire hazard**



Example images of severe hot spots caused due to cell cracks [1]

- In this work, a modified mechanical durability test sequence is proposed to evaluate module design with respect to crack durability

Proposed Testing Sequence



Objective: Evaluate a module design with respect to crack creation and crack opening

Module Technologies

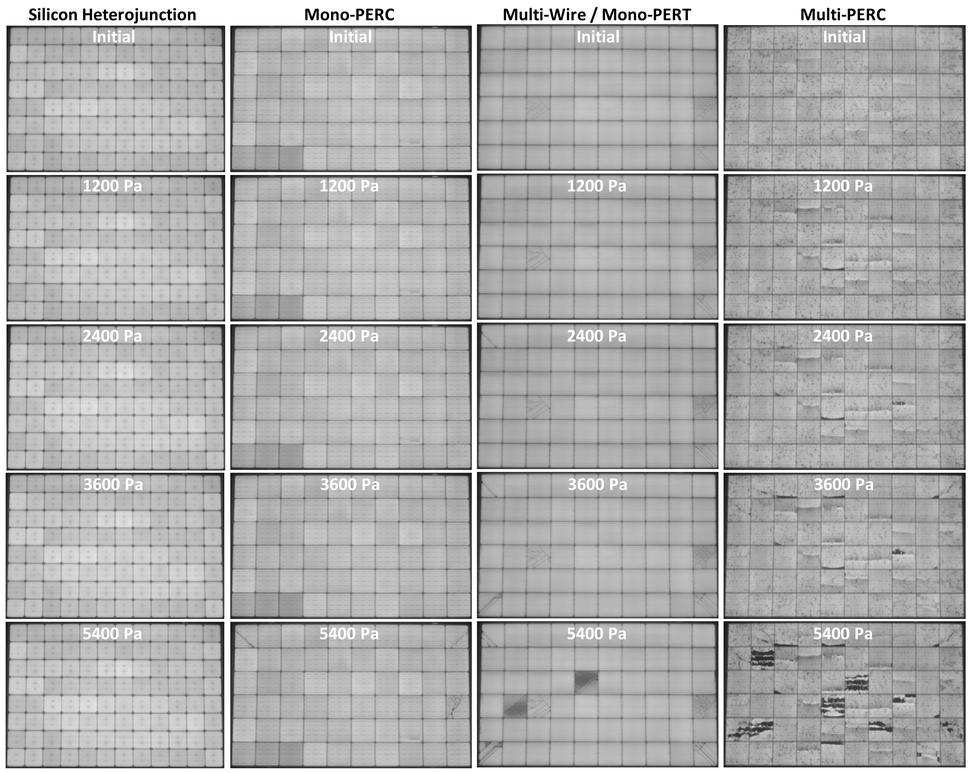
Cell Technology	Interconnect Technology	Cell Size	Number of Cells
Silicon Heterojunction	Low Temperature Interconnects	5 inch pseudo-square	96
Mono-PERC	4 Busbar Solder Interconnects	6 inch pseudo-square	60
Multi-PERC	4 Busbar Solder Interconnects	6 inch square	60
Mono-PERT	Multi-Busbar Interconnects	6 inch pseudo-square	60

[1] "Hot spots: Causes and Effects" *PV Magazine* 2017

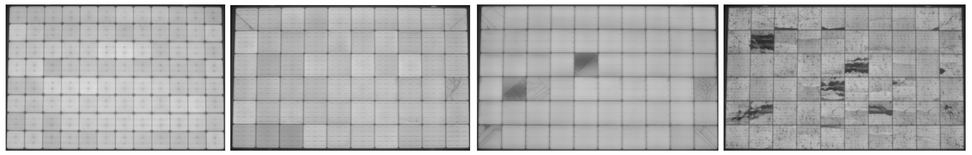
[2] M.W. Rowell, S.G. Daroczi, D.W.J. Harwood, A.M. Gabor, "The Effect of Laminate Construction and Temperature Cycling on the Fracture Strength and Performance of Encapsulated Solar Cells" *45th IEEE PVSC*, pp 3927-3931, 2018

Experimental Results

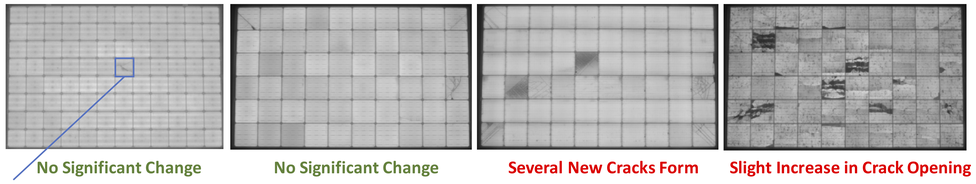
STEP 1: Frontside Load up to 5400 Pa



STEP 2: 1000 Cycles at ±1000 Pa

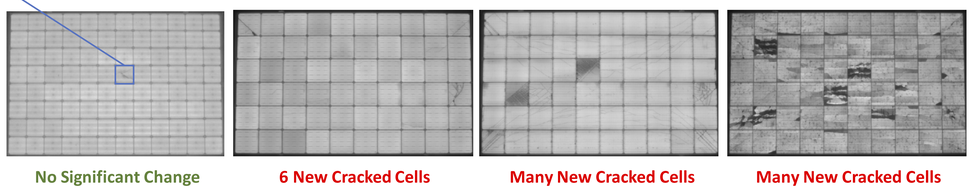


STEP 3: 50 Thermal Cycles / 10 Humidity Freeze Cycles



Handling Mistake During Transportation

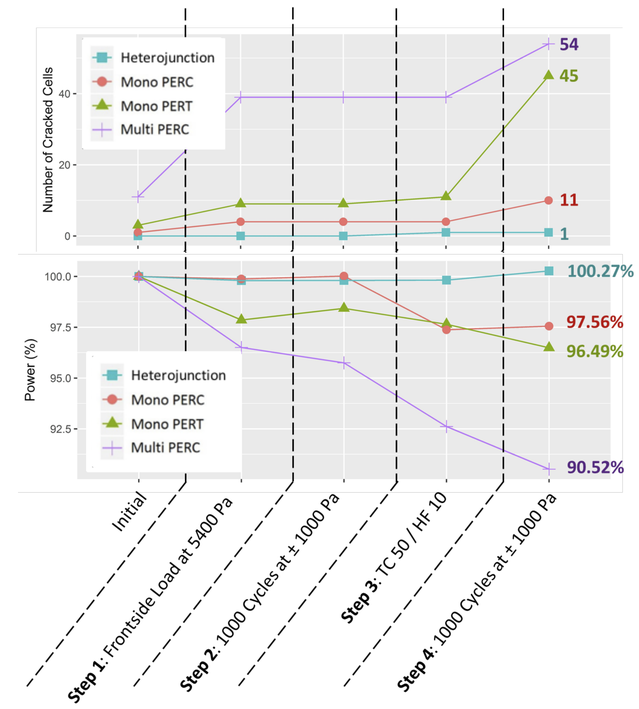
STEP 4: 1000 Cycles at ±1000 Pa



- Thermal Cycling has a major impact on the creation of new cell cracks
- Cell cracks appear to initiate near busbars and propagate with only a mild load of 1000 Pa
- The low temperature interconnect process is the likely reason for superior performance of silicon heterojunction modules with respect to crack formation. The interconnect geometry and packaging materials may also limit microcrack formation during TC/HF. [2]

Experimental Results

I-V data was captured to assess the impact on performance due to each exposure step. In addition, the number of cracked cells was counted to identify which exposure steps contributed to cell cracks.



Conclusions

- A modified testing sequence was proposed to evaluate module design with respect to crack durability
  - A large front side static load is used to create cracks
  - Subsequent cyclic loading and thermal cycling is used to open cracks
  - Dynamic mechanical loading after TC/HF exposes microcracks that develop during thermal cycling
- Testing sequence replicates stressors that could occur in real-world operation

Snow → Wind / Vibration → Daily Temperature Variation → Wind / Vibration

Key Takeaways

1. Large variation in crack durability across commercially available modules
2. Mechanical loading after thermal cycling causes a significant number of new cracks for modules with solder interconnects
3. Silicon heterojunction modules, utilizing a symmetric cell structure and low temperature interconnect process, exhibit high durability with respect to crack generation

FSEC

SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

This material is based in part upon work supported by the U.S. Department of Energy's Solar Energy Technologies under Office Award Number DE-EE0008152

Summary of DC Losses Observed Using Aerial Infrared Inspection Across 3 GW

Rob Andrews, Colin Savoy, Xing Min Su, and Elissa Dow
inspections@heliolytics.com
The 2019 NREL/SNL/BNL PV Reliability Workshops, Lakewood, CO, February 26 – February 28, 2019

Aerial inspections are rapidly becoming the standard method for large scale assessment of portfolio DC health. These inspections capture infrared (IR) and visual (RGB) imagery and are coupled with advanced algorithms to allow for 100% DC anomaly detection. Thermal imagery captured from aerial IR inspections is processed to allow for precise identification and mapping of under-performing portions of an array.

To date, **Heliolytics Inc. has scanned > 18 GW** of solar power plants. This work presents a summary of anomaly rates for a 3 GW subset of data with sites ranging from 0.01 MW to over 250 MW. This subset of data is comprised of:

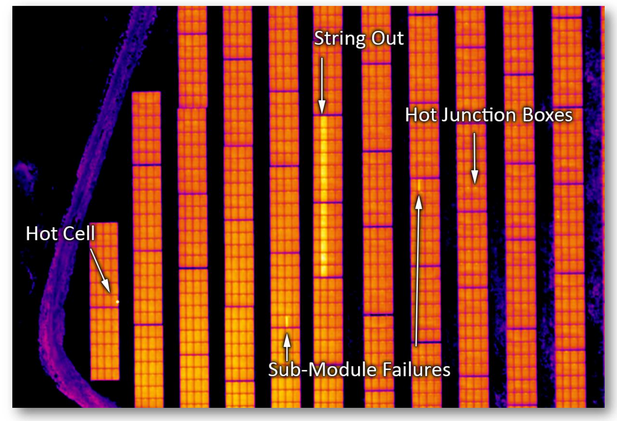
- Sites distributed across 28 states/provinces
- **545 scans included, > 13 million modules analyzed**

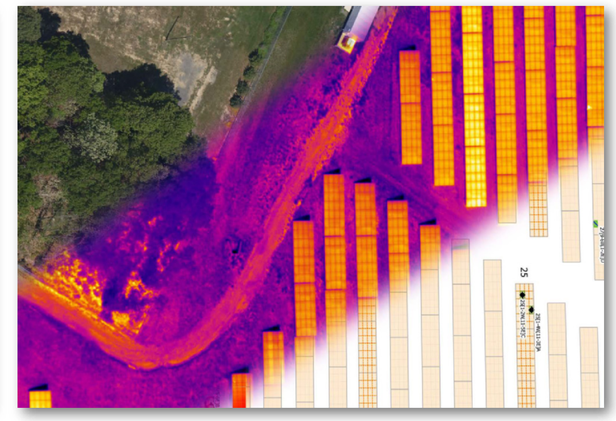
This study investigated data from a client opt-in **anonymized database** and analyzed factors such as site age, type, size, and location.

The following were excluded from these analyses:

- Large-scale balance of system anomalies with a failure rate > 10%
- Anomalies caused by vegetation and soiling
- Transient anomalies

The table below highlights the anomalies included in this analysis. Observed anomalies are given a weighting based on type of issue and severity of presentation. Values from 0 – 1 are given based on typical impact to power production.
Ex. Hot cell → 0.2, string outages → 1



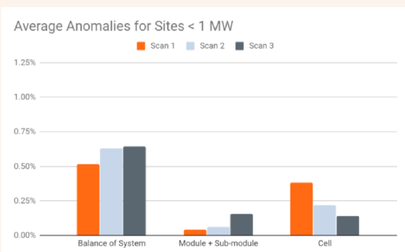


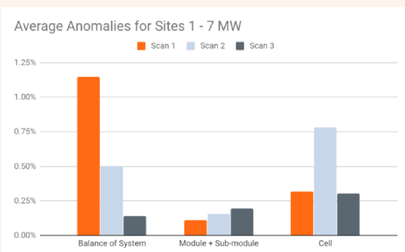
IR Failure Modes

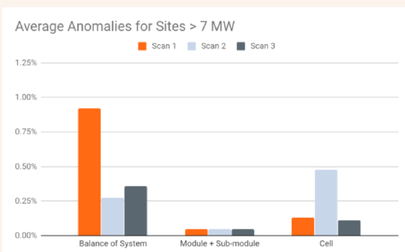
	Cell	Sub-module	Module	String
Example root cause	Hot spots caused by inactive regions in cells, solder issues and other mechanical damage	Broken cells, solder issues, faulty bypass diodes causing at least 1/3 of the module to be deactivated	Full module failure caused by junction box issues, or severe module damage	Wiring errors causing reversed polarity, loose connection or blown fuse causing string outages
Typical impact to overall DC production	Low	Moderate	High	High
Relative ease of remediation	Difficult (module swap, but hard to justify)	Moderate (module swap)	Moderate (module swap)	Easy
Energy weighting	0.10 – 0.20	0.66	1.00	1.00
Comments		Becomes relevant to owners/operators when observed across a large portion of site and/or attributable to a particular production batch – triggers serial defect or performance warranty claim.		"Low-hanging fruit" for owners/operators

Evolution of Anomalies

Changes in anomalies over time for different site sizes





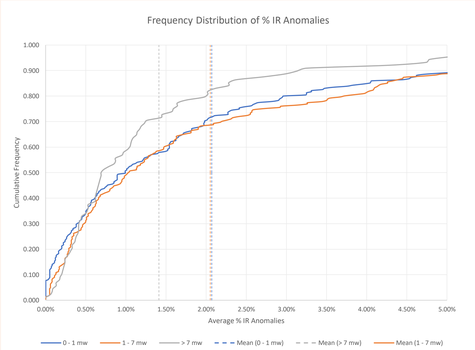


It is seen that rates of balance of system anomalies fluctuate between different site sizes. These anomalies are typically remediated over time.

It is also seen that module and sub-module anomalies tend to increase consistently over time. These can have a cumulative effect on system output over time, and putting in place a program for continuous refurbishment would likely result in net project benefits.

Please note that sample sizes for this analysis are relatively small. It is expected that these results will continue to evolve over time as the dataset grows.

IR Anomaly Quantity Distribution

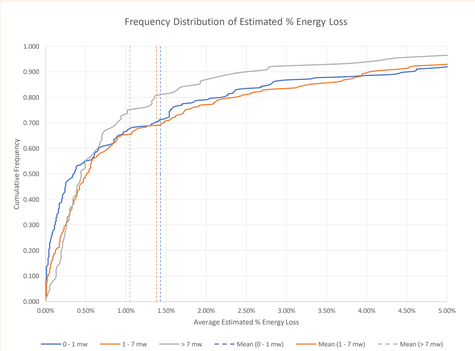


The distribution of anomalies is significantly higher for sites larger than 7 MW compared to sites ranging from 0 – 7 MW.

50% of inspected sites ranging from 0 – 7 MW had an IR anomaly rate of 1.0%, while larger sites (> 7 MW) had a rate of 0.7%. The majority of anomalies are string and cell level, while module level anomalies are approximately 0.3% for all site sizes.

Site Size (MW DC)	Mean	Median	Standard Deviation
< 1	2.07%	0.99%	3.06%
1 - 7	2.05%	1.04%	2.56%
> 7	1.41%	0.70%	1.91%

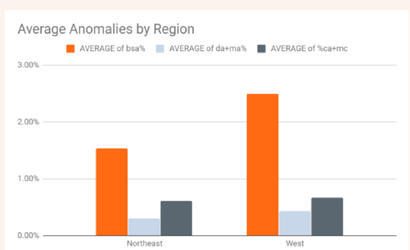
Estimated Energy Loss Distribution



The average estimated energy losses is lower than the average IR anomaly rate since all anomalies (except balance of system anomalies) do not result in full energy loss of affected modules. Average estimated energy losses for all site sizes are still observed to be above 1.0%.

Site Size (MW DC)	Mean	Median	Standard Deviation
< 1	1.43%	0.36%	2.51%
1 - 7	1.38%	0.51%	1.89%
> 7	1.05%	0.44%	1.54%

Anomalies by Region

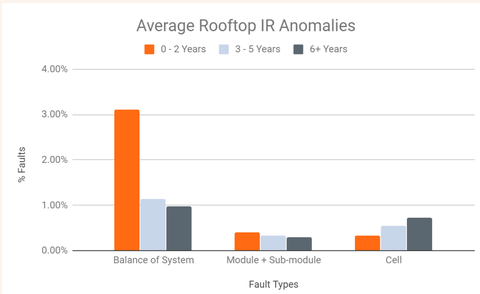


Balance of system anomalies are much larger in the Western region compared to the Eastern region.

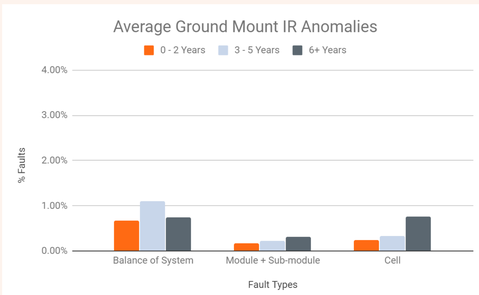
Similar trends are observed for module, sub-module and cell anomalies in both regions.

Rooftops vs. Ground Mounts

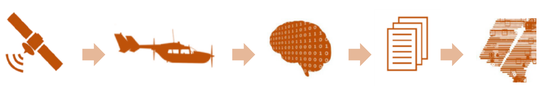
Changes in anomalies based on site age



Balance of system anomalies peak at 3% for new rooftop sites. Interestingly, module and sub-module anomalies appear to be less frequent on older sites.



Balance of system anomalies have a rate of > 0.6% for all ages, while module and sub-module anomalies increase with site age.



Effect of location-specific weather information and PV degradation on power prediction using NREL PVWatts

M.R. Dzurick, B.G. Potter, Jr., W.F. Holmgren, and K. Simmons-Potter

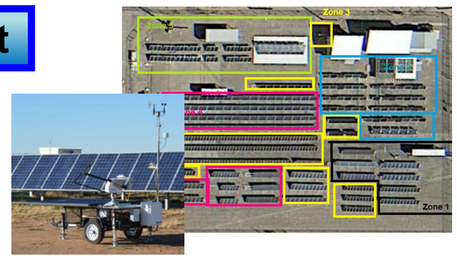
University of Arizona, Tucson, AZ 85721

Introduction and Background

- A key challenge to economically managing and developing the growing solar energy resource is the accurate prediction of solar power plant short-term energy yield (driven by weather and irradiance variability) and long-term energy yield (driven by system degradation).
- The availability of irradiance data, the proximity of the data source to the energy generation site (e.g. modeled irradiance based on satellite imaging or direct, onsite measurements) and a quantitative assessment of module performance degradation are key to increased power generation prediction via effective implementation of irradiance-to-power modeling.
- The present work examines the combined impact of irradiance information proximity and degradation-informed module performance on I-to-P model fidelity.

Facilities and Experiment

Environmental Testing Facility:
Accelerated Lifecycle and Qualification testing for PV (RH, Temp, single-sun) with in-situ performance assessment (I-V, EL imaging).



AzRISE-Tucson Electric Power PV Test Yard: 600 module capacity facility enabling field testing of ~90 kW_{peak} of PV systems including a wide variety of inverter and module technologies. Measurement capabilities: AC/DC power, I_{DC}, V_{DC}, local irradiance, ambient temperature, and module back-side temperature. Data collected at 1 min. intervals.

Field Testing: A two-panel string of multicrystalline Si modules were installed on fixed, open frames at the Arizona Research Initiative for Solar Energy/Tucson Electric Power (AzRISE/TEP) solar test yard (Tucson, AZ). Modules were installed in April, 2017. DC power output and backside temperatures (Type-T thermocouples, standard IES three-sensor arrangement per module) were collected at 1 minute intervals.

Chamber Testing (Accelerated Lifecycle Testing (ALT)): Identical mc-Si module was subjected to Tucson, AZ temperature, relative humidity and irradiance conditions consistent with test yard conditions over the time frame used in the field test [1]. In-situ monitoring of DC power output and module backside temperature.

Irradiance Measurement: *On-site:* *Smart Solar Field (SOFIE) station* - autonomous platform providing site-specific DNI, GHI, DHI, and POA irradiance and weather conditions at minute intervals with cellular upload. Located at AzRISE/TEP test yard. *Remote:* *NREL MIDC – OASIS [2]* - Remote irradiance and weather conditions, located approximately 5.6 miles from field test.

I-to-P Modeling

$$P_{dc} = \frac{E_{eff}}{E_o} P_{dco}\left(1 + \gamma_{pdc}\left(T_{cell} - T_{ref}\right)\right)$$

NREL PVWatts (pvlib-python [3]):

P_{dc} = maximum power point (DC)
E_{eff} = the effective (plane-of-array) irradiance value
E_o = reference irradiance = 1000 W/m^2.
P_{dco} = maximum power point (DC) under reference conditions = 270 W per panel (vendor supplied).
γ_{pdc} = temperature derating factor = -0.0039 (vendor supplied);
T_{ref} = reference temperature = 25 ºC.

T_{cell} = cell temperature (approx. with T_{module} this study); direct measurement and computed (Sandia Array Performance Model (SAPM)):

$$T_m = E_{POA} \cdot (e^{a+b \cdot WS}) + T_a$$

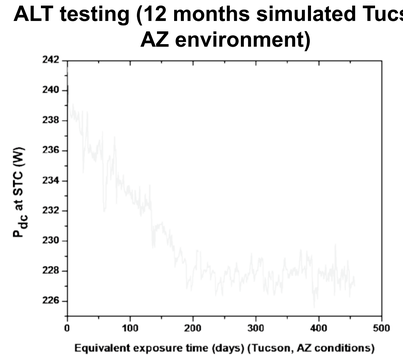
E_{POA} = plane-of-array irradiance
WS = wind speed
T_a = ambient temperature
a,b = constants for glass-cell-polymer module architecture

Results

PVWatts Model Parameter Sources

PVWatts Input Parameters	Model A	Model B	Model C	Model D
E_{eff}	OASIS	SOFIE	SOFIE	SOFIE
T_{cell}	SAPM-modeled	SAPM-modeled	Measured	Measured
P_{dc0}	Vendor	Vendor	Vendor	Degradation-informed

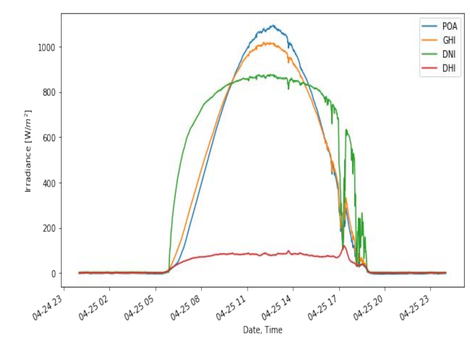
Power generation data during ALT testing (12 months simulated Tucson, AZ environment)

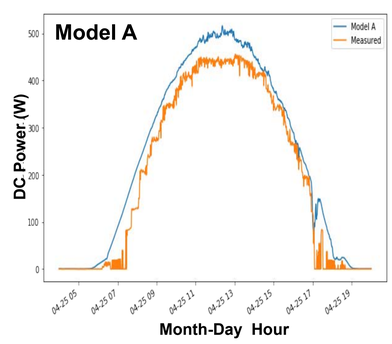


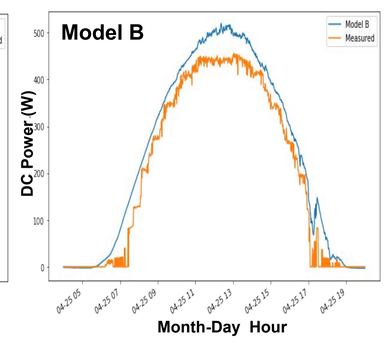
- **Accelerated Lifecycle Testing (ALT) results**: Reduction in P_{dc0} after a 12-month simulated performance cycle == **degradation-informed model input for P_{dc0} of 228.3 W**. (Vendor-supplied P_{dc0} = 270 W.)

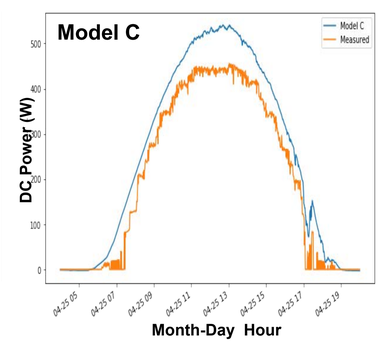
- PVWatts model used to compute output power for comparison with field-based, 2-module test string results.
- Effect of irradiance data source and vendor vs. degradation-informed, maximum power point DC power (P_{dc0}) on model performance examined.
- PVWatts model predicted power vs. measured power for a representative clear-sky day in Spring, 2018

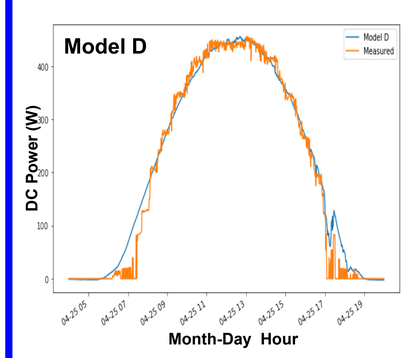
Irradiance Data: April 25, 2018 (SOFIE)

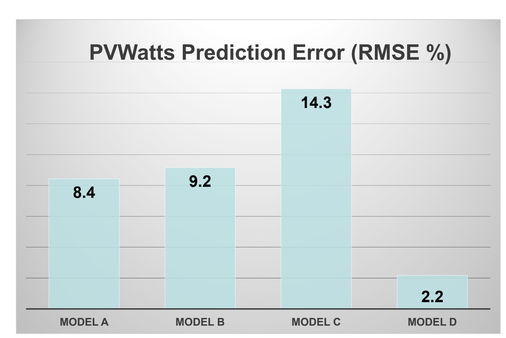












- Effect of irradiance data source (Model A,B) has minimal effect on prediction error (clear sky).
- Measured backside temperature of limited utility in improved power prediction (Model B,C).
- Lowest average RMS error observed when degradation-informed module performance behavior is included (Model D).

Clear Sky conditions:
Degradation-informed model parameters produced the largest impact on I-to-P model fidelity.
Environmentally induced decrease in P_{dc0} → Power prediction RMSE reduced to 2.2%.

Conclusions

- Under clear-sky conditions, irradiance data collection location has limited impact on I-to-P model prediction (anticipated).
- The use of degradation-informed I-to-P model parameters can be effective in significantly improving PV module output prediction.
- ALT-based environmental testing can be used to provide aging-related performance characteristics leading to increased modeling fidelity over extended installation times.

References

[1] T. Lai, B. G. Potter, and K. Simmons-Potter, "Analysis of twelve-month degradation in three polycrystalline photovoltaic modules," 2016, vol. 9938, no., p. 99380O–9938–9.
[2] A. Andreas and S. Wilcox, "Observed Atmospheric and Solar Information System (OASIS); Tucson, Arizona (Data)," NREL Report No. DA-5500-56494. http://dx.doi.org/10.5439/1052226
[3] William F. Holmgren, Clifford W. Hansen, and Mark A. Mikofski. "pvlib python: a python package for modeling solar energy systems." Journal of Open Source Software, 3(29), 884, (2018). https://doi.org/10.21105/joss.00884

Acknowledgements

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Using Satellite Albedo Data to Aid Bifacial Performance Modelling

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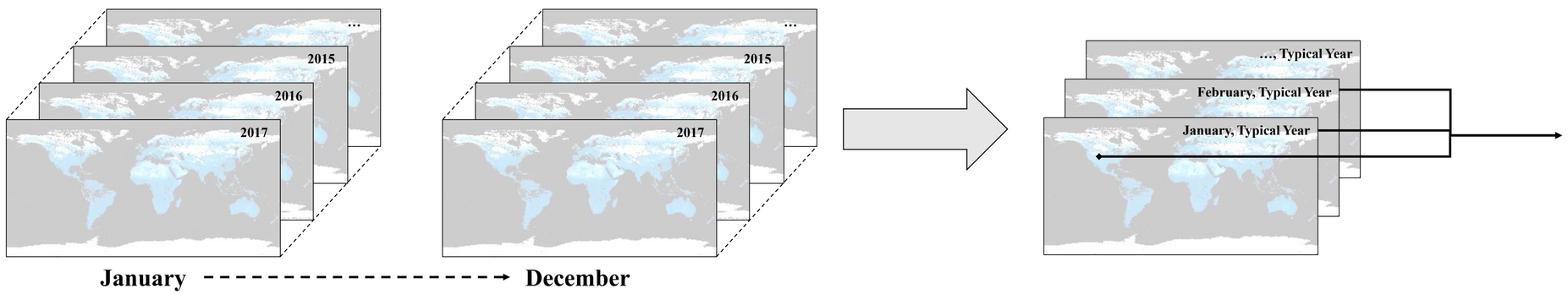
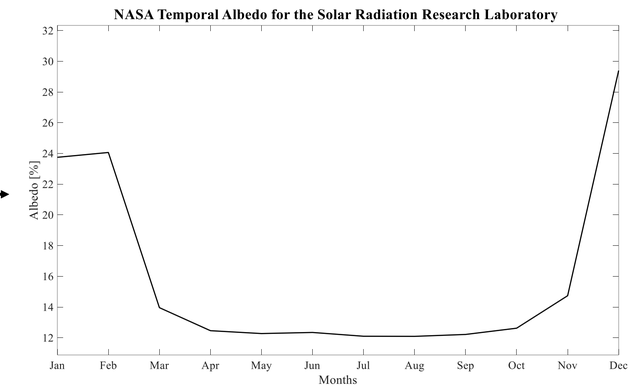
ABSTRACT

With new market interest in the deployment of bifacial modules, accurate ground albedo measurements are required. Albedo, or the reflectiveness of a surface[1], is the main driving factor behind bifacial modules' elevated performance compared to standard monofacial photovoltaic modules. Previously, accurate and reliable albedo data was not part of the typical sensor suite of commonly-deployed meteorological stations and thus there is a dearth of long-term albedo data. Therefore, the bankability of bifacial technology requires a robust method of albedo measurement. The National Aeronautics and Space Administration (NASA) has collected satellite data to create databases for temporal and spatial albedo measurements. The proposed model requires the processing of this NASA data into a database that can be readily used to create typical meteorological year albedo measurements. The reliability of this data should be validated against the National Renewable Energy Laboratory (NREL) Measurement and Instrumentation Data Center (MIDC) albedo instruments to determine whether this is an acceptable method of obtaining accurate albedo measurements.[2]

METHOD

For many decades, NASA has had a robust fleet of Earth-observing satellites. These satellites collect a plethora of Earth data including albedo measurements of Earth's landmass. These measurements are recorded monthly and can be used to create a historical analysis of ground reflectivity for numerous years at a spatial resolution of 0.1 degrees. This database can be broken into months and compiled to create typical meteorological years for spatial-specific albedo. For reference, an albedo of zero represents no reflectivity and an albedo of one represents complete reflectivity.

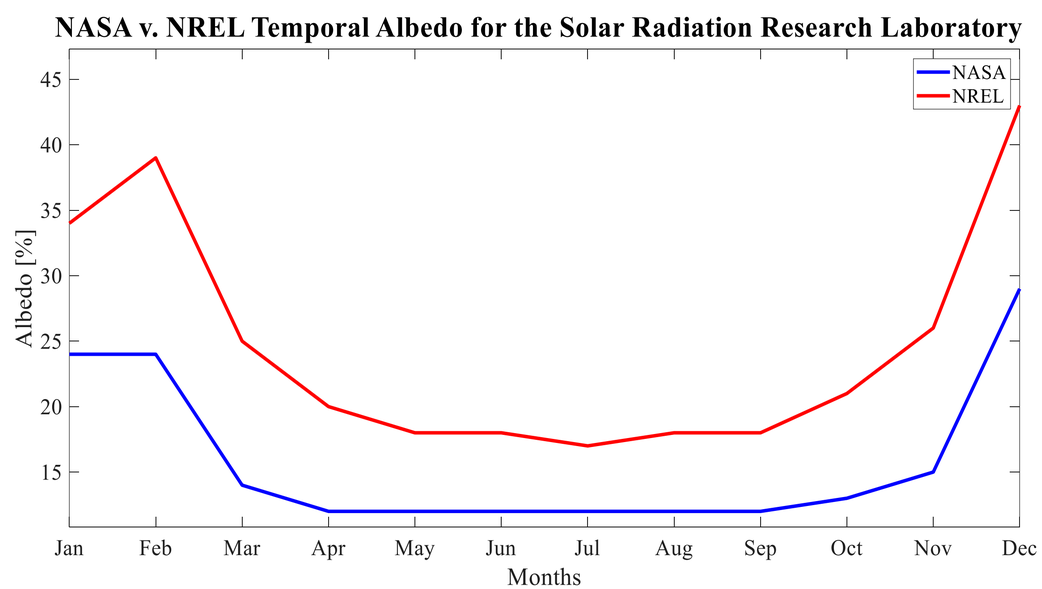




VALIDATION

In addition to NASA's space-based albedo measurements, NREL has been recording ground-based albedo measurements for numerous years. We can compare ground-based observation from the Solar Radiation Research Laboratory to satellite-based observation from NASA spacecraft. By performing the same process used to make a typical year albedo database using NASA data and applying it to the NREL data, we can compare the two methods.

The graph to the right shows the comparison of NASA's satellite-based albedo measurements to NREL's ground-based albedo measurements at the Solar Radiation Research Laboratory.



CONCLUSION

There is significant discrepancy between the ground-based observations and the satellite-based observations of albedo. This discrepancy is interesting as it appears that the albedo measurements are simply a scalar apart. This leads us to believe that this method has merit, but that it requires additional work before the creation of a satellite-based method of collecting bankable albedo measurements.

ACKNOWLEDGEMENTS

The authors would like to thank the National Renewable Energy Laboratory and National Aeronautics and Space Administration for the data that made this study possible.

REFERENCES

[1] "Albedo (1 Month)." *NASA*, NASA, neo.sci.gsfc.nasa.gov/view.php?datasetId=MCD43C3_M_BSA.

[2] Andreas, Afshin Michael. "NREL: Measurement and Instrumentation Data Center (MIDC) Home Page." *NREL: MIDC/SOLRMAP University of Arizona (OASIS)*, midcdmz.nrel.gov/.

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

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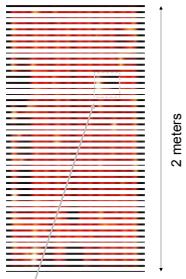
Utilizing TOF-SIMS to Investigate Module Degradation Mechanisms

Steven P. Harvey, Steve Johnston, Christopher P. Muzzillo, Lorelle Mansfield, Harvey Guthrey, Peter Hacke, Mowafak Al-Jassim
Steve.Harvey@nrel.gov

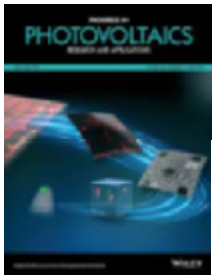
Investigating PID in Field-Failed Polysilicon Modules

Example of degradation in the field: 72-cell silicon module



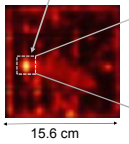
Dark Lock-In Thermography (DLIT) image (46 V_{FWD}, 5 A, 0.5 Hz, 120 s)

See June 2018 cover article in PiP detailing this work.

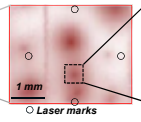


https://doi.org/10.1002/pip.2996

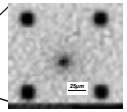
Cell level DLIT



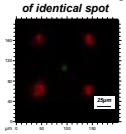
HI-Res DLIT



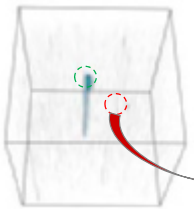
FIB Marks +EBIC



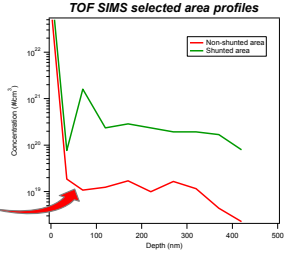
Ga^+, Na^+ Tof-SIMS Image of identical spot



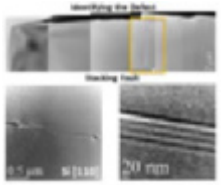
3-D rendering of Na+ 200x200x0.5µm



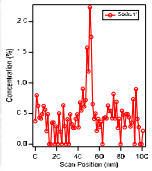
TOF SIMS selected area profiles



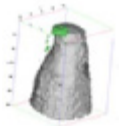
TEM Results show stacking fault in shunted area



STEM line scan consistent with [Na] from TOF-SIMS



Atom Probe Tomography of PID shunt consistent with the TOF SIMS and STEM results



96% Si 0.4% Na

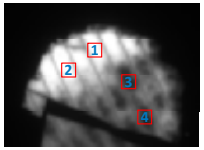
Conclusions: Polysilicon PID

- Multi-scale, multi-technique characterization showed sodium decorating structural defects leads to PID shunting in field-degraded modules.
- TOF SIMS, TEM-EDS linescan data, and APT data both show sodium at a concentration of ~1 atomic % in these shunted defects.

Investigating PID in Single-Crystal Silicon Modules

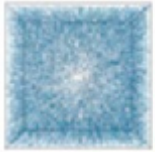
- As with our work on polysilicon field-degraded modules, module scale imaging was used to identify areas of interest for further characterization.
- Circular cores (~1" in diameter) were then removed from the module and imaged with PL, EL and DLIT to identify areas of interest for further characterization.

PL image of module core



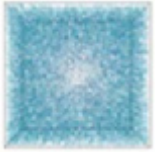
3-D distribution of sodium from 4 marked areas in PL image at left

Non-Shunted Area 1



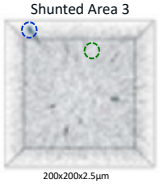
200x200x2µm

Non-Shunted Area 2



200x200x2µm

Shunted Area 3

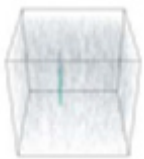


200x200x2.5µm

Shunted Area 4

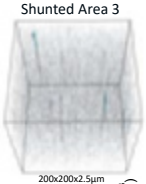
100x100x0.9µm

Shunted Area 4



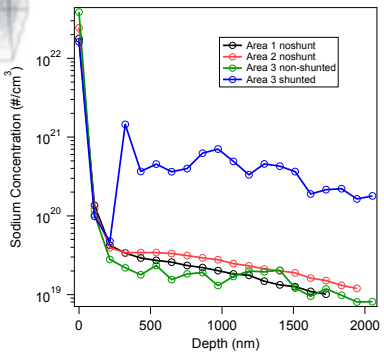
100x100x0.9µm

Shunted Area 3



200x200x2.5µm

Sodium profiles for non shunted and shunted areas is similar to what is seen in polycrystalline silicon modules



Conclusions: Single-crystal Silicon PID

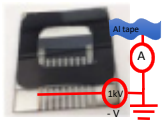
- TOF-SIMS analysis reveals PID shunted areas of a field-degraded module are very similar in polysilicon and single-crystalline modules.
- In both types of modules sodium appears at high concentration in structural defects (presumably stacking faults).
- Away from these structural defects the sodium content is similar to what is observed in non-degraded areas.

Investigating PID in CIGS thin film mini modules

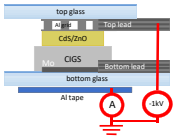
- Multiple CIGS mini-modules were held at 85C 10%RH for 25 hours, with and without PID bias applied
- The PID stressing (-1000V (Al on back) at 85 C and 10% RH resulted in complete module failure after 25 hours.

Potential (V)	Devices	Before/After	Champion performance			
			Eff. (%)	V_{OC} (mV)	J_{SC} (mA/cm²)	FF (%)
0 (control)	7	Before	15.7	707	28.6	77.3
		After	15.5	699	28.9	76.7
-1000	13	Before	16.0	704	30.3	74.9
		After	0	-	-	-

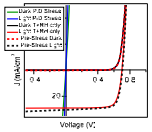
Encapsulated 3" Mini-Modules



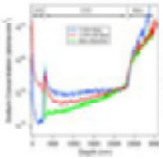
PID Bias Schematic



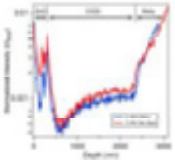
Post stress JV Curves



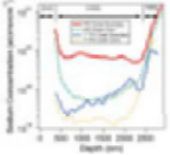
Na Profiles Upon Stressing



K Profiles Upon Stressing



Selected area Na profiles show fast GB diffusion

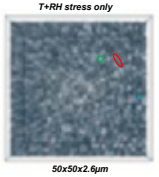


3-D distribution of sodium in CIGS after various states of stress

Unstressed absorber

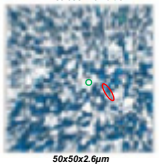
50x50x2.6µm

T+RH stress only



50x50x2.6µm

T+RH stress with bias

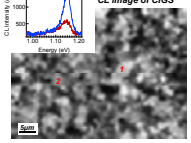


50x50x2.6µm

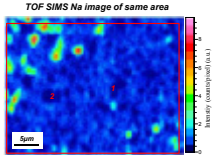
Correlation of Grain Boundaries with TOF-SIMS

Cathodoluminence results shows grain boundary location matches with apparent grain boundaries seen in the TOF-SIMS image.

CL image of CIGS



TOF SIMS Na image of same area



See this work in our recent paper: S. P. Harvey *et al.*, in *IEEE Journal of Photovoltaics*, vol. 9, no. 2, pp. 559-564, March 2019.

Conclusions: CIGS PID Degradation

- TOF-SIMS reveals significant sodium migration upon both temperature and PID stressing.
- Lack of K migration attributed to larger ionic radius than Na.
- TOF SIMS tomography and selected area profiles show evidence for fast grain-boundary diffusion of sodium.
- Correlation of cathodoluminescence and TOF SIMS images confirm sodium at high concentration at grain boundaries.

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory.

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Detection and Localization of Disconnections in PV Strings Using SSTDR

Mashad Uddin Saleh[1]; Christopher Deline[2]; Naveen Kumar[1]; Evan Benoit[1]; Samuel Kingston[1]; Joel Harley[3]; Cynthia Furse[1, 4]; Mike Scarpulla[1]

[1] Department of Electrical and Computer Engineering, University of Utah, Salt Lake City, UT 84112
[2] National Renewable Energy Laboratory, Golden, CO, 80401
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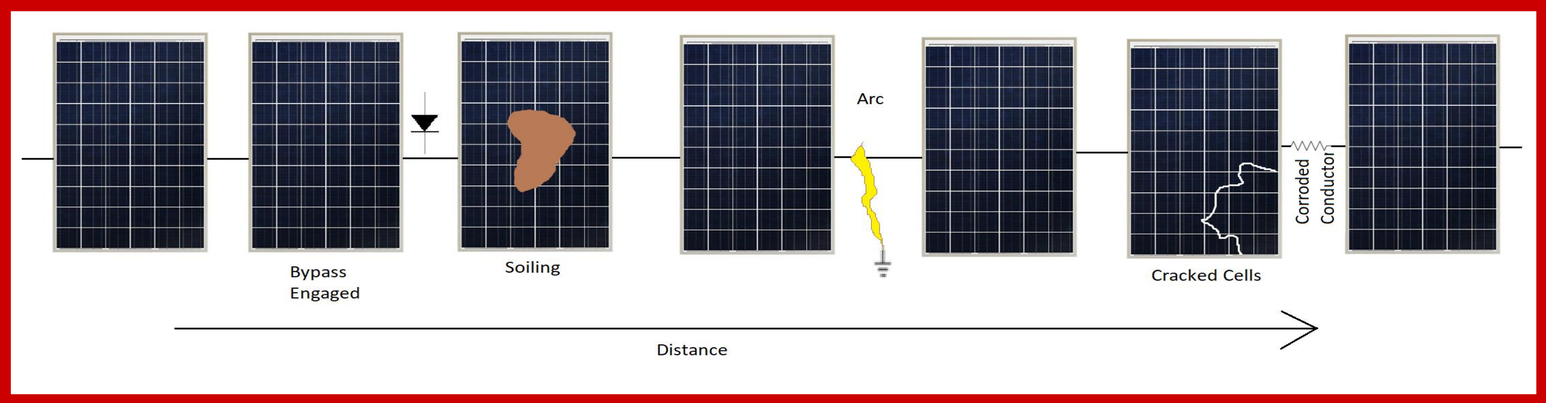
[4] LiveWire Innovation, Salt Lake City, UT 84105

Degradation in performance can occur in PV arrays due to faults in wiring or modules themselves. It is crucial to identify and locate the faults specially disconnections to reduce power loss in PV arrays.

The main goal of our project is to monitor operating strings of PV modules using Spread Spectrum Time Domain Reflectometry (SSTDR) technology.

We present a non-intrusive technique to detect and localize disconnections between modules using SSTDR. To understand the PV module behavior, we investigate the evolution of SSTDR responses due to the addition of PV mini-modules and then extend it to full-sized modules. SSTDR responses significantly change because of the addition of more modules or disconnections at PV connectors or within modules.



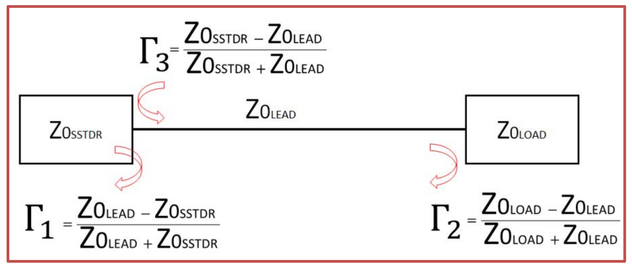
Schematic of a PV string with different faults at different locations causing changes in AC impedance

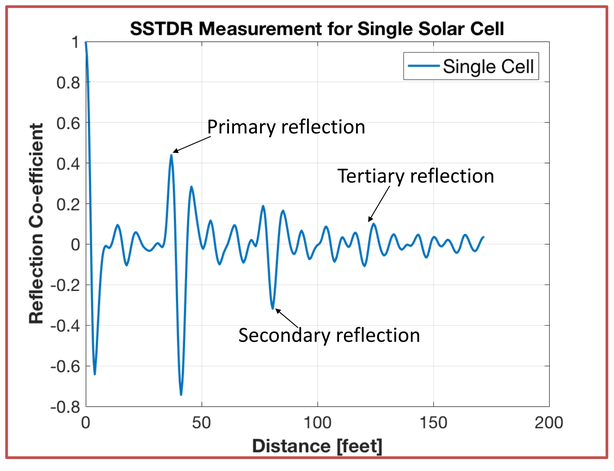
SSTDR TECHNIQUE

Front and back views of a PV module

SSTDR Box we are using for measurement

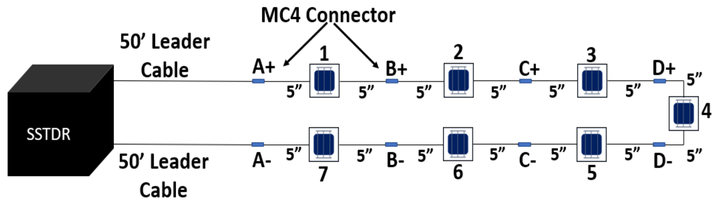
- Conceptually, SSTDR sends signals through the system and "listens" to the "echoes". Because of the multitude of impedance discontinuities in a string, the signal is very rich, but complex to interpret at first glance.
- Time delay is measured from time correlation of the sent digital pseudo-noise code with the reflected waveform is converted to physical distance by a propagation velocity.





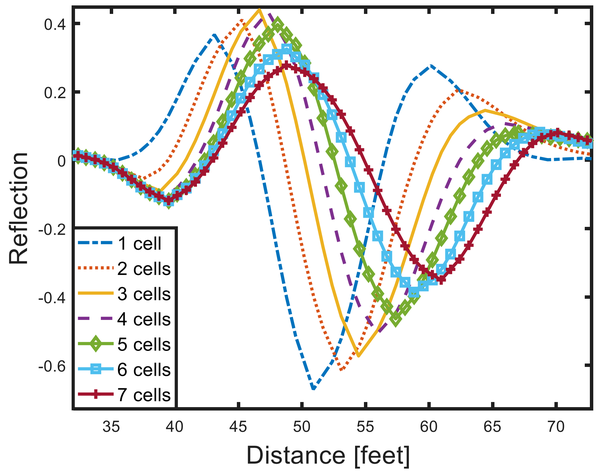
SSTDR measurement for a discrete solar cell. The solar cell was uncovered and placed at 40 feet away from the SSTDR box

DETECTING DISCONEECTIONS IN THE SYSTEM

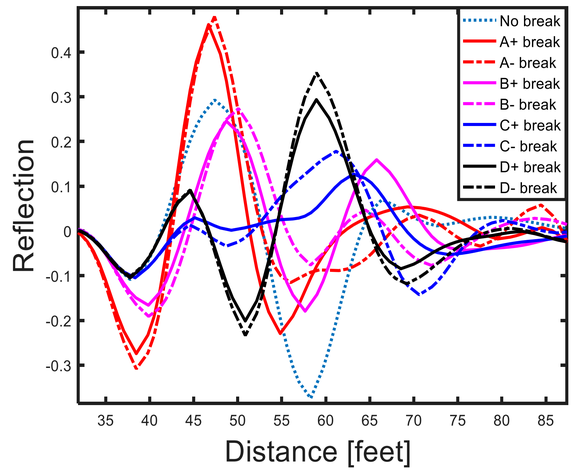


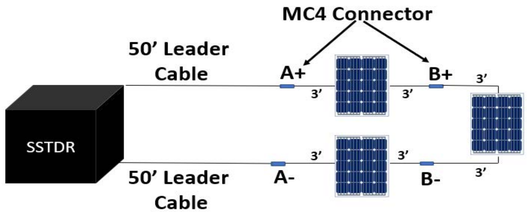
Series connection of 7 single-cell mini-modules. A+, A- etc. are the MC4 connectors connecting the cells.

SSTDR Evolution for series connected mini-modules



SSTDR responses for disconnections at each break

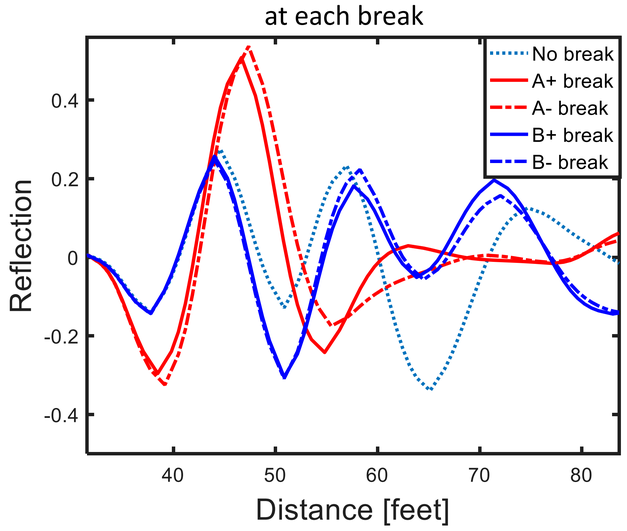




Series connection of three 36-cells PV modules. A+, A- etc. are the MC4 connectors connecting the PV modules.

- Evolution of signal can be understood from addition of cells behaving as leaky capacitors. Evolution from RF short to derivative-like.
- Demonstrates symmetry of SSTDR measurements from signal propagating along both arms of transmission line simultaneously.
- Distinct signals for disconnections at each location.

SSTDR responses for disconnections at each break



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REFERENCES

[1] C. Furse, Y. C. Chung, C. Lo, and P. Pendayala, *Smart Struct. Syst.*, vol. 2, no. 1, pp. 25–46, 2006.

[2] Saleh, Mashad Uddin, et al. *IEEE Journal of Photovoltaics* (2018).

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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Background

Current accelerated testing protocols were designed specifically to test the susceptibility of photovoltaic (PV) modules to known field-failure mechanisms. The standards subject numerous modules to multiple, parallel testing conditions. Despite the relative success of IEC61215, many failures have gone undetected until after deployment due to the mechanism-specificity and single-stress nature of the tests.

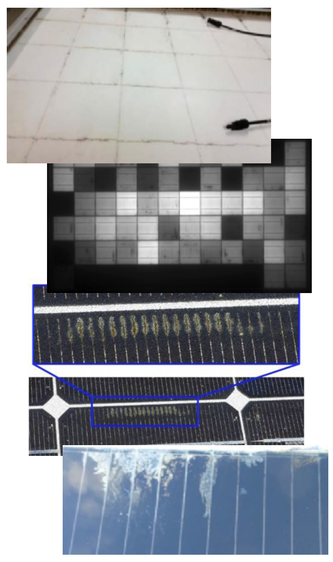
Examples

Backsheet Cracking
→ EVA, UV, hydrolytic, CTE stress

PID
→ system voltage, humidity/moisture, temperature, light

Grid Finger corrosion
→ system voltage, humidity, temperature, light

Snail Trails/Delamination
→ mech. Load, UV, electric field, moisture



This work proposes a combined-accelerated stress test (C-AST) protocol to more appropriately simulate the natural environment and the combined interactions between the various stress factors. The primary objective is to identify potential field-failure mechanisms before deployment, as opposed to after.

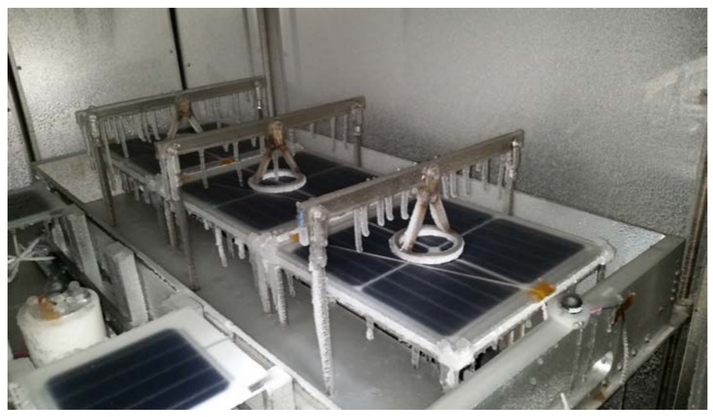
Combined-Accelerated Stress Testing

Atlas XR-260 weathering chamber
- Six 4-cell mini-module
- Air temp. -40 to 95C
- Relative Humidity 5% to >95%

Light stressing
- 4x Xenon Arc lamps
- Filtered to simulate two sun full-spectrum filtered Xe light @ 340nm
- Reflector troughs for UV albedo to backsheet
- 4x white-light LED strings for minimum 50W/m^2

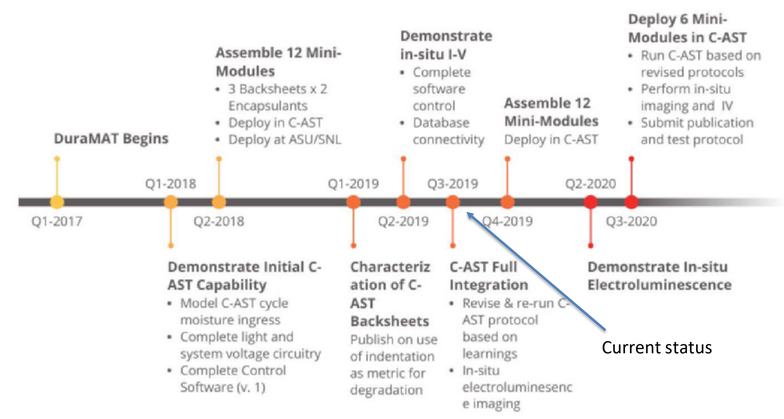
Mechanical Stress
- Hydraulic actuators
- Applying pressure to module surface with 100mm diameter teflon "donuts"

High Voltage Stress
- 2x Stanford high voltage power supplies
- Leakage current monitored via Keithley 2700 multimeter



Inside the chamber during wet freeze stage

Timeline & Progress



- Spataru et al "*Combined-Accelerated Stress Testing System for Photovoltaic Modules*" WCPEC, 2018
- Owen-Bellini et al "*Combined-Accelerated Stress Testing for Advanced Reliability Assessment of Photovoltaic Modules*" EUPVSEC, 2018
- Miller et al "*Use of Indentation to Study the Degradation of Photovoltaic Backsheets*", Solar Energy Materials and Solar Cells, 2019 (submitted)
- Owen-Bellini et al "*In-situ Performance Characterization of Photovoltaic Modules during Combined-Accelerated Stress Testing*" IEEE PVSC, 2019 (submitted)

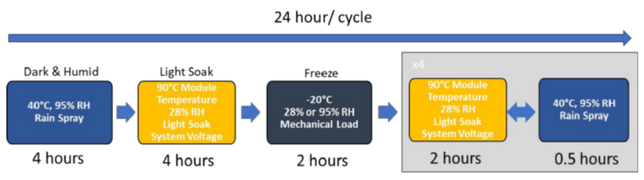
Demonstration Experiment

→ Backsheets failed in field but failures not detected in conventional testing
→ Can we identify failures through combined testing?

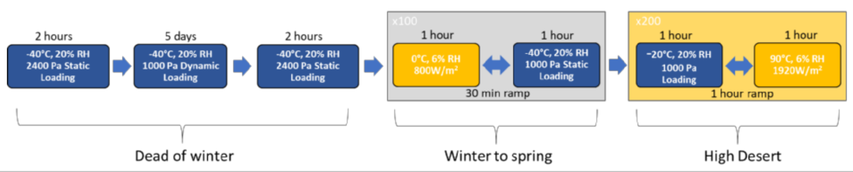
	PVF-PET-PVF	Polyamide (PA)	PVDF
UV Absorbing rear EVA	✓	✓	✓
UV non absorbing EVA	✓	✓	✓

Two phase test protocol to cover multiple environments and seasons

Phase 1 – Based on ASTM D7869 for tropical conditions



Phase 2 – Multi-season



Identified Failure Mechanisms

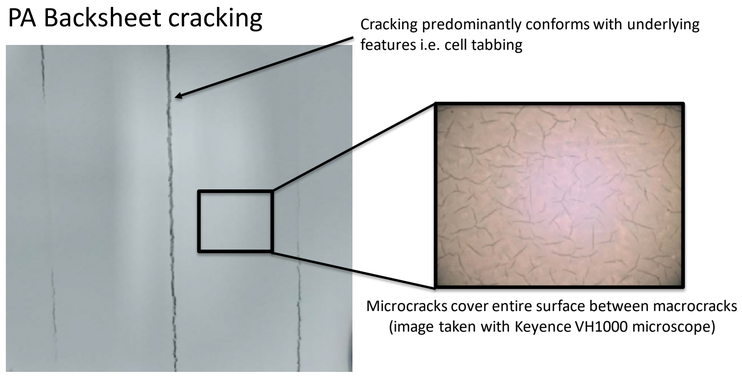
Mode	Mechanism	Relevant Stress Factors
Solder bond failure leading to open-circuit	Insufficiently bonded solder joint at bus ribbon. Possibly comprised during soldering of junction box, joule heating in the conductors	Mechanical and thermomechanical stress on conductors. Applied light leading to joule heating in conductors
Light-induced Degradation	UV degradation of cell fronts by loss of hydrogen passivation in modules using UV-pass EVA leading primarily to short-circuit current and open-circuit voltage loss	UV component of full spectrum light applied
Cracking of Backsheet	Loss of volatile compounds, oxidative and hydrolytic reactions in PA and PVDF backsheets	Heat, mechanical and thermomechanical stress
Corrosion, Ion migration	Ion formation and migration of ionic species facilitated by humidity and tensile stress	Heat, humidity and system voltage bias
Potential-Induced Degradation	Ion formation and migration facilitated by humidity electric field	Heat, humidity and system voltage bias, modulated by applied light
Backsheet delamination	Moisture ingress into interface reducing adhesion, separation by mechanical and thermomechanical stress	Heat, humidity, mechanical and thermomechanical stress
Cell cracks	Crack progression from tensile stress	Mechanical pressure, thermomechanical stress

PA cracking initiated after 4.5 months of phase 1

PVDF cracking after 6 months phase 1 + 1 round of phase 2 (1 month)

Backsheet Cracking

PA Backsheet cracking



PVDF Backsheet cracking

Cracking initiated along cell tabbing but quickly spread to areas between tabbing

Advanced material characterization is conducted on both materials

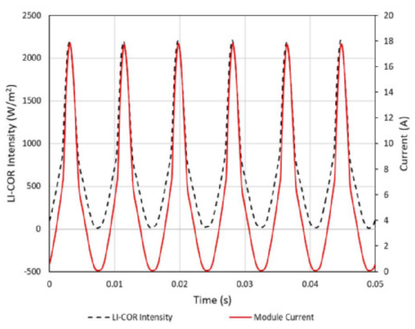
See poster **"Correlation of advanced accelerated stress testing procedures with field data through advanced characterization and data analytics"**

In-Situ Module Characterization

IV Curve Tracing

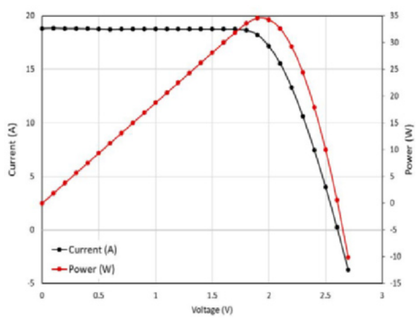
- Xe light source driven by AC supply means light fluctuates at ~100Hz
- Makes IV measurements difficult

Solution:
- Pulse voltage and take multiple current measurements (100kHz)
- Filter for highest current value where highest irradiance is known



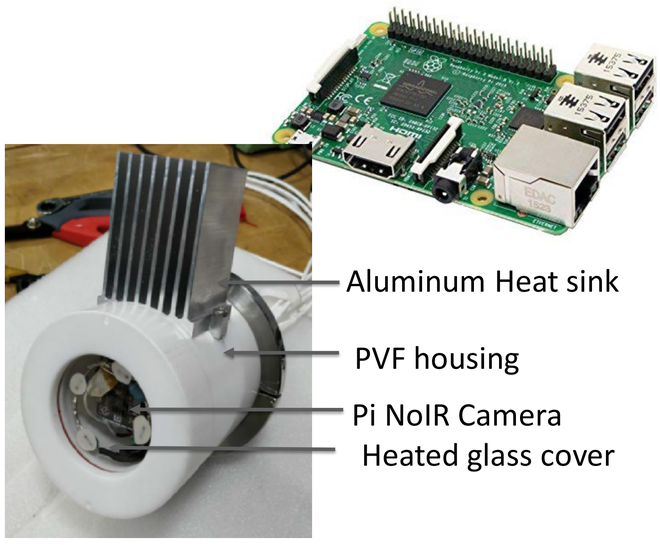
Current measurements for a 0.05s 0.1V pulse

Repeat & Filter



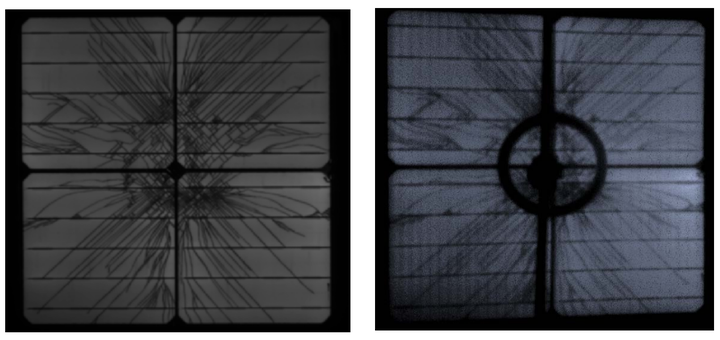
Light-IV curve constructed from multiple pulses in 0.1V increments

Electroluminescence Imaging



- Raspberry Pi 3 with NoIR (No IR Filter) camera provides low-cost solution for imaging inside climate chamber

Cracked c-Si mini-module 25°C, 8.5A, 3V



CCD Camera NoIR Camera

This work was authored in part 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.

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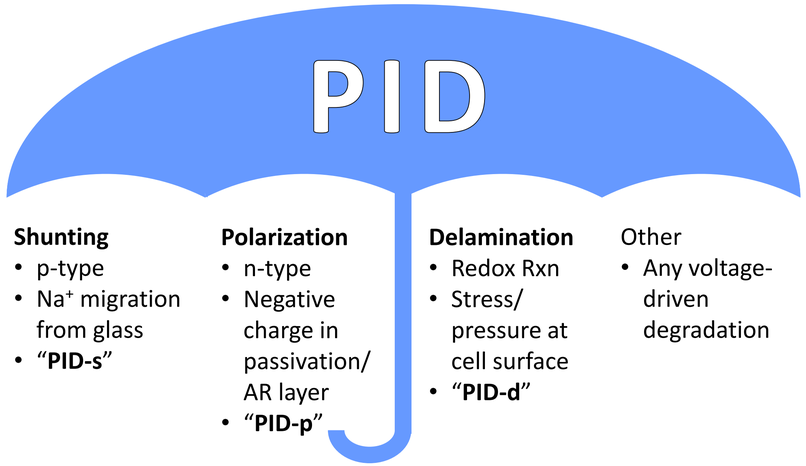
Photovoltaic Reliability Workshop
Denver, CO
2/25/2019 – 2/28/2019
NREL/PO-5K00-73367

Encapsulant resistivity is not predictive of PID-s susceptibility

Brian M. Habersberger[1], Peter Hacke[2], Lisa Madenjian[1]

[1]The Dow Chemical Company [2]National Renewable Energy Lab

Background

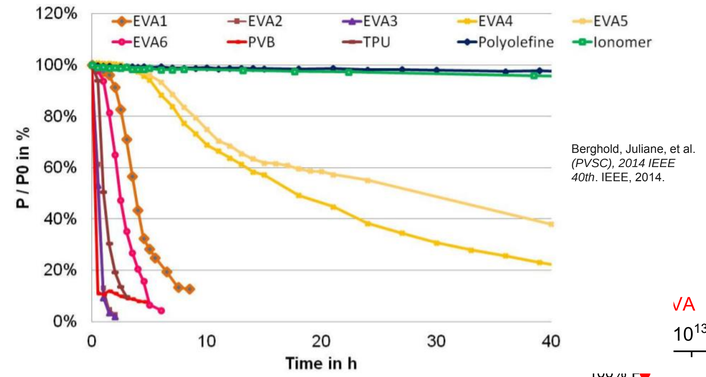


Shunting
- p-type
- Na^+ migration from glass
- "**PID-s**"

Polarization
- n-type
- Negative charge in passivation/ AR layer
- "**PID-p**"

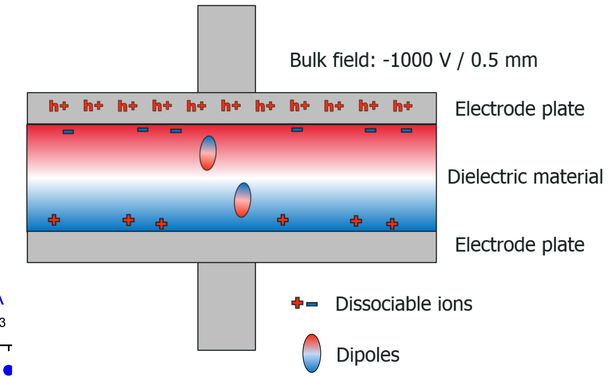
Delamination
- Redox Rxn
- Stress/ pressure at cell surface
- "**PID-d**"

Other
- Any voltage-driven degradation



Berghold, Juliane, et al. *(PVSC), 2014 IEEE 40th*. IEEE, 2014.

Material	Typical resistivity (Ω·cm)
EVA	$10^{13} – 10^{15}$
Polyolefin	$10^{16} – 10^{17}$
Ionomer	$10^{16} – 10^{17}$



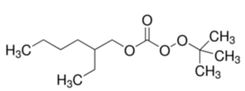
- POE and ionomer prevent PID-s
- POE and ionomer have higher resistivity than EVA
- "Post hoc ergo propter hoc"

Laboratory resistivity measurements
- Current is due to ions present in material
- Sodium is not substantially present
- Why should this have any relation to PID-s?

PID-s study

3 POE resins, 1 EVA resin
- POE resins have identical crystallinity and MW
- All converted to film in the same facility in one day
- Same UV stabilization package in all films
- Same curing package used in all films

1%



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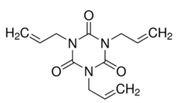

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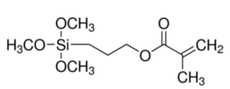
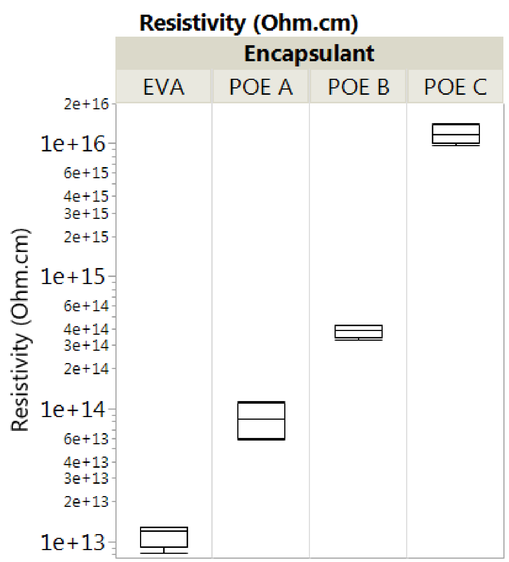
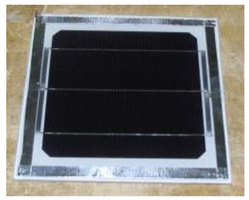
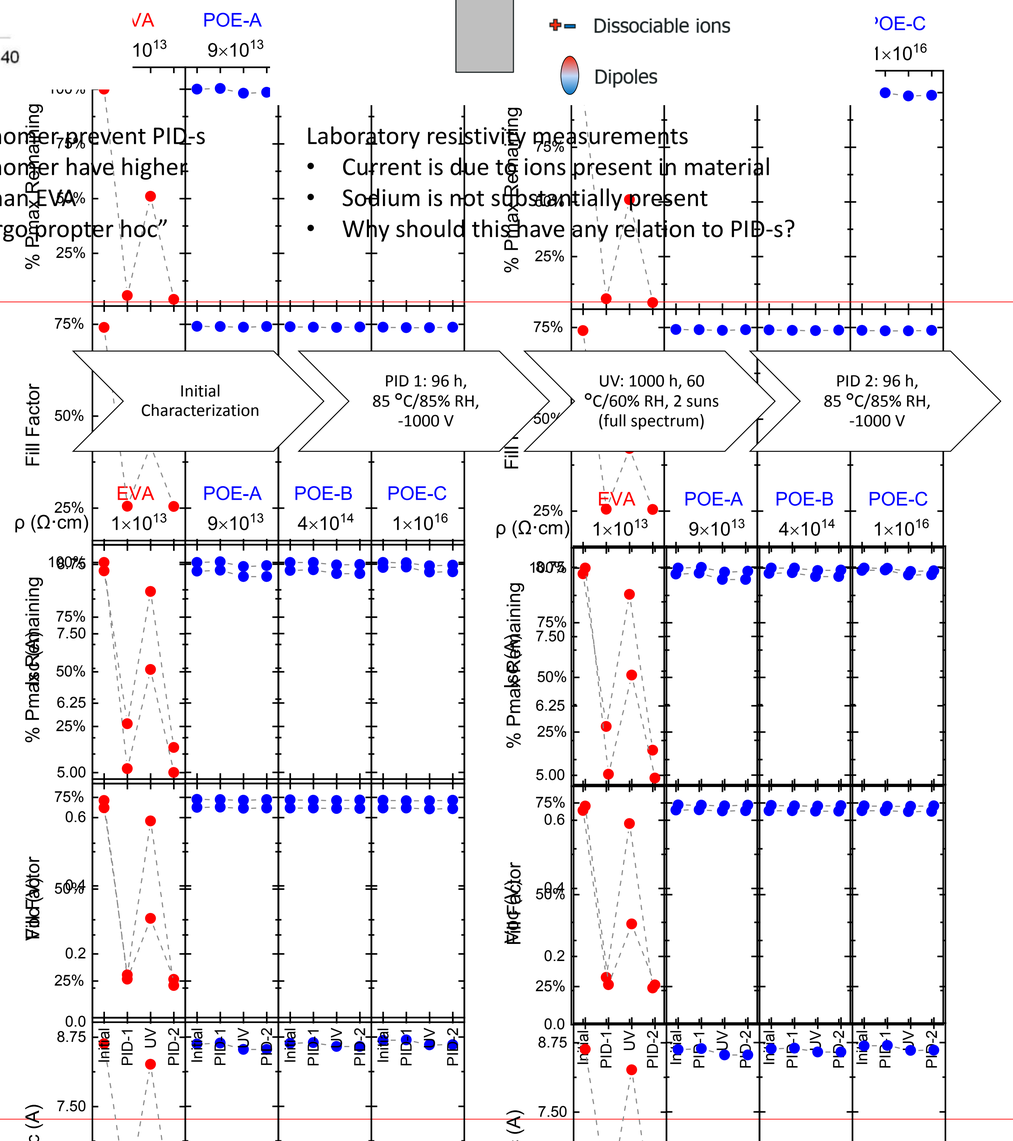






Films were used to construct 1-cell mini-modules
- Modules containing POE exhibit no PID-s, regardless of the encapsulant resistivity
- Modules containing EVA exhibit severe power loss

Conclusions
- Polyolefins are impermeable to Na+, regardless of the presence of other ions
- Different PID mechanisms are sensitive to different material properties



(BI)PV power architecture reliability & performance aspects

Johan Driesen, KU Leuven & EnergyVille

Building-integrated PV challenges

BIPV = multi-functional use

- As building component
- To generate electricity

Long lifetime required

- 30-40 years or >100k hours (more than aerospace!)
- Problem for converters?

What will drive BIPV ?

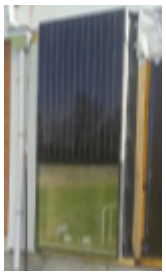
- Façade-integration of PV for tall NZEB-compliant buildings
- PV-roofs with improved esthetics
- Lower overall cost (building + PV)

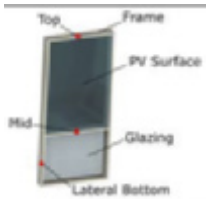
Example of window-integrated transparent thin-film modules at EnergyVille test-building

BIPV research @ EnergyVille

EnergyVille in Belgium: research collaboration of KU Leuven, imec, Vito and Uhasselt investagated the full value-chhain of BIPV:

- Materials, cells, module design and construction
- Power converter design and architecture
- Modelling and field testing

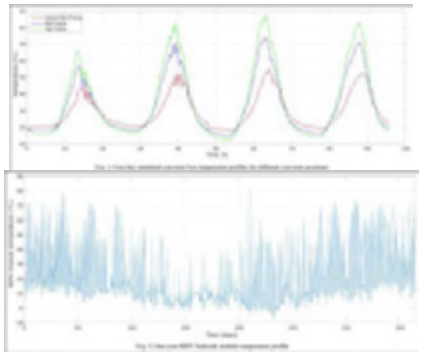




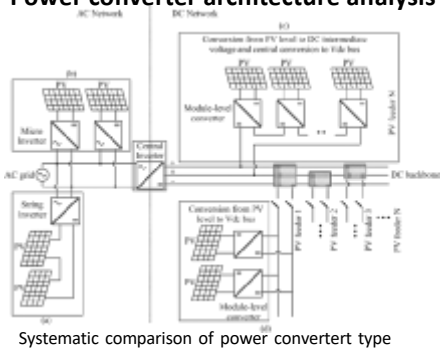
Façade BIPV element designed and in test by EnergyVille + indication positions MLC converter

Module-level converter conditions

Modelling + experimental approach to obtain operating conditions of module-level converters inside BIPV module: cooling performance, temperature profiles, humidity → input for converter design and lifetime estimation



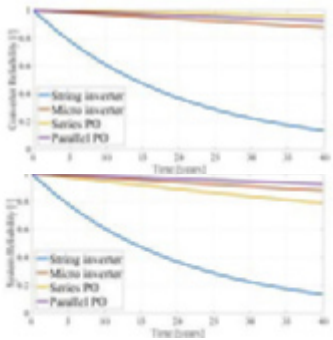
Power converter architecture analysis



Systematic comparison of power convertert type and placement options for BIPV

BIPV converter: reliability aspects

Reliability analysis of a DC-DC converter placed in BIPV module frames: best results for parallel power optimizer design



Use of GaN switch technology

Power converter design employing wide bandgap semiconductors (GaN)

- Lower losses, lower cooling requirement
- Small size and form factor

Build-in improved resilience using temperature sensing and component redundancy (e.g. multi-phase dc-dc in example)

dc-dc in Si Mosfet 115x250x30 mm³

dc-dc in GaN 55x175x30 mm³

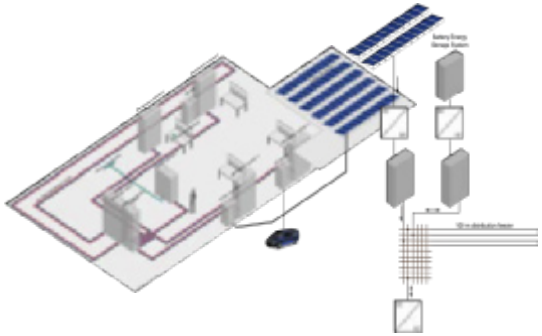
BIPV power architecture based on LVDC: towards DC nanogrids

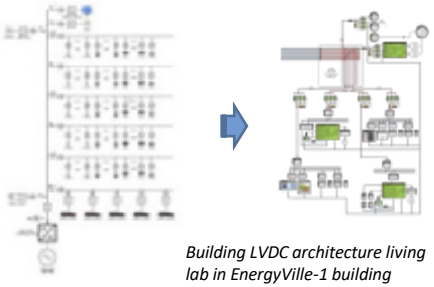
Increasing importance of LVDC generation (BIPV conversion), loads (IT, LED) and storage (batteries) in buildings

Expand LVDC power architecture to the whole building: towards the DC nanogrid

Lowest CAPEX (-30%) and OPEX (-5%) for bipolar architectures

Energyville designed and operates an in-building max 100 kW, max +/-500V scalable LVDC nanogrid/microgrid living lab for research on performance, stability and protection





Building LVDC architecture living lab in EnergyVille-1 building

Can we help?

For more information, contact us:
johan.driesen@kuleuven.be

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

Correlation of advanced accelerated stress testing procedures with field data through advanced characterization and data analytics

Michael Owen-Bellini[1], Laura T. Schelhas[2], Stephanie L. Moffitt[2], Ashley M. Maes[3], James Y. Hartley[3], Donald R. Jenket II[1], Todd Karin[4], Anubhav Jain[4], Peter Hacke[1]
[1]National Renewable Energy Laboratory, [2]SLAC National Accelerator Laboratory, [3]Sandia National Laboratories, [4]Lawrence Berkeley National Laboratory

DuraMAT Capabilities

1. Data Management & Analytics, DuraMAT Data Hub
2. Predictive Simulation
3. Advanced Characterization & Forensics
4. Module Testing
5. Field Deployment
6. Techno-Economic Analysis

Capability Goals

This work will leverage state-of-the-art AST, materials characterization, simulation, and data analytics to drive the establishment of best practices and validation of AST protocols for the PV industry. We will specifically investigate the correlation between different AST testing protocols and fielded modules by characterizing changes in the backsheet material properties.

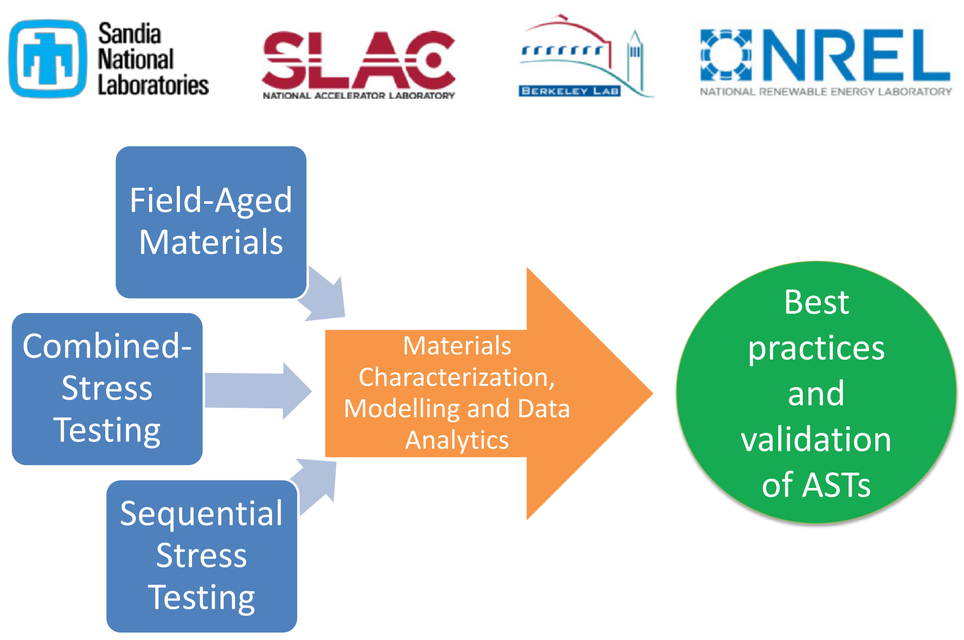
Milestones

Year 1: Characterization of "unaged" backsheets and encapsulants used for C-AST mini-modules, and of closest available "unaged" materials to fielded modules'
Year 2: Acquire 3 different sets of fielded module samples
Year 3: Submission of publication summarizing the results of the demonstration project. Deliver recommendations to industry for adjustments and/or adoption of new AST methodology to de-risk adoption of new module packaging materials.

Outcomes and Impact

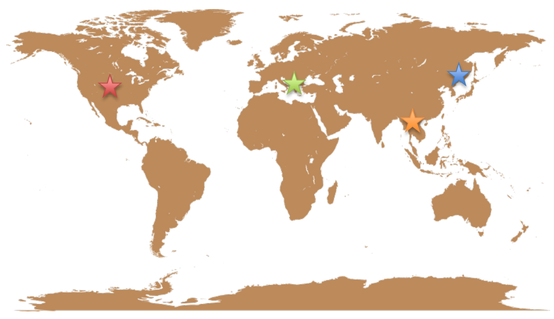
The approach developed by this work can be applied to additional materials systems, providing a new capability for DuraMAT stakeholders to use for discovering, de-risking, and enabling the commercialization of new materials and designs.

Project Overview and Approach



Field-Aged Modules

Goal: Source fielded modules with similar bill of materials

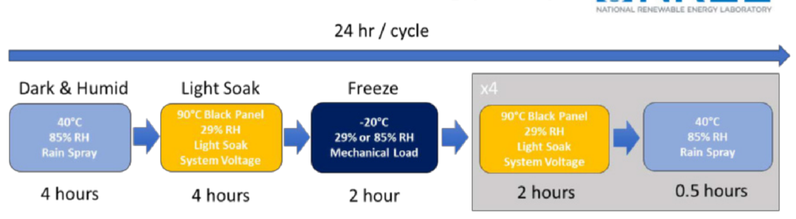


- Fort Collins, CO
- Rome, Italy
- Thomkrataithong, Thailand
- Changshu, China

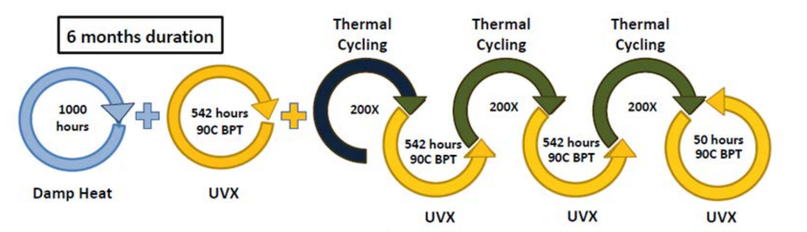
We are currently looking for field-aged PVDF

Accelerated Testing Approaches

Combined-Accelerated Stress Testing (C-AST)

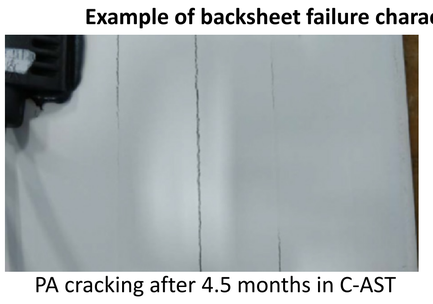


Sequential Accelerated Stress Testing (M-AST)

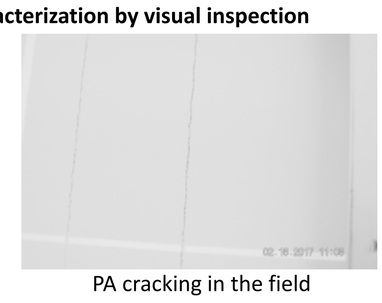


Materials Characterization

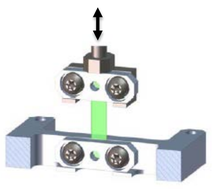
Example of backsheet failure characterization by visual inspection



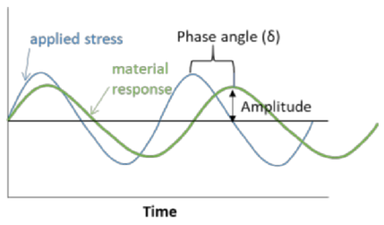
PA cracking after 4.5 months in C-AST



PA cracking in the field



from: Netesch Operating Instructions DMA242E

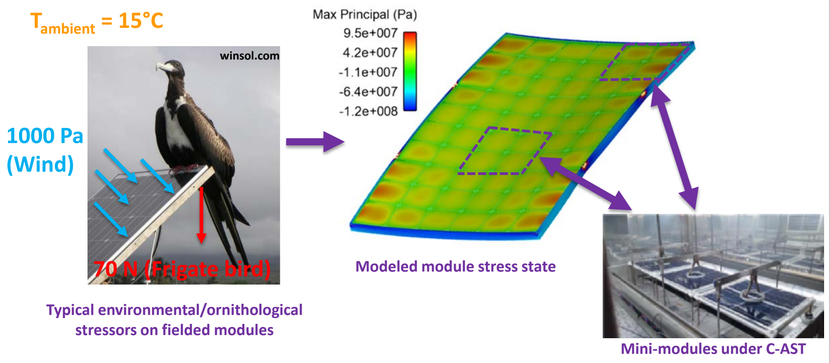


Characterization methods:

- Small and wide angle X-ray scattering (SAXS/WAXS): Chemical and structural
- X-ray photoelectron spectroscopy (XPS): chemical
- X-ray absorption spectroscopy (XAS)/ FTIR: chemical
- Dynamic mechanical analysis (DMA): mechanical
- Differential Scanning Calorimetry (DSC): thermoanalytical

Thermo-mechanical modeling

Field equivalency of accelerated stress testing stressors to be confirmed and compensated for using modeling

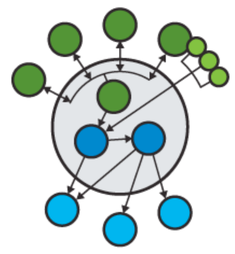


Questions to be answered:

- Are there field stressors not captured in C-AST/M-AST or vice versa?
- Do mini modules accurately capture backsheet stress at each cell position?
- How might any differences affect failure mechanism or frequency?

Data analytics and machine learning

DuraMAT Data Hub

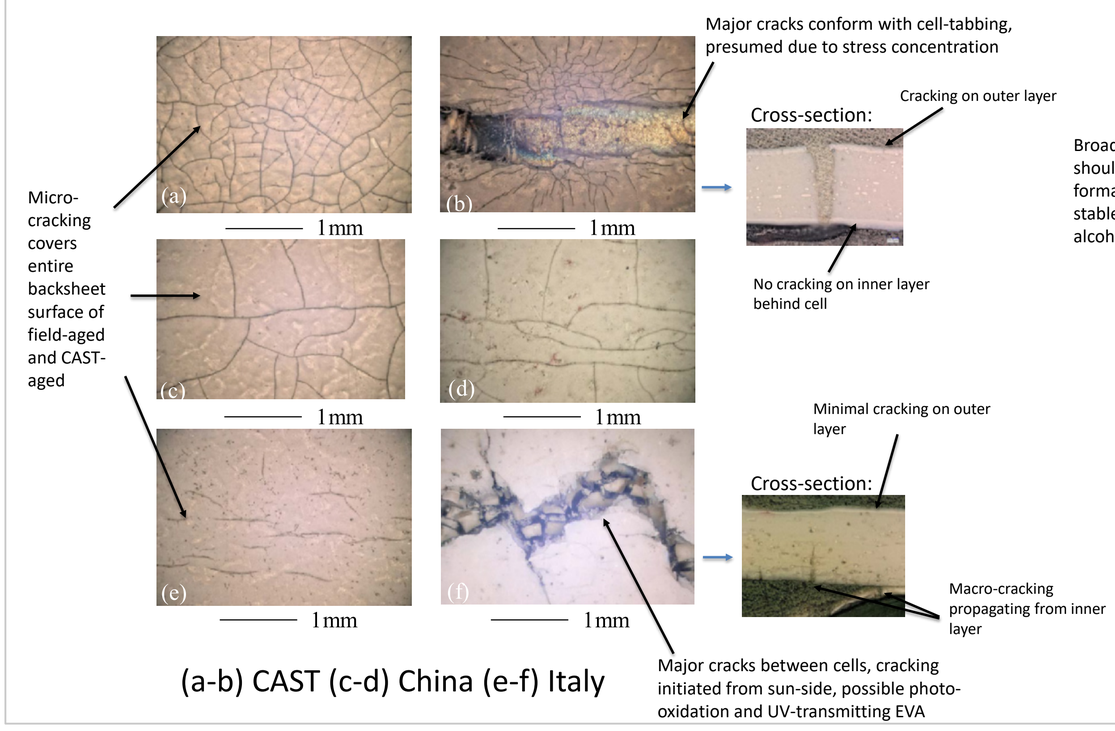


Data analytics

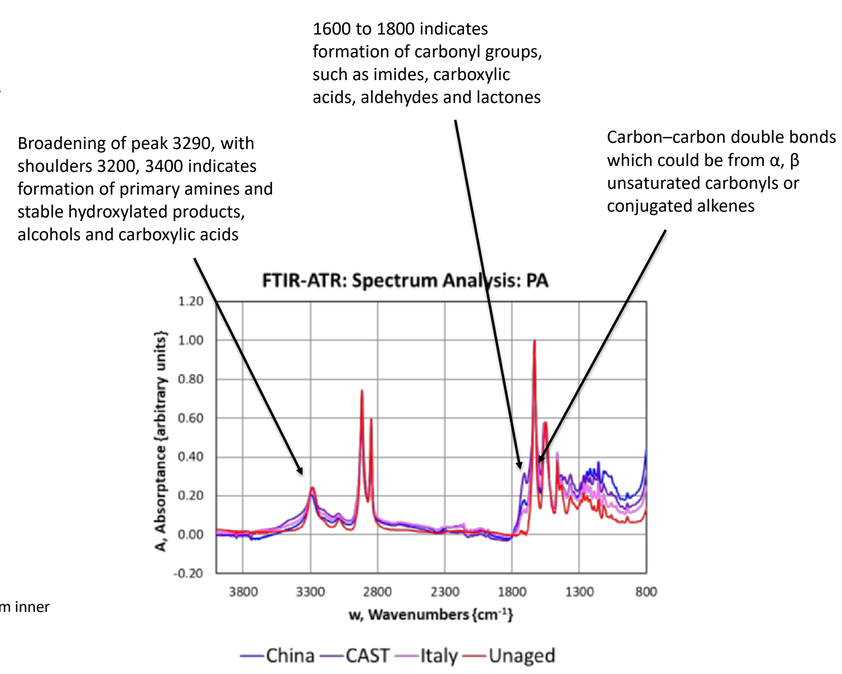
Approach and Outcomes:

- Data from thermo-mechanical, chemical and structural characterization will be aggregated and analyzed for C-AST, M-AST and field tested modules
- Determine if modules show the same aging mechanisms and quantify the different time scales using regression analysis:
  - Quantify how C-AST/M-AST compare to each other
  - Quantify how C-AST/M-AST compare to field aged modules
- Using data mining and machine learning determine which environmental stressors are most correlated with the material and thermo-mechanical properties
- Additional results: correlation of destructive and non destructive testing to improve validation of future accelerated test protocols for other materials

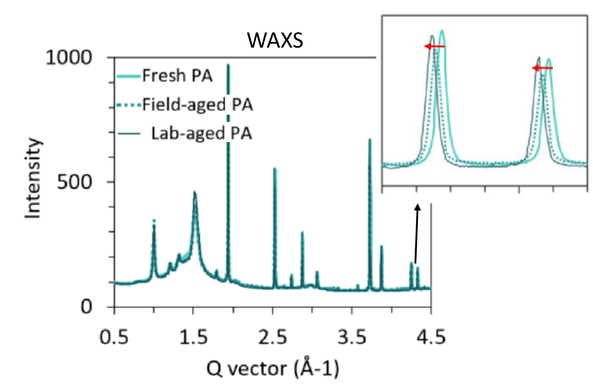
Polyamide Backsheet Degradation Analysis



(a-b) CAST (c-d) China (e-f) Italy



- Polyamide AAA backsheets (PA) were measured by WAXS in transmission geometry. The scattering pattern reveals a semi-crystalline polymer, as indicated by the prevalent strong and narrow peaks.
- A shift in peak position is seen when comparing patterns of fresh PA with PA that was either collected from fielded modules in China or underwent CAST.
- Both aged PAs show a shift to higher Q-vectors indicating that the chain-to-chain packing structure in the crystalline polymer is increasing in size.



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NREL/PO-5K00-73368

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

25 Year Low Cost Flexible Frontsheet

David Okawa[1], Hoi Ng[1], Abby Taussig[1], Hiram Dunn[1], Mike Kempe[2], Peter Hacke[2]

[1]SunPower Corporation [2]National Renewable Energy Laboratory

SUNPOWER®

DuraMAT Capabilities

- Data Management & Analytics, DuraMAT Data Hub
- Predictive Simulation
- Advanced Characterization & Forensics
- Module Testing
- Field Deployment
- Technology-Economic Analysis

Industry Goals

- Develop a reliable, low-cost, light-weight, easy-to-install, high efficiency next generation solar module
- Replace glass superstrate with polymeric frontsheet
- Enable frameless design and fast-install which lowers down the LCOE of PV system
- Test frontsheet material options and evaluate the lifetime to meet 25 years target

Capabilities / Accomplishments

Combined resources to calculate frontsheet lifetime:

- SunPower capabilities
  - Strong industry relationship with material suppliers
  - Module making and rapid iteration testing capabilities
  - Extensive field data on materials and performance
- NREL capabilities
  - Combined cycle stress testing and environmental aging

Outcomes and Impact

- **Define** testing standards for frontsheet lifetime analysis
- **Identify** weaknesses in available materials that do not have a 25-years lifetime
- **Partner** with suppliers to strengthen existing materials and develop lower-cost materials
- **Incorporate** frontsheet lifetime result into PV module lifetime model (for example, PVLife)

1. Cost Driver

- PV module and installed system costs have dropped significantly in the past decade
- Non-module costs drop more slowly
- Light-weight, direct attach modules have potential to
  - Reduce the BOS & labor soft costs (15-50 cents/W)
  - Open up new markets such as low-load rooftop
- Reduction in product lifetime has substantial negative impact on project economics
- Frontsheet options with proven lifetime, like ETFE, are substantial cost adders (3-6 cents/W)
- **A low-cost, 25-years rated frontsheet that is suitable for systems within our mission profile can enable lower LCOE PV system**

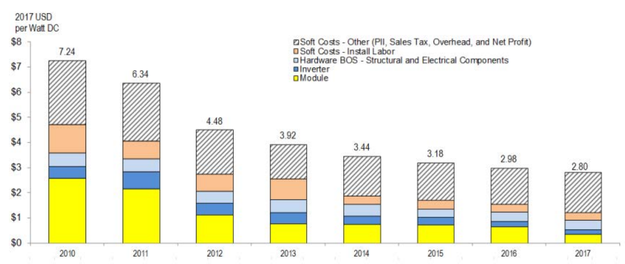
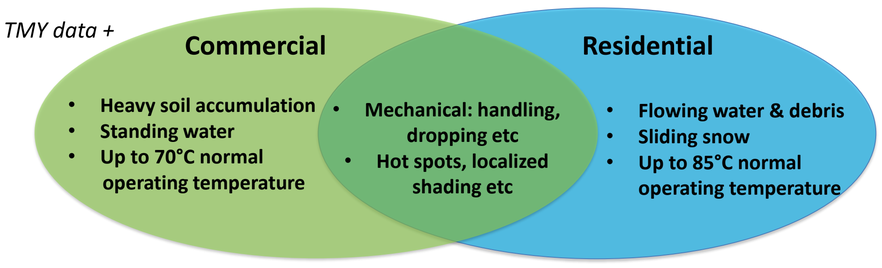


Figure 1. NREL residential PV system cost benchmark summary (inflation adjusted) Q4 2009 – Q1 2017

Mission Profile (derived from TMY data + system conditions):



2. Lifetime Analysis Model

Goal: Predict lifetime of polymer frontsheets given a variety of mission profiles

1. The defined degradation mode relevant to this analysis is transmission loss. Yellowness index and UV-cut will also be considered. However, the main metric will be the Solar Quantum Efficiency Weighted Transmission (SQEWT) calculated from the UV-Vis % transmission spectrum (200nm-1500nm, 1nm interval) of the material, weighted by c-Si QE profile.

2. Use accelerated lifetime tests to understand reaction kinetics associated with photo-thermal degradation mechanisms quantified by rate of change in SQEWT. Use the activation energy (E_a) and linearity coefficient (x) to establish reaction kinetics in various photo-thermal environments.

$$\frac{\Delta SQEWT}{\Delta t} = C \cdot UV_{eff}^{x} \cdot e^{\frac{-Ea}{kT}}$$ *Modified Arrhenius-Peck Relationship with UV*

C = constant
UV_{eff} = ratio of UV intensity at test condition over the standard UV intensity (AM1.5)

3. The values of E_a and *x* are acquired by solving two linear equations simultaneously:

$$y_1(\tfrac{1}{T}) = ln(\frac{\Delta SQEWT}{\Delta t}) = lnC + x \cdot lnUV_{eff} - \frac{Ea}{k} \cdot (\frac{1}{T})$$ *Data at constant UV intensity (y1)*

$$y_2(UV_{eff}) = ln(\frac{\Delta SQEWT}{\Delta t}) = lnC + x \cdot lnUV_{eff} - \frac{Ea}{kT}$$ *Data at constant temperature (y2)*

4. Utilize E_a, x, C, and a specified critical transmission loss ($\Delta SQEWT_{crit}$) to calculate the lifetime of the material for any field conditions:

$$t_{failure} = \Delta SQEWT_{crit} \cdot UV_{eff}^{-x} \cdot e^{\frac{Ea}{kT}} \cdot C^{-1}$$ *Accelerated experiment*

$$lifetime = \underbrace{UV_{eff}^{x} \cdot e^{\frac{Ea}{k}(\frac{1}{T_{field,eq}} - \frac{1}{T_{exp}})}}_{\text{Photo-Thermal deg.}} \cdot \underbrace{\frac{L_1}{L_2}}_{\text{Time}} * t_{failure}$$ *Outdoor lifetime*

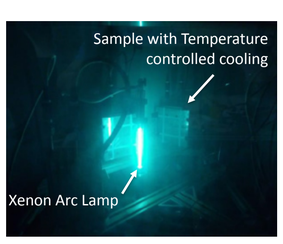
Acceleration Factor:

L_i = daily fraction of exposure on test (1) over field (2)
$t_{failure}$ = accelerated failure time
$T_{field,eq}$ = equivalent temperature of any field condition [4]
T_{exp} = temperature of experiment

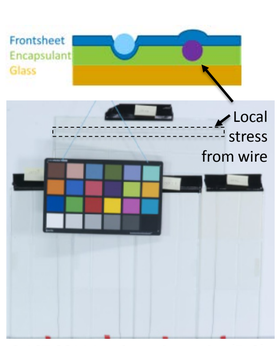
3. Material Candidates and Exposure Conditions

- Literature and industry research on low-cost, optically transparent material were conducted
- 15 candidates (including positive and negative controls) that can potentially meet the lifetime target at reasonable cost have been sourced
- Polyethylene Terephthalate (PET) is the most economical option but has poor UV stability. Different designs such as a UV-filtering coating or integrated UV blockers are evaluated to extend the PET lifetime

Material	Cost
ETFE	High
PVDF	Medium
PC with Acrylic coating	
PET with **PVF** layer	
PET with Fluoro-coating (2 options)	
PET with Acrylic-coating (3 options)	Medium - Low
PET with UV-Blocker (4 options)	
PET without coating/UV-Stabilizer (2 options)	Lowest



Xenon-Arc Experiment Samples



C-AST COL1 Laminated samples (5x3)

- Exposure conditions have been determined based on the mission profile of the target applications
- Xenon Arc chambers and dry ovens are selected as the indoor accelerated tools to understand the photothermal degradation
- Bare-film for transmission loss measurement are prepared for all conditions while selected conditions contain tensile test and coupon samples

UV Irradiance*	Temperature [°C]	
1X	70	Constant temperature
10X	70	
2X	70	Constant UV irradiance
2X	50	
2X	80	
2X	90	
Dark	60	Temperature degradation only
Dark	85	
Dark	100	
Dark	150	Extreme condition

**1X= 0.4W/m²-nm @ 340nm*

- Combined-Accelerated Stress Testing (C-AST) is critical to discover failure modes that are not covered by the Xenon-arc and dry oven-experiment such as: temperature cycling, moisture and mechanical stress all under UV
- COL1 comprises laminated samples (no cells) of all 15 candidates whose yellowness index, cracking, and delamination are monitored
- COL2 will consist of mini-modules (with cells) of the down-selected samples from the Xenon Arc and COL1 result

4. Weathering Accelerated Lifetime Results

To date, the 500 hour results of the *Xenon-Arc* experiment has been completed, summarized below:

Material	Cost	Ea (eV)	x	C	70C 1X	70C 2X	70C 10X	50C 2X	80C 2X	90C 2X
ETFE	High	**								
PVDF	Medium	**								
PC + Acrylic-coating	Medium	0.24	0.01*	-875						
PET + **PVF** layer	Medium	0.15	0.03	-45						
PET + Fluoro-coating 1	Medium	**								
PET + Fluoro-coating 2	Medium	**								
PET + Acrylic-coating 1	Med-Low	0.20	0.01*	-286						
PET + Acrylic-coating 2	Med-Low	0.20	0.01*	-51						
PET + Acrylic-coating 3	Med-Low	0.20	0.06	-322						
PET + UV blocker 1 (low)	Med-Low	**								
PET + UV blocker 1 (high)	Med-Low	**								
PET + UV blocker 2 (low)	Low	0.22	0.01*	120						
PET + UV blocker 2 (high)	Low	0.16	0.01*	100						
PET w/o Acrylic-coating 1	Lowest	0.23	0.67	-2300						
PET w/o UV blocker 1	Lowest	0.04	0.82	-2						

Delta SQEWT: 4.5, 3.5, 2.5, 1.5, 0.5, -0.5, -1.5, -2.5, -3.5, -4.5

**Fit model reached lower bound for X valued at 0.01 suggesting no significant UV sensitivity although more data is needed*
***No significant degradation to be modeled*

Key results of the *Xenon-Arc* experiment:

- The two fluoropolymer options remain unchanged at the first readout
- Both negative controls (PET without coating or UV blockers) have significant SQEWT changes in severe conditions
- Adding UV blockers or Acrylic-coating significantly protects the PET from transmission loss
- UV-filtering coating effectiveness depends on the coating material and formulation
- UV blocker 1 is notably more effective than UV blocker 2
- The UV-stabilized materials (UV blocker 2) are potentially being depleted, thereby increasing SQEWT
- Polycarbonate with Acrylic-coating shows major weakness at higher temperatures

Key results of the C-AST COL1:

- To date, the laminated samples have gone through 7 days of Arctic Spring and 2 weeks of High Desert cycles
- No sample has exhibited any delamination or cracking, with slight yellowing on the PET without stabilization

5. Timeline

Overall project timeline

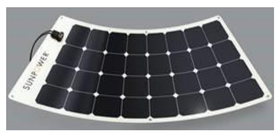
Key Milestone	Month (Year)	Jun (18)	Q3 (18)	Q4 (18)	Jan (19)	Feb (19)	Mar (19)	Apr (19)	May (19)	Jun (19)	Jul (19)	Aug (19)	Sep (19)	Oct (19)
	WW	25-26	27-40	41-52	1-4	5-8	9-13	14-17	18-21	22-26	27-30	31-34	35-39	40-43
Define Mission Profile														
Literature and Industry Research														
Sample Sourcing														
Baseline Measurement														
Xenon-Arc Experiment												4000 hours		
Dry Oven Experiment													4000 hours	
Outdoor Experiment													6 months	
C-AST Experiment						COL1					COL2			
Data Analysis and Modeling														
Technical Review / Poster			★			★		★					★	

DuraMAT Workshop — Today — Mid-term Review — Final Review

6. Conclusion and Next Steps

Progress to date:

- Extensive literature and industry survey conducted to identify 15 polymer candidates
- Experimental conditions selected to support modeling material lifetimes vs expected mission profiles
- 500 hour data exhibited expected trends of photothermal degradation
  - Expensive monolithic fluoropolymer showed no degradation
  - The non-stabilized PETs (negative controls) showed significant transmission loss while the protective coating or UV blockers in the same material showed no change in most conditions



Next steps:

- Continue the Xenon-Arc experiments to 4000 hours
- Start the dry oven experiments
- Review the mid-term result to downselect options for C-AST COL2
- Explore failure modes other than photothermal degradation that are critical to frontsheets
- Determine acceleration factors and predict frontsheet lifetime

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[3] Kempe, M. D., Nobles, D. L., Weigel, M. D., Nachtigal, A. K., Roehrig, M. A., Berniard, T. J., . . . Schubert, C. M. (2015). Evaluation of the durability of flexible barrier materials. 2015 IEEE 42nd Photovoltaic Specialist Conference (PVSC). doi:10.1109/pvsc.2015
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Non-uniform Wind-Load on Floating Solar Panel under Wind-Wave Environment

工業技術研究院 Industrial Technology Research Institute

*Shu-Tsung Hsu (ITRI), Wei-You Lin (ITRI), Kao-Chun Su (NCKU)

Abstract

Solar power generation has been regarded as an important indicator of global renewable energy policy. Currently, some Asia countries are actively promoting floating solar systems on water, but solar systems are often damaged by strong wind like typhoon. Generally the land based solar system are subjected to non-uniform wind pressure due to the environmental factors such as wind speed (V), wind direction angle (β) and module tilt (α). Similarly, the floating solar system on water need to withstand high winds and waves together, the additional factors are wave direction angle (γ) and wave period (T). This work study the wind-wave effect for floating solar panels on water. Firstly, review the hydrological data of three offshore observatories (Longdong, Hsinchu and Qiqi) in Taiwan, and analysis the extreme condition (wave height, wave period) in the typhoon time. Secondly, analyze the floating PV system sport behavior on water, and define the extreme condition of tilt angle during the wave period (T). Finally, do CFD simulation to get wind-pressure coefficient (C_p) distribution on the floating solar panel under the above extreme conditions. Results have delivered a fully database of non-uniform wind pressure distribution on solar panel under wind-wave environment, and meet the requirements of wind load testing. In addition, some worst conditions occur when the wind and wave are in the same direction, lead to the solar panel is subjected to a more higher and concentrated loading near panel's leading or trailing edge. Whether it is a frond wind (β = 180°) or a back wind (β = 0°), the wind resistance increases as the tilt (α) angle increases.

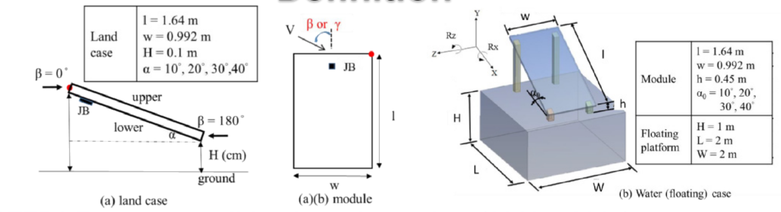
Typhoon Damaged PV System

Beaufort number (BN)	Description	Wind speed V (m/s)
0	Calm	< 0.3
1	Light air	0.3-1.5
2	Light breeze	1.6-3.3
3	Gentle breeze	3.4-5.4
4	Moderate breeze	5.5-7.9
5	Fresh breeze	8.0-10.7
6	Strong breeze	10.8-13.8
7	Near gale	13.9-17.1
8	*Gale	17.2~20.7
9	*Strong gale	20.8~24.4
10	*Storm	24.5~28.4
11	*Violent storm	28.5~32.6
12	*Hurricane (*Typhoon)	32.7~36.9
13		37.0~41.4
14		41.5~46.1
15		46.2~50.9
16		51.0~56.0
17		56.1~61.2
>17		>61.2

Taiwan (2016)

Japan (2016)

Definition

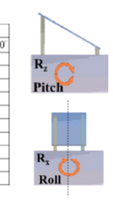


STEP1 Extreme condition in typhoon time (2013 ~ 2017)

Date: 20150808 Typhoon: SOUDELOR Near center max. wind speed 48 m/s	Max. wave height (m)	Wave period T (times/ sec)	Wave direction (°)	Max. wind speed (m/s)	Wind direction (°)
Longdong (test condition for step 2)	17.12	15.1	56	20.0	56
Hsinchu	6.79	18.9	33	28.6	43
Qiqi	13.96	9.5	258	14.3	320

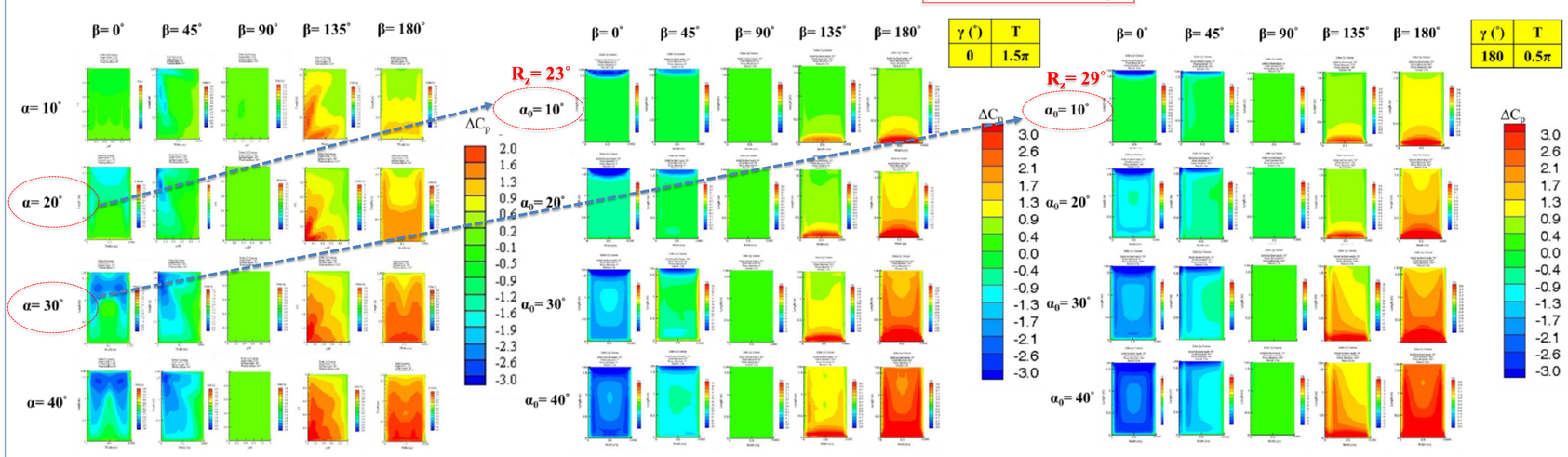
STEP2 Behavior of floating system on water

$R_Z = \alpha_0 + \Delta R_Z$	α_0 = 10°										α_0 = 20°		α_0 = 30°		α_0 = 40°	
	γ = 0°		γ = 45°		γ = 90°		γ = 135°		γ = 180°		γ = 0°	γ = 180°	γ = 0°	γ = 180°	γ = 0°	γ = 180°
T	Rz	Rx	Rz	Rx	Rz	Rx	Rz	Rx	Rz	Rx	Rz	Rz	Rz	Rz	Rz	Rz
0π	10	0	10	0	10	0	10	0	10	0	20	20	30	30	40	40
0.25π	4	0	6	7	10	11	-1	-5	22	0	14	32	24	42	34	52
0.5π	0	0	3	10	10	15	-6	-8	29	0	10	39	20	49	30	59
0.75π	5	0	4	7	10	11	0	-6	22	0	15	32	25	42	35	52
π	11	0	11	0	10	0	9	0	10	0	21	20	31	30	41	40
1.25π	22	0	16	-10	10	-11	21	6	0	0	32	10	42	20	52	30
1.5π	23	0	18	-11	10	-15	26	8	-6	0	33	4	43	14	53	24
1.75π	15	0	15	-8	10	-11	19	6	-4	0	25	6	35	16	45	26
2π	10	0	10	0	10	0	10	0	10	0	20	20	30	30	40	40

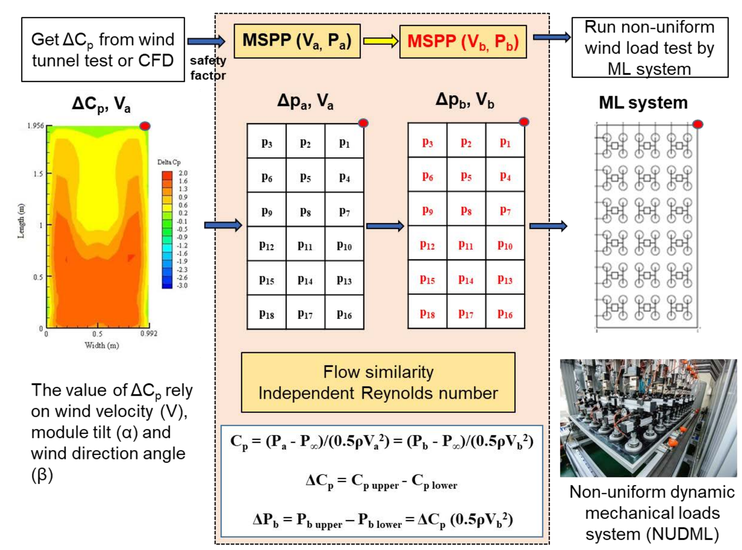


STEP3 ΔC_p (= $C_{p\ upper}$ - $C_{p\ lower}$) Distribution

α (or R_z)= α_0+ΔR_z
Initial tile angle:α_0



Mean surface pressure pattern (MSPP@p_1~p_{18})

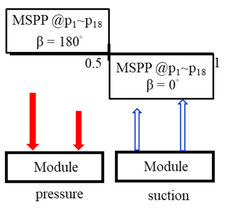


The value of ΔC_p rely on wind velocity (V), module tilt (α) and wind direction angle (β)

Note: ● is the origin of a Cartesian coordinate system

Test samples, Cyclic test, Test data

test sample	module	bracket
Land case	two modules, l = 1.956 m, w = 0.992 m, 72 cell, poly, half-cut	three brackets – 120cm x 8cm x 4cm
Water case	two modules, l = 1.956 m, w = 0.992 m, 72 cell, mono	four brackets – 110cm x 5cm x 5cm



Cyclic test
Cycle rate = 7 cycs /min

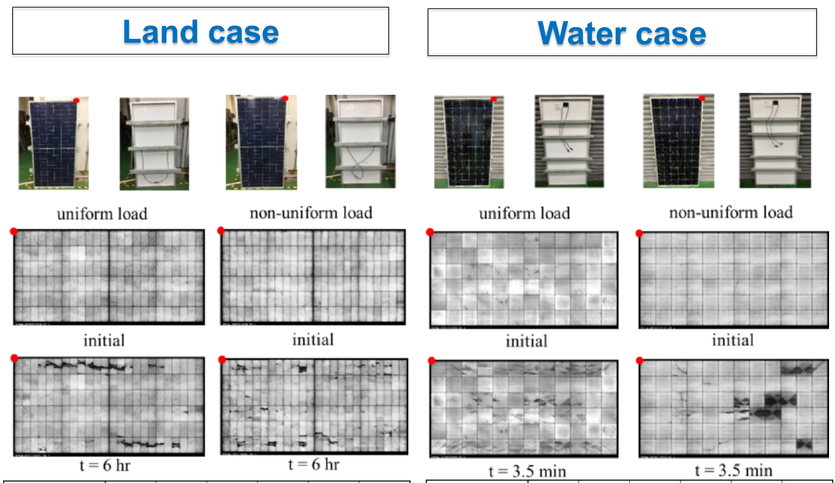
Uniform load (AVE) vs non-uniform load (MSPP)

Land case	β= 0° MSPP@P_1~P_{18}(Pa)			β= 180° MSPP@P_1~P_{18}(Pa)		
α= 30° V=61.2 m/s l/w =1.97	-9710	-11165	-9710	3192	2514	3192
	-11091	-8413	-11091	5449	4495	5449
	-7511	-1234	-7511	6783	5208	6783
	-5953	-4075	-5953	8312	7626	8312
	-5622	-5227	-5622	9289	11450	9289
	-3220	-3134	-3220	8316	11146	8316
	AVE = -6637 (Pa)			AVE = 6665 (Pa)		

Water case	β= 0° MSPP@P_1~P_{18}(Pa)			β= 180° MSPP@P_1~P_{18}(Pa)		
α_0= 10° γ=180° T=0.5π R_Z=29° V=61.2 m/s l/w = 1.65	-9852	-13644	-9987	4583	5306	4557
	-2015	-1583	-1944	5159	5958	5216
	-2229	-1582	-2278	5266	6136	5300
	-2376	-2008	-2417	5572	6832	5614
	-2411	-2290	-2485	6383	8575	6372
	-1664	-1810	-1785	12255	18193	12431
	AVE = -3576 (Pa)			AVE = 7206 (Pa)		

"+" means pressure; "-" means suction

Experiment data: EL, IV



land case	ΔI_{sc}	ΔV_{oc}	ΔP_{max}	ΔFF	ΔR_s	ΔR_{sh}
uniform	-0.4%	-0.1%	-3.2%	-2.8%	7.0%	-41%
non-uniform	-1.7%	-0.2%	-4.9%	-3.1%	8.9%	-64%

water case	ΔI_{sc}	ΔV_{oc}	ΔP_{max}	ΔFF	ΔR_s	ΔR_{sh}
uniform	-0.6 %	-0.4 %	-3.9 %	-2.9 %	4.6 %	-76 %
non-uniform	-1.8 %	-0.3 %	-5.2 %	-3.1 %	4.3 %	-65 %

Δ : (post-pre)/pre; t: test time

Conclusion

1. **Land case (V, α, β)**
   - Wind flow and wind speed (V) cause PV module to bear uneven pressure. The influence of wind direction angle (β) also change the net pressure coefficient (ΔC_p) distribution of the module surface. Whether it is a frond wind (β = 180°) or a back wind (β = 0°), the wind resistance increases as the module tilt (α) increases.
2. **Water case (V, α_0, β, γ, T)**
   - The installation of the PV system in the land based requires consideration the influence due to wind flow, similarly, the floating system on the water need to withstand high winds and waves.
   - The wave angle (γ) and the period (T = 0~2π) can change the pitch angle (R_Z). The maximum R_Z occurs at (γ = 0°, T = 1.5π) and (γ = 180°, T = 0.5π), the pitch angle also increases as the initial module tilt (α_0) increases.
   - In the case of a change in pitch angle (R_Z), the separation flow generated by the wind flowing through the leading edge (or trailing edge) of the module is not immediately generated downstream, so the maximum local wind pressure is generated at the leading edge (or trailing edge).
   - Under the similar condition of module tilt (α or R_Z = α_0+ΔR_z), the local maximum wind load (pressure or tension) in the water case is larger than the land case. However, there is no obvious trend in the overall average load comparison.
3. **Summary**
   - Analysis of environmental factors (V, α, β, γ, T) or special conditions (γ = 0°, 180°; β = 0°, 180°), and derivation the severity test data such as MSPP, can provide NUDML system to simulate non-uniform wind load on PV module, and meet the scenarios for land or water cases.
   - Research work and results will continue to be discussed and compromised by PVQAT TG7 and IEC TC82 WG2, and help to draft the non-uniform wind load testing standards.

1.Shu-Tsung Hsu, Wei-You Lin, Shih-Jui Wu, Environmental Factors for Non-uniform Dynamic Mechanical Load Test due to Wind Actions on Photovoltaic Module, Energy Procedia (2018) pp. 50-57 DOI information: 10.1016/j.egypro.2018.09.008.

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4.Shu-Tsung Hsu, Hung-Sen Wu, Chin Lien, Mean Surface-Pressure Pattern on PV Module for Non-Uniform Dynamical Mechanical Load Test, PVSEC 27, 2017.

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2019 Photovoltaic Reliability Workshop (PVRW), Lakewood, CO, 2/27/2019

Daily soiling rates correlated with air quality in Oakland CA

Jessica Forbess
Sunshine Analytics

Introduction

Analysis of a twenty 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 6.8 to 32.5 ug/m³.

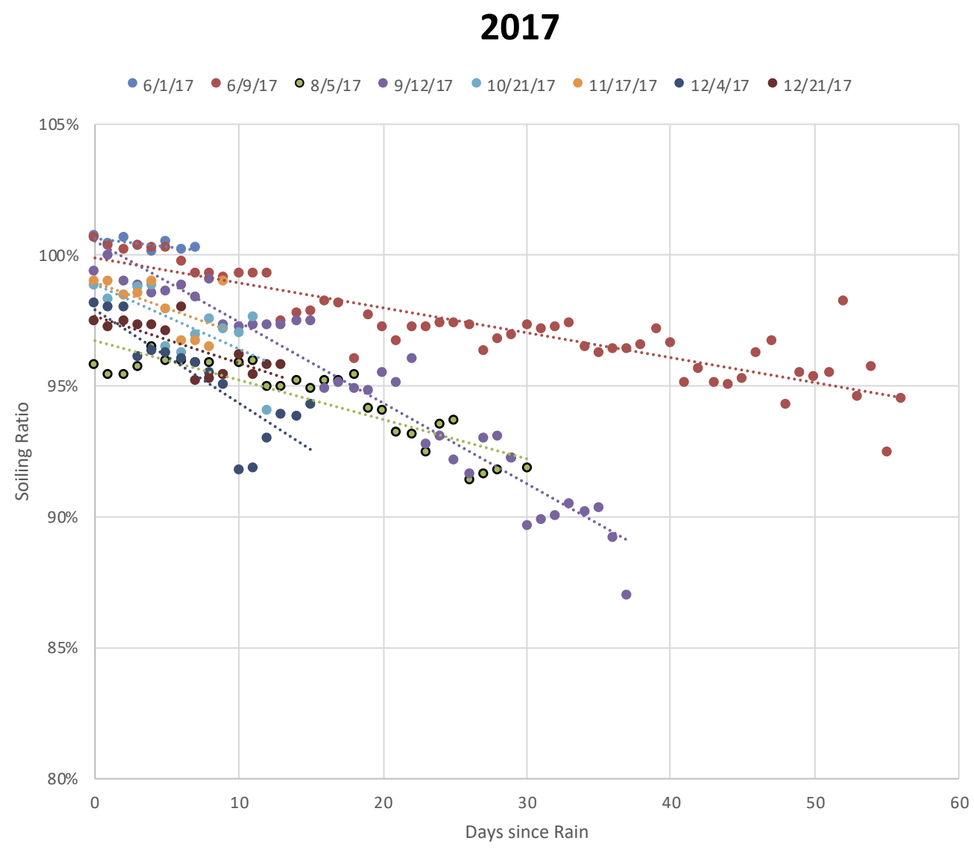
Objectives

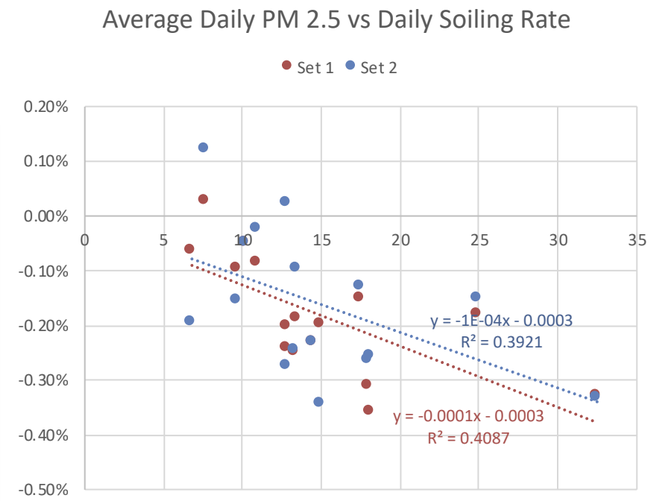
- Capture soiling data for light industrial urban neighborhood
- Calculate daily soiling loss rate
- Test correlation of soiling and air quality data
- Test correlations with other meteo data

Methods

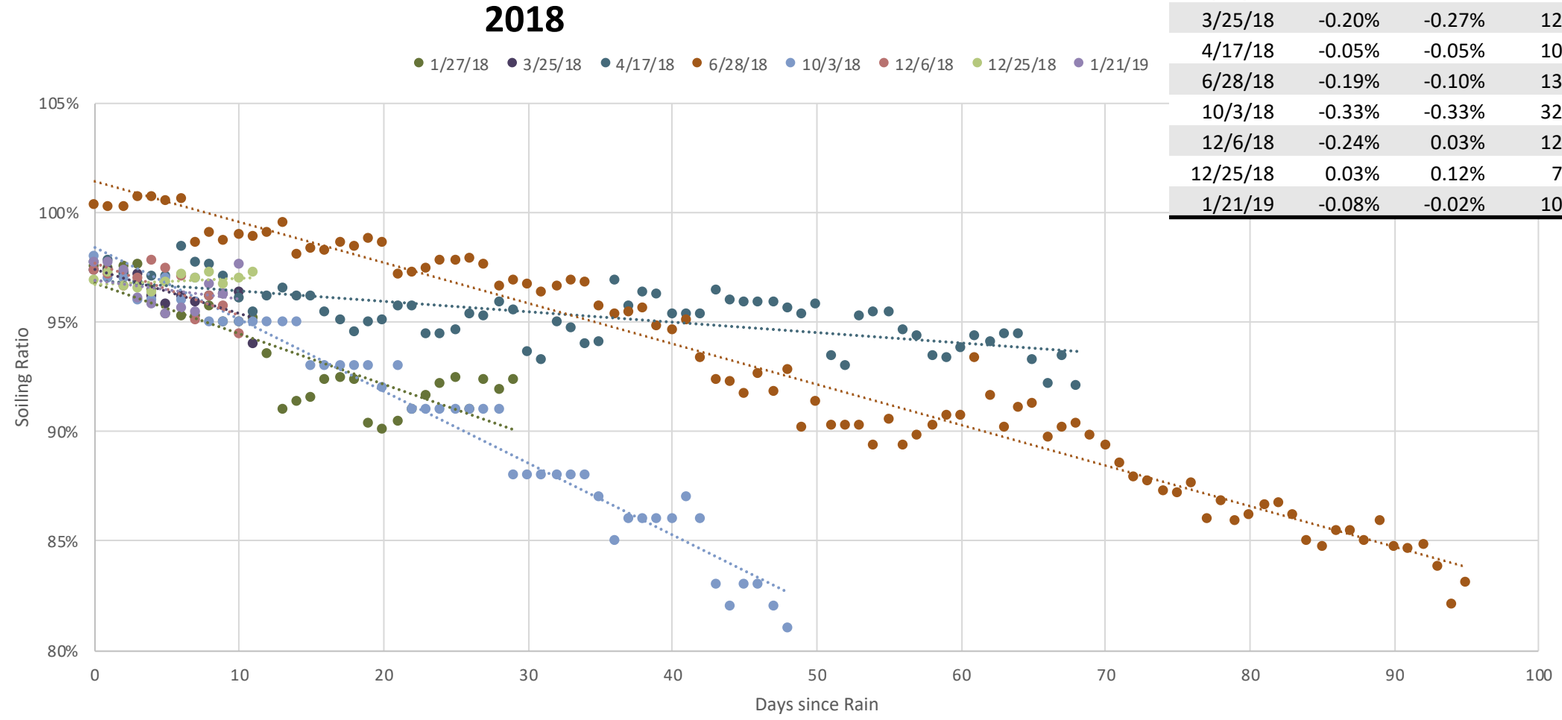
- Microinverter based rooftop PV array
- 10° tilt, SW az, landscape 280 poly-Si
- Identified two pairs of unshaded modules
- Cleaned one of each pair weekly
- Calculated Soiling Ratio based on daily energy
- Collected daily PM 2.5 average from EPC site <1km away

Results





	Set 1	Set 2	Avg Daily PM2.5 (ug/m3)
6/1/17	-0.06%	-0.19%	6.79
6/9/17	-0.10%	-0.15%	9.63
8/5/17	-0.15%	-0.13%	17.48
9/12/17	-0.31%	-0.26%	17.95
10/21/17	-0.25%	-0.24%	13.34
11/17/17	-0.20%	-0.34%	14.98
12/4/17	-0.36%	-0.26%	18.06
12/21/17	-0.18%	-0.15%	24.88
1/27/18	-0.23%	-0.23%	14.43
3/25/18	-0.20%	-0.27%	12.74
4/17/18	-0.05%	-0.05%	10.10
6/28/18	-0.19%	-0.10%	13.40
10/3/18	-0.33%	-0.33%	32.48
12/6/18	-0.24%	0.03%	12.78
12/25/18	0.03%	0.12%	7.67
1/21/19	-0.08%	-0.02%	10.85



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- M. Deceglie, M. Muller, S. Kurtz, and Z. Defreitas, "A Scalable Method for Extracting Soiling Rates from PV Production Data," IEEE Photovoltaic Specialist Conference, Portland, Oregon, 2016.

Conclusions and Future Work

- There is a seasonal pattern to daily soiling loss rates for the sub-annual dataset under analysis
- PM2.5 air quality captured has a reasonably strong correlation, fit with the regression y = -0.0001x – 0.0003
- Potential for increase in adhesion from wildfire soot is not proven yet due to short data set. One indicator may be that the soiling ratio has not recovered to 100% since the wildfires, despite some heavy rains.

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Impact of Satellite-Based Solar Resource Models (SRM) on Utility Scale PV System Design and Project Economics

Brandon Liang, Grace Keliher, and Jacob Banitt

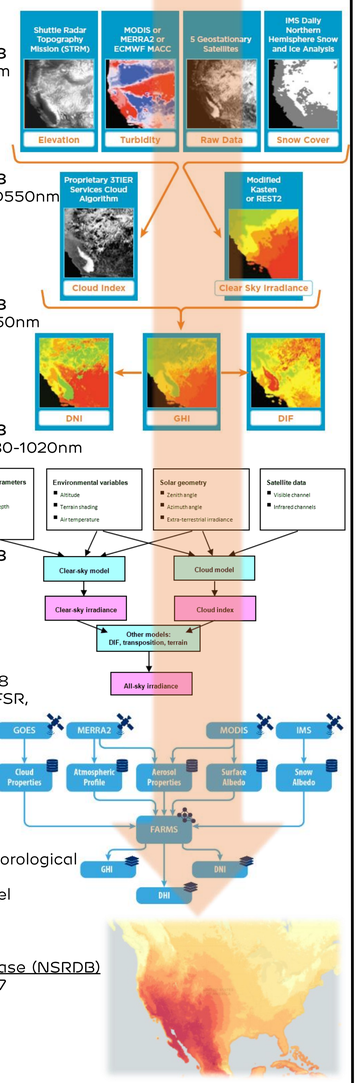
edp renewables powered by nature

Introduction to Satellite-Based Solar Resource Models (SRMs)

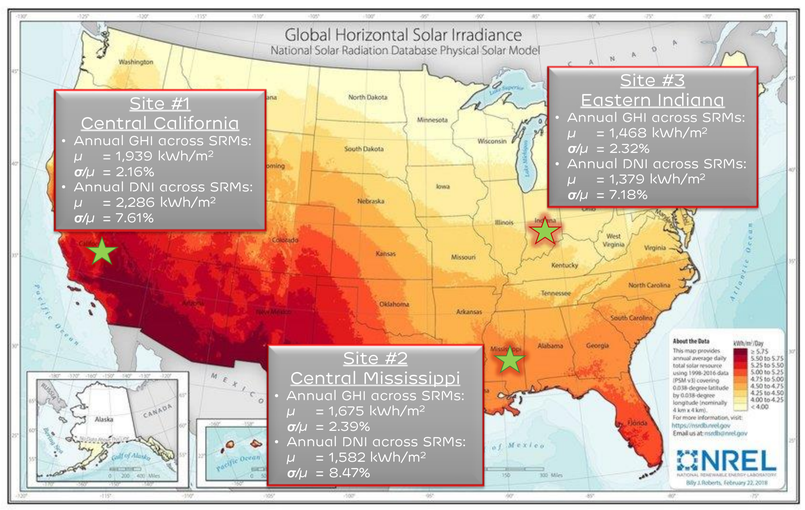
NREL (National Renewable Energy Laboratory) · SOLARGIS · VAISALA · Clean Power Research (Powering Intelligent Energy Decisions®) · Meteonorm

- **TMY2**
  by NREL, National Solar Radiation Database (NSRDB)
  - Hourly data from 239 stations (56 primary measured & 183 secondary modeled), **1961-1990**
  - Based on Sandia National Laboratories (Hall *et al.* 1978) method that created the 1952-1975 **SOLMET/ERSATZ** database (TMY1), with modifications
  - Sandia empirical TMY method

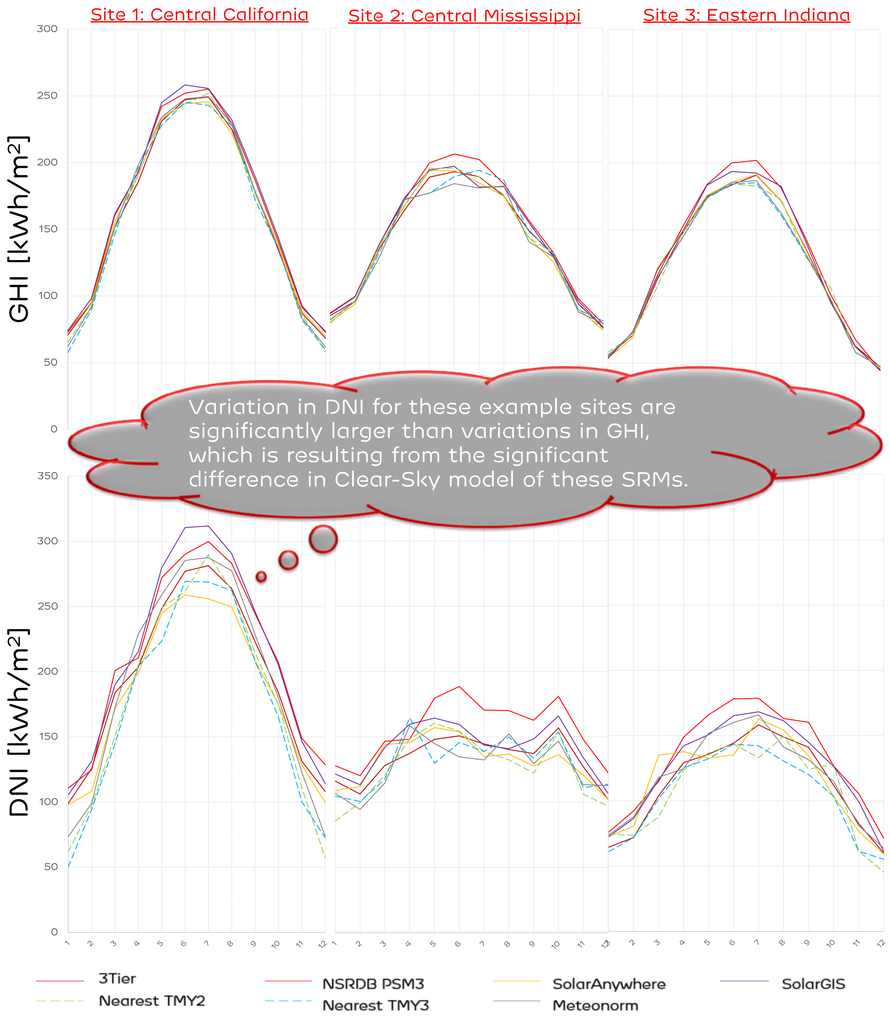
- **TMY3**
  by NREL, National Solar Radiation Database (NSRDB)
  - Hourly data from 1020 stations (Class I, II and III), **1991-2005**
  - Based on Sandia National Laboratories (Hall et al. 1978) method that created the 1952-1975 **SOLMET/ERSATZ** database (TMY1), with modifications
  - NREL TMY weighting method
- **Meteonorm**
  Version 7.3.1, by Meteotest
  - Various spatial and temporal resolutions, **1981-1990** and **1991-2010**
  - Data Source: GEBA (WMO), AOD from Solar Consulting Services®
  - **Shepard's Gravity 3-D Inverse Distance Interpolation** amongst nearest stations, coupled with MSG satellite data or ERA5 reanalysis data that uses HelioSAT method
- **3TIER 1.0 Dataset**
  Version 1.0.2, by Vaisala
  - 3x3 km spatial, hourly temporal resolution, **1997-2018**
  - Data Source: GOES, MODIS Terra, Monthly AOD550nm
  - **Modified Kasten** Clear-Sky Radiation Model
  - Proprietary Cloud Model
- **3TIER 1.1 Dataset**
  Version 1.1.2, by Vaisala
  - 3x3 km spatial, hourly temporal resolution, **1997-2018**
  - Data Source: GOES, MODIS Terra/Aqua, Monthly AOD550nm
  - **Modified Kasten** Clear-Sky Radiation Model with Proprietary Cloud Model
- **3TIER 1.2 Dataset**
  Version 1.2.2, by Vaisala
  - 3x3 km spatial, hourly temporal resolution, **1997-2018**
  - Data Source: GOES, MODIS Terra/Aqua, Daily AOD 550nm
  - **Modified Kasten** Clear-Sky Radiation Model
  - Proprietary Cloud Model
- **3TIER 2.0 Dataset**
  Version 2.0.2, by Vaisala
  - 3x3 km spatial, hourly temporal resolution, **1997-2018**
  - Data Source: GOES, ECMWF-MACC, 3-Hourly AOD 380-1020nm
  - **REST2** Clear-Sky Radiation Model
  - Proprietary Cloud Model
- **3TIER 2.1 Dataset**
  Version 2.1.2, by Vaisala
  - 3x3 km spatial, hourly temporal resolution, **1997-2018**
  - Data Source: GOES, MERRA2, Hourly AOD 550nm
  - **REST2** Clear-Sky Radiation Model
  - Proprietary Cloud Model
- **SolarGIS**
  Version 2.1.26
  - 4x4 km spatial, 30min temporal resolution, 1998-2018
  - Data Source: GOES, MERRA2, MACC-II, MeteoSAT, CFSR, CFSv2, GFSprod, *etc.*
  - **SOLIS** Clear-Sky Radiation Model
  - Proprietary Cloud Model
- **SolarAnywhere**
  Version 2.3, by Clean Power Research
  - 10x10 km spatial, hourly temporal resolution, 1999-2018
  - Data Source: GOES in conjunction with various meteorological sources
  - Enhanced **Perez SUNY v1.0** Clear-Sky Radiation Model
  - Proprietary Cloud Model
- **Physical Solar Model (PSM)**
  Version 3.0.2, by NREL National Solar Radiation Database (NSRDB)
  - 4x4 km spatial, 30min temporal resolution, 1998-2017
  - Data Source: GOES, MERRA2, MODIS, IMS, *etc.*
  - **FARMS** All-Sky Radiation Model, coupled with **REST2** Clear-Sky Radiation Model
  - **PATMOS-x** Cloud Properties Retrieval



Characteristics of Selected Sites

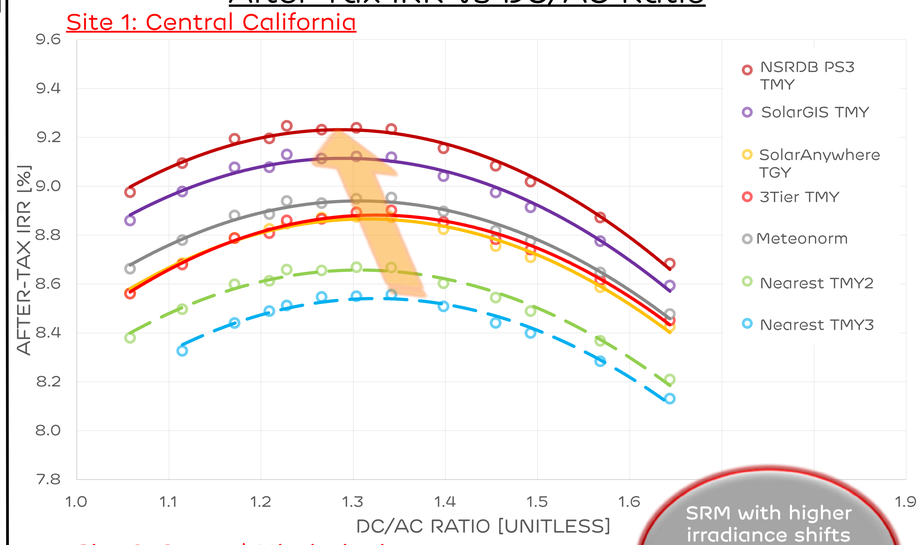


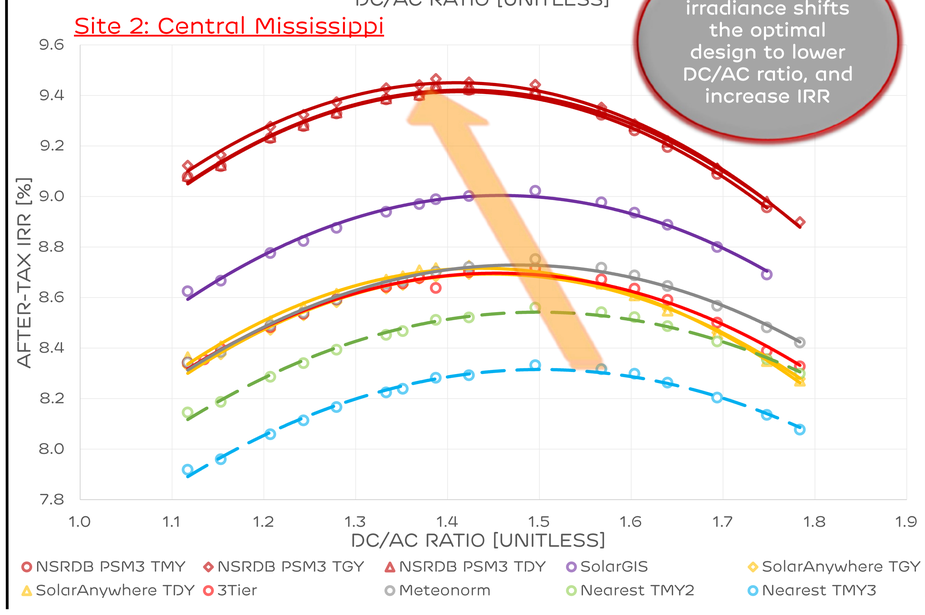
Monthly GHI & DNI of Selected Sites



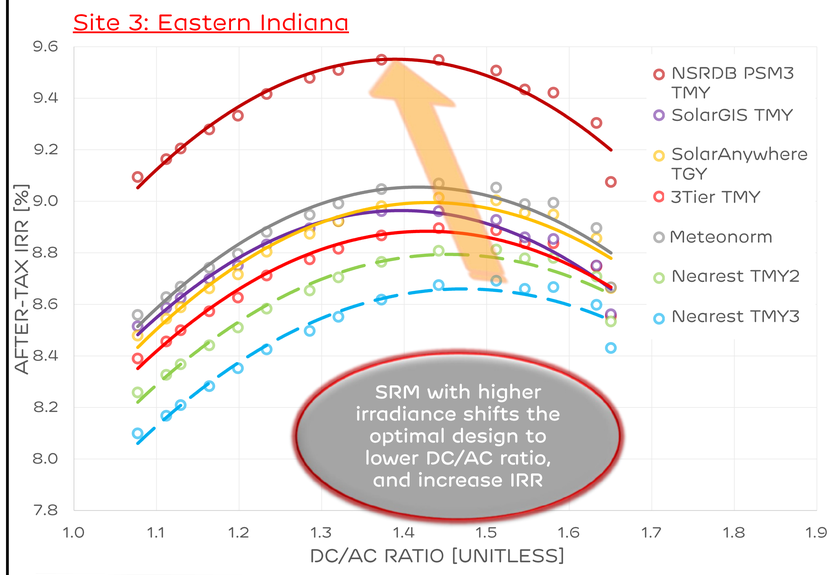
SRM Impact on Design Optimization

After-Tax IRR vs DC/AC Ratio

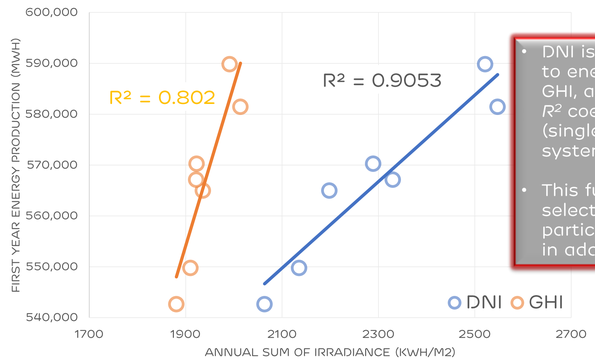




After-Tax IRR vs DC/AC Ratios – Cont.



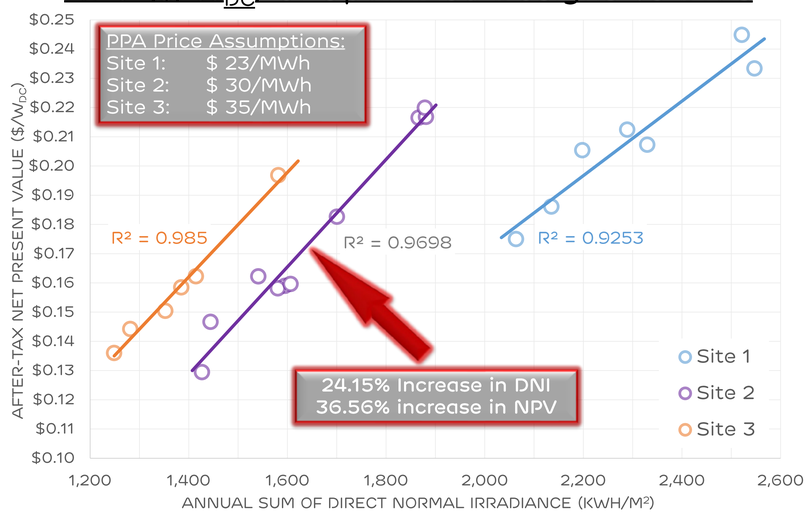
DNI GHI Impacts on Energy Production



- DNI is more directly related to energy production than GHI, as reflected by larger R^2 coefficients, *esp.* for SAT (single-axis tracker) systems.
- This further indicates that selecting SRMs should pay particular attention to DNI, in addition to GHI

SRM Impact on Project Economics

NPV ($/W$_{DC}$) of Optimized Designs vs DNIs



Key Takeaways / Summary

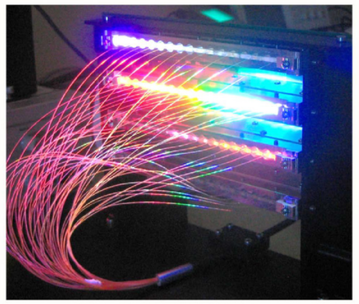
- Accurate evaluating solar resource models (SRMs) is of paramount importance to both design optimization and project economics.
- Project design in terms of optimal DC/AC ratio is strongly dependent on SRMs; higher irradiance in general enables designing at lower DC/AC ratio, and consequently better economics, *e.g.* higher IRR and NPV.
- Example site with high variations in DNI across SRMs (at Central Mississippi, 8.47% Coefficient of Variance), a 24.15% increase in DNI results in a 36.56% increase in NPV, which represents roughly $0.09/W$_{DC}$ difference. This means $9 Million difference for a 100MW$_{DC}$ project!!
- DNI is more directly related to energy production, *esp.* for single-axis tracker systems, therefore SRM selection should pay particular attentions to DNI, in addition to GHI.
- False SRM selection (as a result of such as merely looking at GHI alone, improperly averaging/balancing SRMs, *etc.*) could lead to false optimization on higher or lower DC/AC ratios with lower or higher project economics, respectively.

High Speed Quantum Efficiency Measurements of Solar Panels

Tau Science Corporation
Kyle Lu

Problem Statement

Quantum efficiency (QE) measurements of individual solar cells encapsulated in a panel are difficult to interpret due to variable electronic load presented to the device under test (DUT). Simultaneous optical and electrical bias control loops are often used to constrain the DUT voltage. We introduce an alternative DC open-circuit measurement technique that eliminates the need for external electrical bias while preserving the relative QE curve.

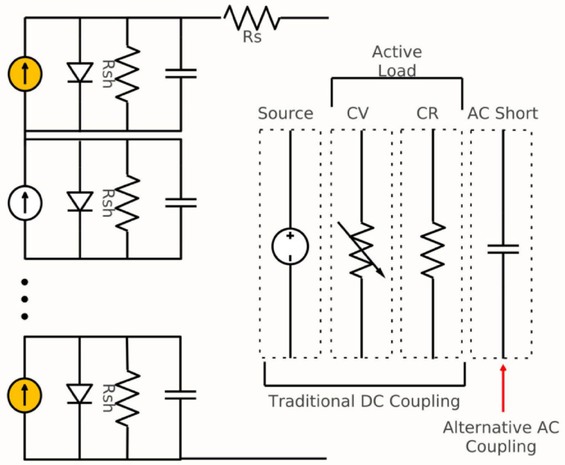


Local Cell Voltage Model

Cell QE is measured at short-circuit (SC) load conditions. Local cell SC measurement conditions are not enforceable in module measurements. External voltage bias has traditionally been applied to prevent the cell under test from suffering reverse bias damage. The local shaded cell voltages of an illuminated DC-coupled panel range from:

RLoad = ∞ : → Vdut = 0V
RLoad = 0 : → Vdut = -(nCells -1) * Voc_cell

Damage occurs when the wrong DC load is connected to the panel!



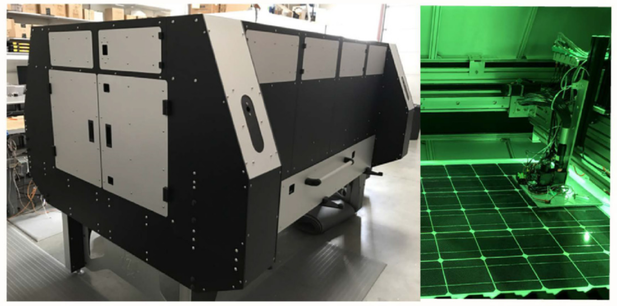
AC Short-Circuit Measurements

As previously observed, the relative QE curve is preserved for DC connected panels in either cell or module connection configurations at various bias conditions[1]. We extend this observation to include AC coupled panels where the local cell voltage is constrained to the first quadrant by the amount of light incident on the DUT. This technique has several key advantages:

- Eliminates the risk of reverse bias damage.
- Reduces measurement complexity and a source of measurement noise.
- Increases measurement probe sensitivity by 2-3 orders of magnitude.

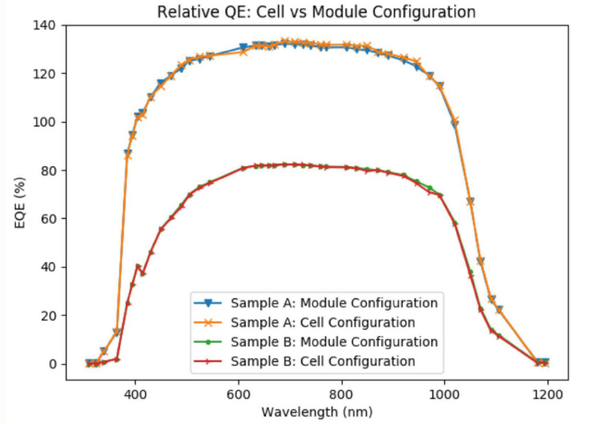
PulseQE Hardware (Module Configuration)

- Ultra stable 64 channel solid state light engine[2,3].
- Local broadband DC Light Bias (~5mW, configurable)
- Stage gantry equipped for 1.1m x 2.1m panels
- Low noise electronics allow full spectrum acquisition in ~5s / site
- Chamber light bias ~ 1mW/cm^2



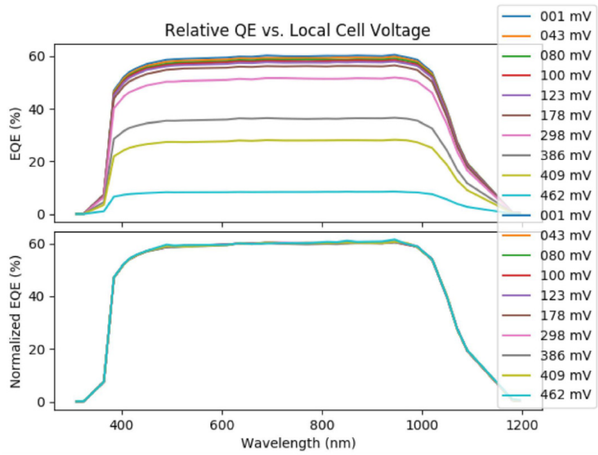
Relative QE of Cells and Modules

For comparison, we scratched through two encapsulated panels and compared the measured QE response in both cell and module configurations.



Relative QE vs Local Voltage Bias

We also compared the relative QE in panel configuration when the local cell bias is not constrained to a particular operating point.



Module QE Configuration

The QE of a module is ill-defined and cell QE standards cannot be applied to modules since local cell terminals are not accessible. We compare two configurations in this poster:

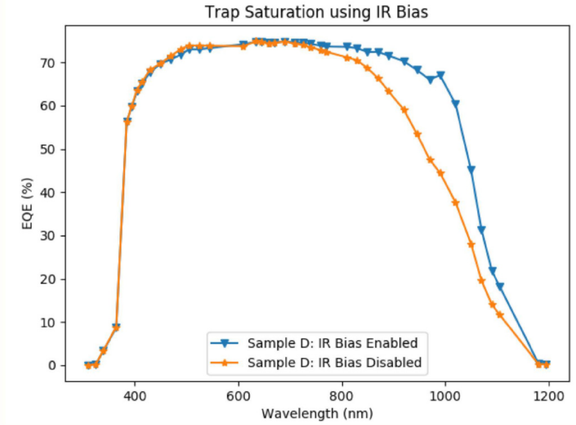
- Cell Configuration: Direct physical measurement of cells in a panel.
- Module Configuration: Measurement of cell in panel using panel terminals.

Table I: Sample Description

Sample #	Number of Cells	Dark Cell Voltage (mV)	Terminal Voltage (Voc)	Sample Type
A	72	120	40.95	156 - multi
B	72	27	39.7	125 - mono
C	60	N/A	34.93	156 - multi
D	60	N/A	35.69	156 - mono
Cal	3	1	1.74	3-mono

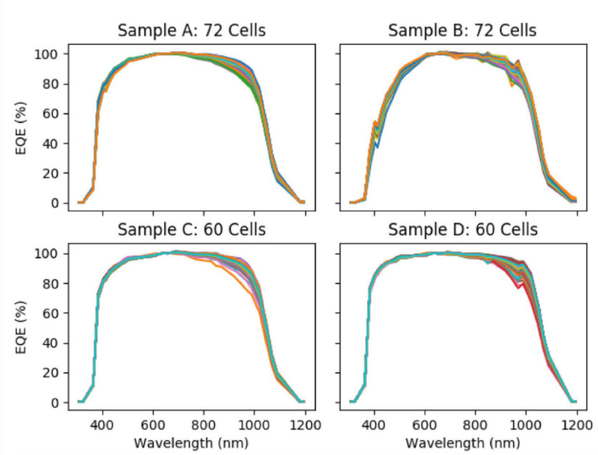
Relative QE vs Local Light Bias

The measured QE response of some panels may be affected by traps. Local light bias applied to the region under test is needed to fill these traps before the QE curve is measured as observed in Sample D.



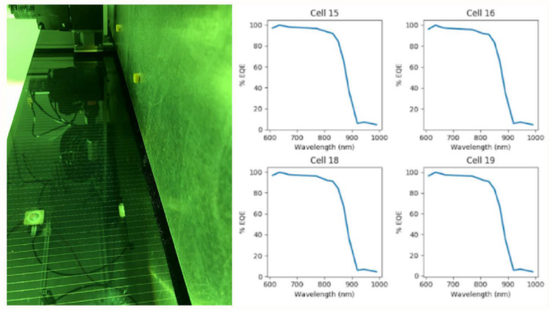
Module QE Scanning Mode

We extend the AC coupling technique to scan every cell in the module sample set. Each module scan is completed in under 10 minutes.



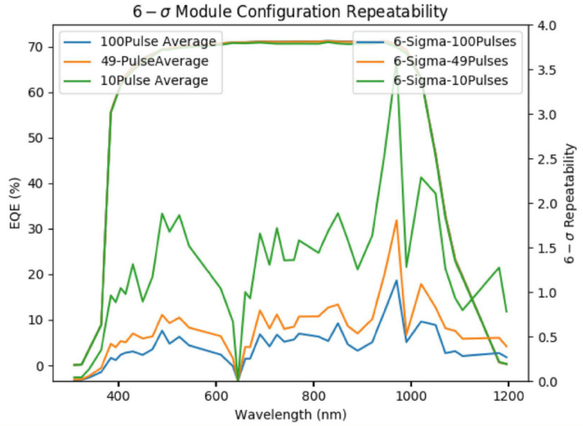
CdTe Panel Measurement

Thin film panels are particularly susceptible to reverse voltage bias damage. AC coupled measurements prevent DC current from flowing through the shunt and forcing the DUT into reverse bias. Custom shades and optical bias units are used to illuminate all cells except for the cell under test.



6-Sigma Repeatability

The AC coupling techinque and low noise electronics reduce measurement time to under 5s per site. Here, the same site is measured 100x using 10, 49, 100 pulses per wavelength. Pulse repetition frequency is set to 1kHz.



Summary

- Local cell voltage bias conditions are not enforceable in modules.
- Relative QE in most panels is insensitive to the local cell voltage bias.
- AC coupling preserves the relative QE between cells and modules.
- AC coupling reduces measurement complexity and noise.
- AC coupling eliminates the risk of reverse bias damage.
- AC coupling increases measurement sensitivity.

References

1) Emery, K., Dunlavy, D., Field, H., Moriarty, T. "Photovoltaic Spectral Responsivity Measurements" NREL, Presented at 2nd World Conference and Exhibition on Photovoltaic Solar Energy Conversion, July 1998.
2) Young, D.L, B. Egaas, S. Pinegar, and P. Stradins. A new real-time quantum efficiency measurement system. in 33rd IEEE PVSC 2008. San Diego, CA: IEEE.
3) David L. Young et al, US Patent #US8239165B1, Midwest Research Institute Alliance for Sustainable Energy LLC, issued August 7, 2012.

ECOPROGETTI
SPECIALIST IN PHOTOVOLTAIC PRODUCTION PROCESS

LONG TERM PERFORMANCE OF LIGHT-EMITTING DIODES IN IV CURVE TESTING OF PV MODULES

Ing. Federico Quartiani, Ecoprogetti Srl

ECOPROGETTI 20th ANNIVERSARY

ABSTRACT

Ecoprogetti is an Italian Company that since 1998 has been designing and assemblying production solutions for PV module manufacturing and testing.
The LED technology improves day by day and Ecoprogetti studies this development to always introduce the latest innovation. Thanks to this continuous R&D study it is possible to achieve the best performance from the LED light source. As a result of this continuous innovation adn research the efficiency of the light source is alwyas updated so even the efficiency of the machine is enhanced

HISTORY OF THE LED SUN SIMULATOR

2009
Start the development of the LED light source in Ecoprogetti.
Research and study about the light spectrum and LED driver.

2010
Release of First model of the machine.
Presentation of PV Sec - Valencia.

2011
Release of new Led Board; TÜV certification with TÜV intercert;
Software improvement.

2012
Instrumentation improvement; New power supply;
SQL database redesigned.

2013
Led upgrade to improve power; Mechanical improvement; Release of the Automatic version; Release of the tester for string before bussing; Release of the mobile version

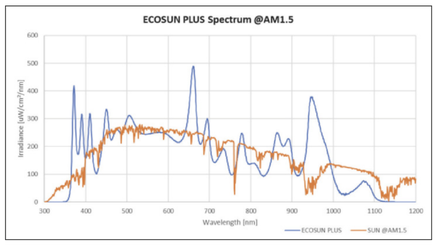
2014
New instrument for I-V measure.
Release of a big version of Ecosun.

2015
New Led board with more LED types.
New Led driver to extend the stability and the control of the light;

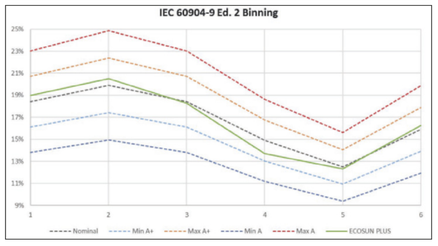
2018
Extended Spectrum 300nm to 1200nm

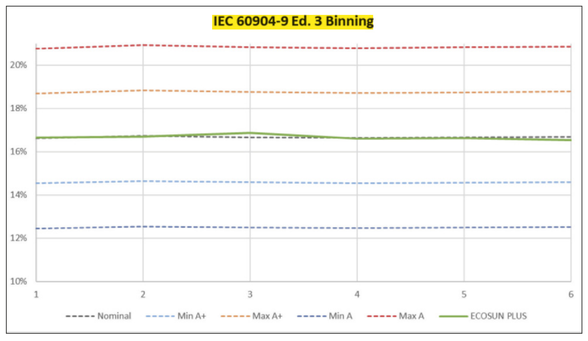
IEC norm Ed.3 - SPECTRUM

Spectrum (Class A+)
The spectrum of our LED source is ± 8% in the whole testing area (the best in the industry). It is almost similar to the light generated by the sun. Possible to achieve this spectrum by the combination of 17 different LED's.

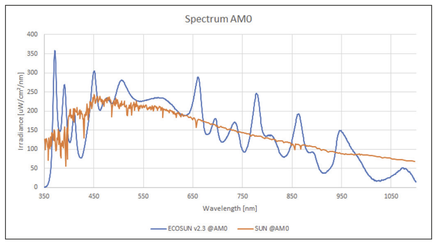


Spectrum (Class A+):
The new ECOSUN PLUS spectrum is **suited to IEC 60904-9 Ed.3.0** and can be reprogrammed in 10 minutes to the current Ed.2.0 (2007).
Spectrum range 300nm to 1200nm.



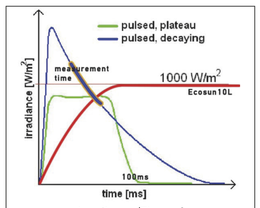


Spectrum (Class A)
The new ECOSUN PLUS spectrum can be reprogrammed in 10 minutes to match the AM0 spectrum for space applications



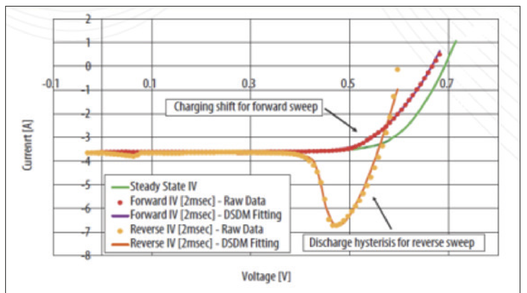
APPLICABILITY TO DISTINCT MODULE CLASSES

LIGHT STABILITY
The light source stability in time is better than 0.125% with 200ms of I-V Sweep

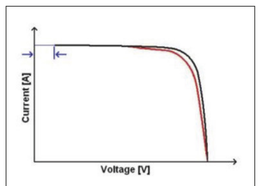


Irradiance/Time of different LED Sun Simulators

NO CAPACITIVE EFFECTS:
Very similarly to the Sun the measurement is performed in a long and stable condition thus not simply in a short pulse.



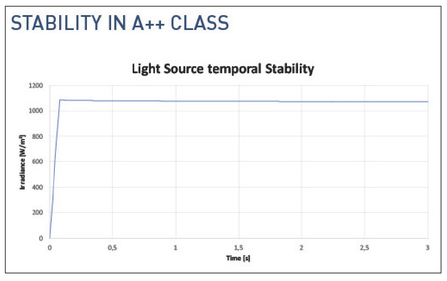
I-V Curve Capacitive effect

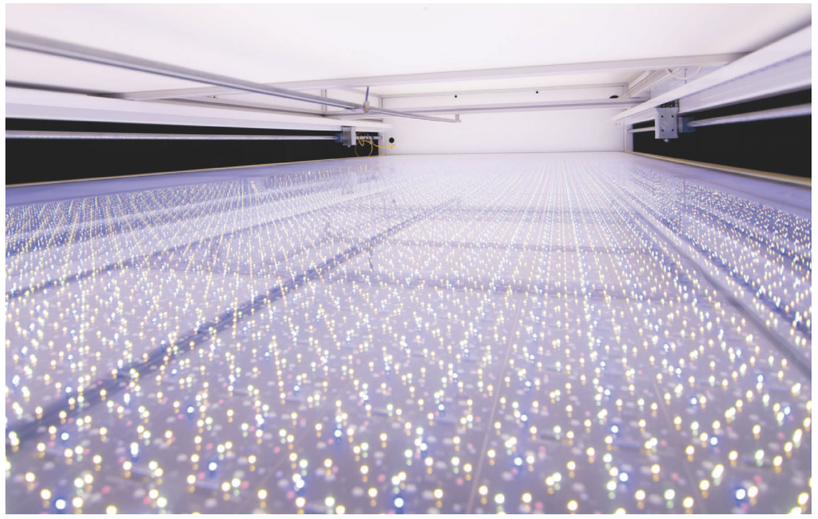


I-V Curve Capacitive effect

Ecoprogetti's LED sun simulators can perform any kind of test since the light stability is better than 0.125%. This allows to **avoid capacitive effects** which could occur during "short tests" on the new generation of high efficiency solar cells (PERC, Bifacial, etc...).

LIGHT SOAKING:
It's possible to perform the "**light soaking**" on our LED sun simulators (from 5sec to 5min) (i.e. Ecosun Plus) necessary for some CIS nad CIGS cell technology.





ADVANTAGES OF THE LED TECHNOLOGY IN SUN SIMULATORS

- No Recharging time
- No Capacitive effect
- Long Sweep: 100ms - 5s
- Lifetime: Low spare part costs;
  Uniformity and spectrum stable against time;
  Low maintenance;
- Flexible spectrum

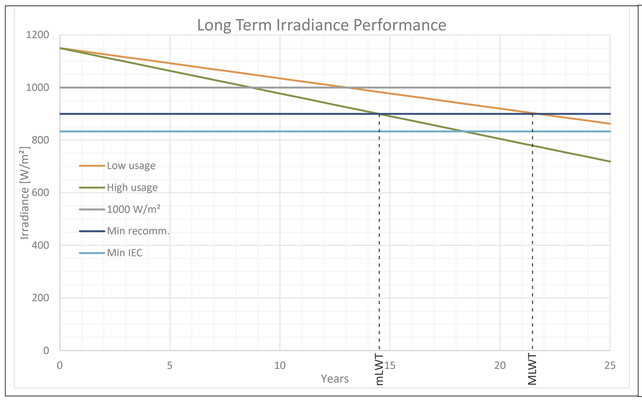
REPORT "LONG TERM PERFORMANCE"

Mean Time Between Failure

- Electronic Load: 166 years
- Pyranometer: 83 years
- Data acquisition board = 83 years

LED BOARD
Failure of one single LED channel in 1 out of 77 boards in the machine = 3.5 years

DRIVER BOARD
Any fault in 1 out of 77 boards in the machine = 10.5 years



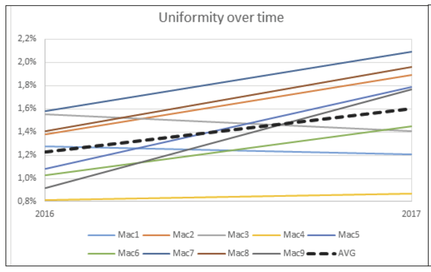
An average irradiance power loss of 0.5% per year for a 250MW line.

The irradiance performance has a degradation between 1% and 1.5% per year depending on the usage of the machine itself.

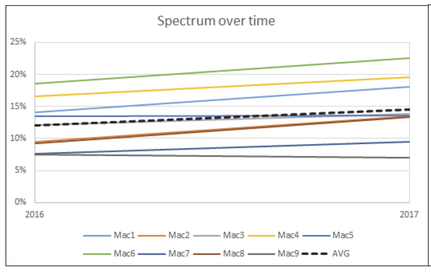
Minimum LED working time: 14 years
Maximum LED working time: 21 years

Mean Cost to Repair

- Electronic Load: 100 €/year
- Pyranometer: 20 €/year
- Data acquisition board: 15 €/year
- LED Board: 30 €/year
- Driver Board: 10 €/year
- Complete machine (with 77 LED boards): 200 €/year



The recommended interval for performing and restore the uniformity on test area is every 2 years. Uniformity deviation collected from 9 sun simulators after 1 years of production and more than 300.000 flashes done per machine corresponding to 100MW of tests. Average "degradation" of about 0.4% in 1 year and 100MW of production.



An average "degradation" of 2.5% of the spectrum binning over 100MW of production line.

EL-Sweep Module Imaging System

J. Gallon[1], E.J. Schneller[2], Siyu Guo[2] G.S. Horner[1], K. Davis[2] L.A. Vasilyev[1]
[1]Tau Science Corporation, Hillsboro, OR, USA
[2]Florida Solar Energy Center, University of Central Florida, Orlando, FL, USA

Abstract

The EL-Sweep Module Imaging System provides real-time, non-destructive analysis of cell operating parameters. The module is simply loaded into the system and connected to the built-in power supply. Operation is fully automatic and recipe-driven. Advanced analysis algorithms are used to report maps of cell voltage, saturation current densities, and series resistance. A series of electroluminescence (EL) images is acquired from 0A to 0.25A per cell, and the dark I-V curve is measured simultaneously. The electroluminescence EL emission from each cell is then analyzed as a function of bias, and one I-V curve is calculated for each cell in the module. Algorithms then use non-linear diode analysis to calculate maps of saturation current densities, series resistance, and cell operating voltage.

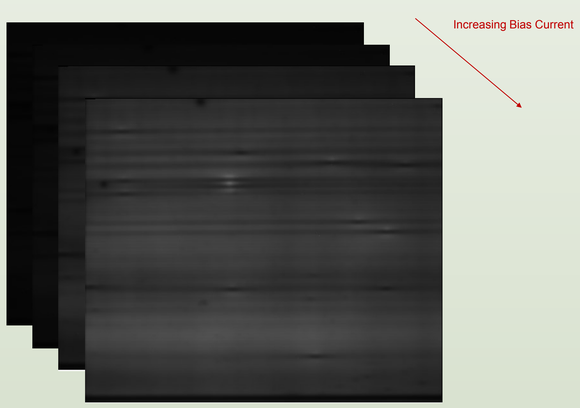
Background

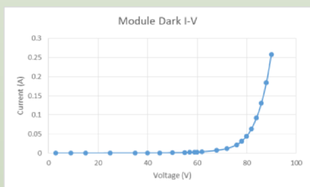
Traditionally IV data has been used to characterize PV cells. However once the cell is incorporated into a module the individual cell contacts are no longer available, leaving only the module IV characteristics available for monitoring. The EL-Sweep system described here can characterize the current and voltage of individual cells within a module by analyzing a set of EL images and the electrical conditions under which they were taken . Once an IV curve is established for each individual cell in the module, then R_s, R_{sh}, V_{oc}, n, J_o can also be calculated for each cell.

Advanced analysis algorithms developed at UCF by Schneller et al use EL images taken at various points on the module's IV curve to calculate these parameters for the individual cells in a module. These results are then compiled and displayed visually as device characteristic maps. This allows individual cells to be measured in a module at any stage of the module's life without damaging the module. The sweep takes approximately 60 seconds, and we discuss here the first results from thin-film modules.

Series of EL Images

To measure the IV curves of each cell in a module, EL images and bias conditions are simultaneously collected of the entire module at various points on the module's IV curve. This is done by applying known bias currents to the entire module. As with single cell EL measurements, the exposure time is adjusted to avoid image saturation at higher bias, and to make there is sufficient signal to noise ratio at lower bias.





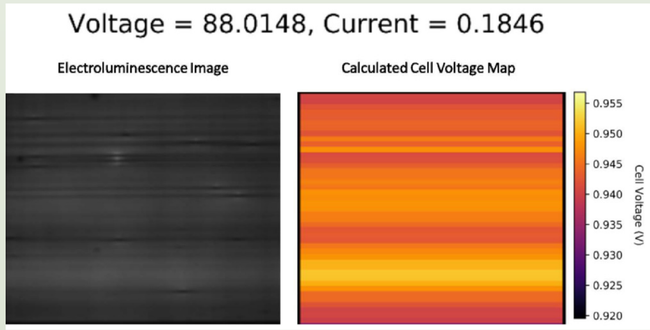
Software automatically controls the hardware to follow a used specified recipe to speed the data collection process. The ability to save recipes allows a user to define a recipe for a specific type of module, then run many similar modules though the EL-Sweep system at a rate of about one module per minute.

Individual Cell IV Curves

Once the EL images and dark IV measurements have been collected, the ratio of the power dissipated in each cell relative to the power dissipated in the entire module can be established. This is possible because the ratio of EL emission from each cell compared to that of the entire module is directly related to the ratio of the voltage across each cell compared to the voltage across the entire module.

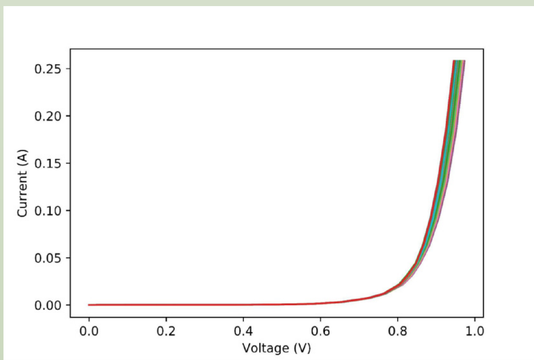
$$V_{mod} = \sum_{i=1}^{N_{cell}} V_{op}^{i} = \sum_{i=1}^{N_{cell}} V_T \ln\left(\frac{\Phi^i(x_{max}^i)}{C}\right) + R_{mod} I$$

with $\Phi = k_opt * \exp(V(x)/V_T)$



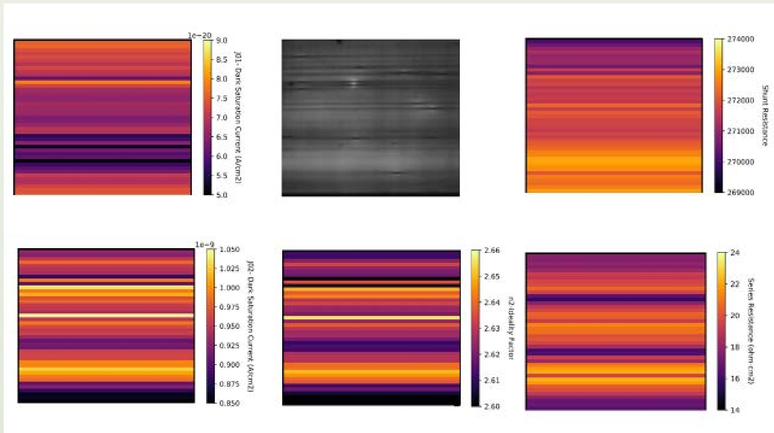
An individual voltage can be assigned to each cell. Since we have measured the current and calculated a voltage for each cell in the module, we can now build individual IV curves for each cell. Once the individual cell dark IV curves are constructed, the individual cell parameters such as R_s, R_{sh}, V_{oc}, n, J_o can be determined using a standard two diode model. These results are then mapped to illustrate the individual cell parameters of all of the cells in the module.

Cell IV Curves



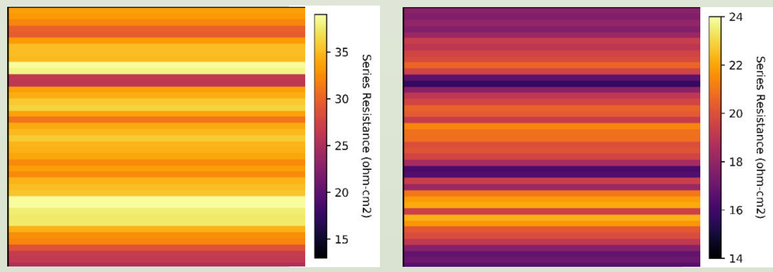
Cell Level Maps

Tau Science has mapped the device parameters (R_s, R_{sh}, V_{oc}, n, J_o) of multiple types of PV modules with EL-Sweep systems. Displayed below are some quantitative examples of a CdTe module, as well as a Si module for comparison. Each cell in these modules is individually analyzed before the results are compiled into complete module maps.

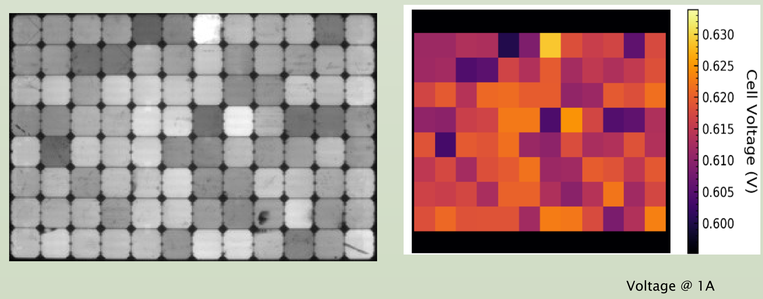


Individual Cell Series Resistance

40F 65F



Individual Cell Series Resistance



Summary

The EL-Sweep system has been used to map device parameters of individual cells in modules. The technique provides a method to measure R_s, R_{sh}, V_{oc}, n, J_o of individual cells in a module in a nondestructive manner. The speed and ease with which this system operates makes it useful both in a production quality assurance environment and pre or post installation environments in the field. We are currently looking for collaboration partners to demonstrate the EL-Sweep technique on thin film PV modules.

Module Reliability Journey

Path to reliable REC products

Franco Lim, Tan Teck Cheng

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Introduction

Develop extended tests to determine point of relevance for early detection of module failures and weaknesses.

	PID		DH		JB Robustness		LeTID	
	IEC	REC	IEC	REC	IEC	REC	IEC	REC
Standard	62804:2015	61215:2018 CD	61215:2016		61215:2016			61215:2018 CD
Procedurals		MQT 21	MQT 13.1		MQT 14.1			MQT 23.1
Temp. (°C)	60	85	85					75
RH (%)	85		85					
Other procedures		With/without Al foil			40 N pull	> 400 N pull (indoor & outdoor)		
Duration	96 h		1000 h	2000 h	10 s	Pull to Fail		162 h (2 consecutive cycles of < 1%)
Elec. Bias	+/- 1000 V		0		0			I_{sc}-I_{mpp}
Pass	5%		5%		JB retention			5%

- Are the extended tests sufficient?
- Are the extended tests too stringent?
- How much extended should the test be?
  - Extend beyond 2 IEC cycles?
  - Combined cycle test (MLT+PID+DH+TC+HF)?
  - Multiple combined cycles?
  - Model after "Thresher test"?

Potential Induced Degradation (PID)

- Extended PID tests was used to scrutinize module weakness across different cell types (Fig.1)
- System level assessment validates that mono cells have strong PID resistivity in Hot & Humid region (Fig. 2)
- **Point of relevance**:
  - At least 3 PID cycles are sufficient to emerge module failures

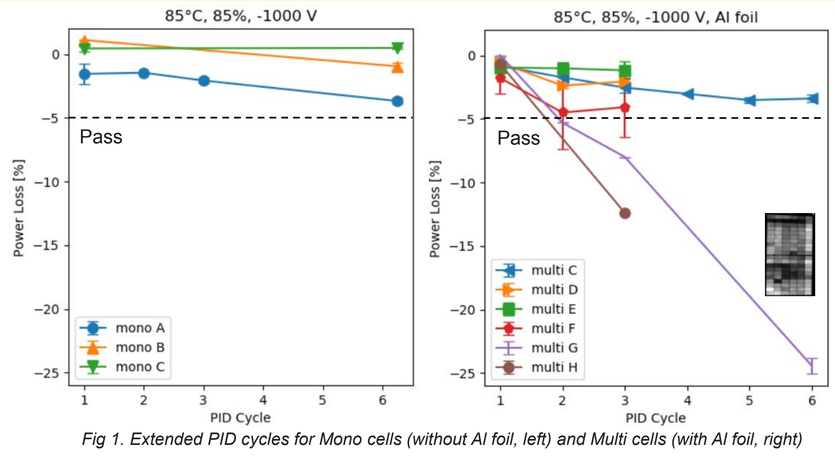

Fig 1. Extended PID cycles for Mono cells (without Al foil, left) and Multi cells (with Al foil, right)

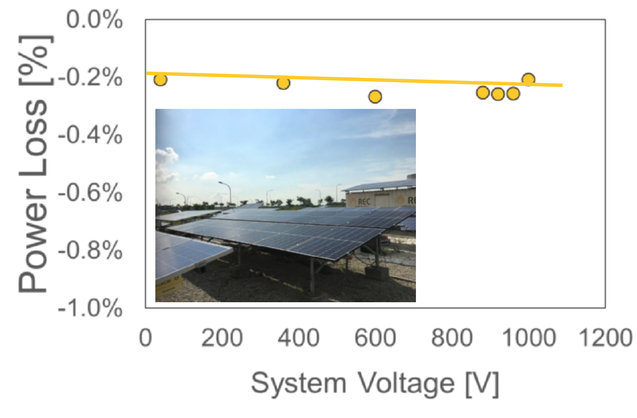

Fig 2. System-level PID assessment of mono product at various system voltages

Damp Heat (DH)

- Case study – Striation rings in mono cells (Fig. 3)
- DH1000: Determine the severity of ring amounts to power degradation
- Module weakness discovered in more than 2 cycles (Fig. 4)
- **Points of relevance**:
  - Low risk of power loss up to 15 striation rings (validated with field projections)
  - At least 2 DH1000 cycles required to screen weak products

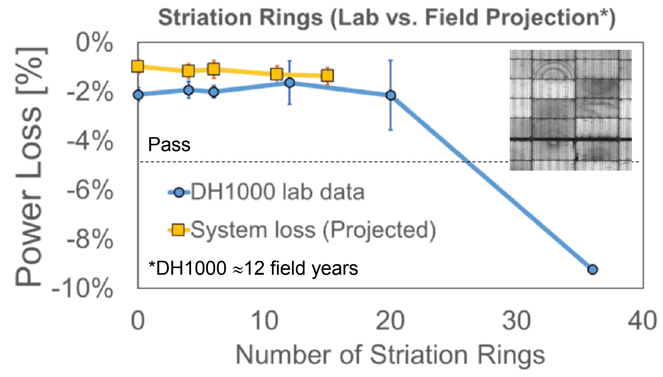

Fig 3. DH1000 data and System projected loss of mono modules with different amount of striation rings

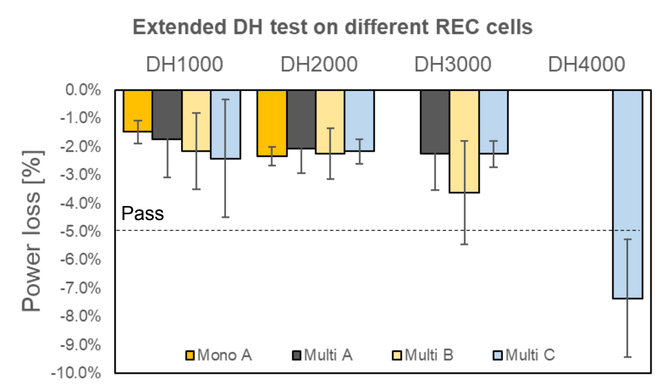

Fig 4. Extended DH cycles for Multi and Mono cells

Junction Box Robustness

- Evaluate the quality of junction box sealant adhesiveness to the back sheet with extended JB robustness "pull-to-fail" test (Fig. 5 and 6)
- Hot and humid storage condition is more susceptible to JB robustness failures compared to Ventilated and dry conditions (Table 1)
- Inferior JB sealant supplier identified (Table 1)
- **Points of relevance:**
  - "Pull-to-fail" after outdoor exposure is effective to screen inferior supplier with poor sealant adhesive strength at outdoor-world conditions

Fig 5. Test setup (left) and dislodge of junction box after test (middle and right)

Table 1 Extended JB Robustness test on 2 JB sealant suppliers at 2 different storage conditions

Condition	Storage duration before pull test	JB Sealant Supplier	Pull to fail (N)
Indoors (Ventilated and dry)	30 days (Ambient indoor lights)	A	900
		B	1200 (Pass)
Outdoors (Hot and humid)	30 days (100 kWh/m²)	A	600
		B	1200 (Pass)

Fig 6. Extended JB robustness pull-to-fail test setup for MQT14.1 in REC

Light at elevated temperature induced degradation (LeTID)

- Early adoption of "LeTID Detection" protocol at IEC draft
- All PERC multi and mono products are not "LeTID sensitive" (Fig. 7)
- Outdoor assessment of PERC cells at Singapore & Germany shows no significant LeTID losses after 4 years (Fig.8)
- **Point of relevance:**
  - Further optimization of test conditions to accurately represent realistic outdoor conditions
  - Participate in NREL Round Robin Program

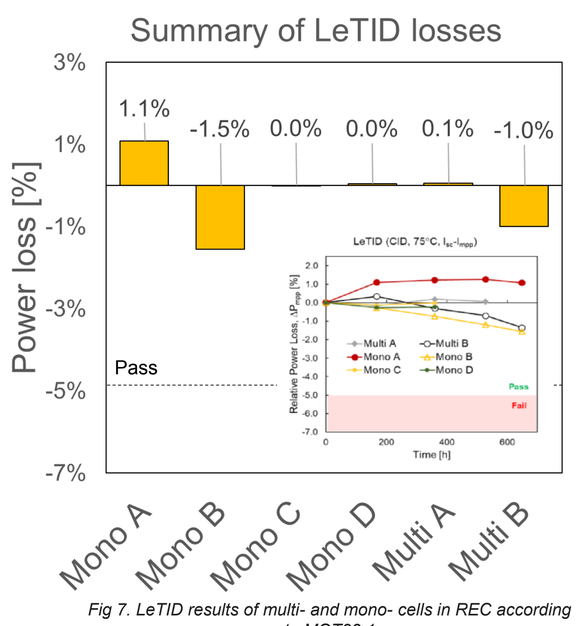

Fig 7. LeTID results of multi- and mono- cells in REC according to MQT23.1

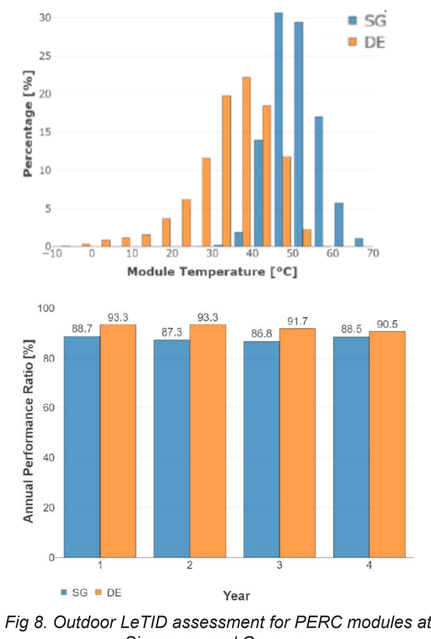

Fig 8. Outdoor LeTID assessment for PERC modules at Singapore and Germany

Comparison of Solder Bond Degradation Mechanisms in Fielded PV Modules at Different Climates

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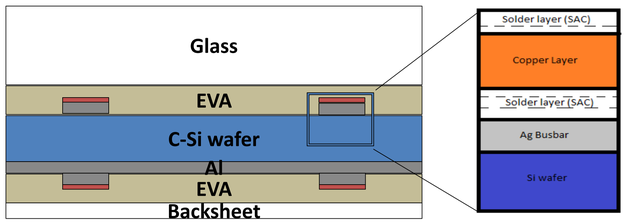
INTRODUCTION

- Solder bond degradation is one of the top two degradation modes in the fielded PV modules.
  - series resistance (Rs) ↑ and fill factor (FF) ↓ → output power (Pmax) ↓
- It is caused by the individual or synergistic mechanisms of the intermetallic compounds (IMC) formation at copper core/solder or solder/silver busbar interfaces, or the thermomechanical fatigue due to mismatch in the thermal coefficients of different components.



- Studying the influence of different climatic factors is critical to understand the dominant underlying mechanism and its impact on the module performance and service lifetime.

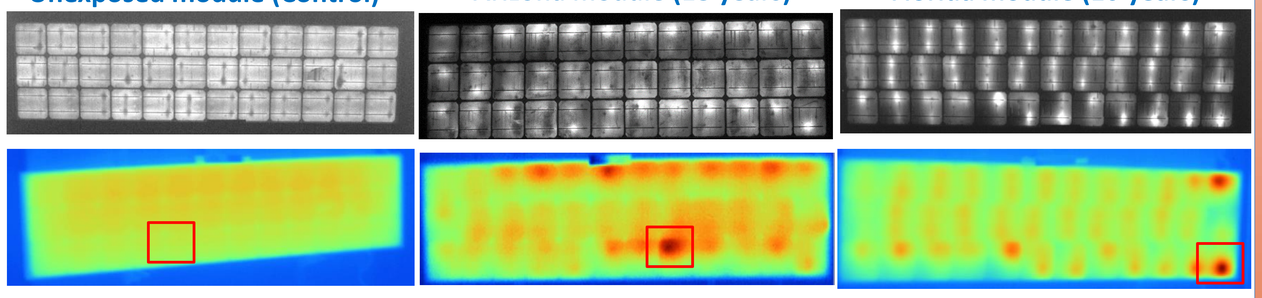
EXPERIMENTAL: MODULE CHARACTERIZATION

- Two climates: Arizona (hot and dry) and Florida (hot and humid)
- Three modules of same manufacturer with similar construction and solder type (Sn60-Pb40)
  - Unexposed module
  - AZ module – 18 years old
  - FL module – 10 years old

Light and Dark I-V Measurement

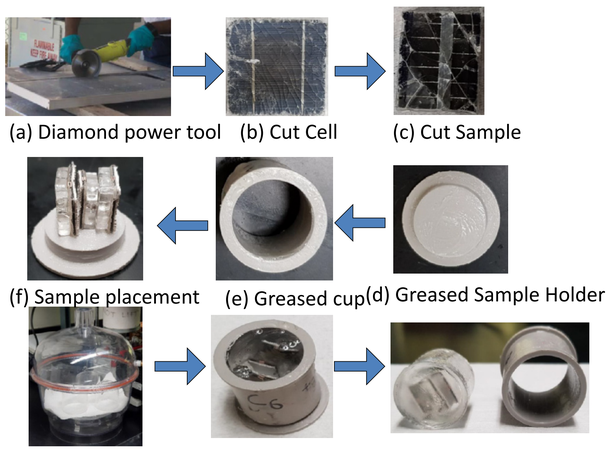
	I_{sc} (A)	V_{oc} (V)	FF (%)	P_{max} (W)	R_s (Ω)
Unexposed	3.22	22.23	74.1	53.1	0.71
FL aged (10 years)	3.06	22.05	57.4	41.8	1.47
Deg rate (%/yr)	0.50	0.08	2.25	2.13	10.7
AZ aged (18 years)	3.02	21.84	63.8	42.2	1.52
Deg rate (%/yr)	0.35	0.10	0.77	1.14	6.3

Unexposed module (Control) | **Arizona module (18 years)** | **Florida module (10 years)**



SAMPLES PREPARATION FOR SEM CHARACTERIZATION

Sample cutting and epoxy encapsulation

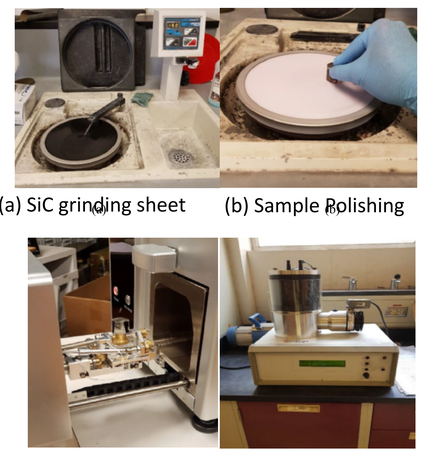


(a) Diamond power tool (b) Cut Cell (c) Cut Sample

(f) Sample placement (e) Greased cup (d) Greased Sample Holder

(g) Vacuum chamber (h) Uncured epoxy (i) Encapsulated samples

Sample polishing and carbon coating

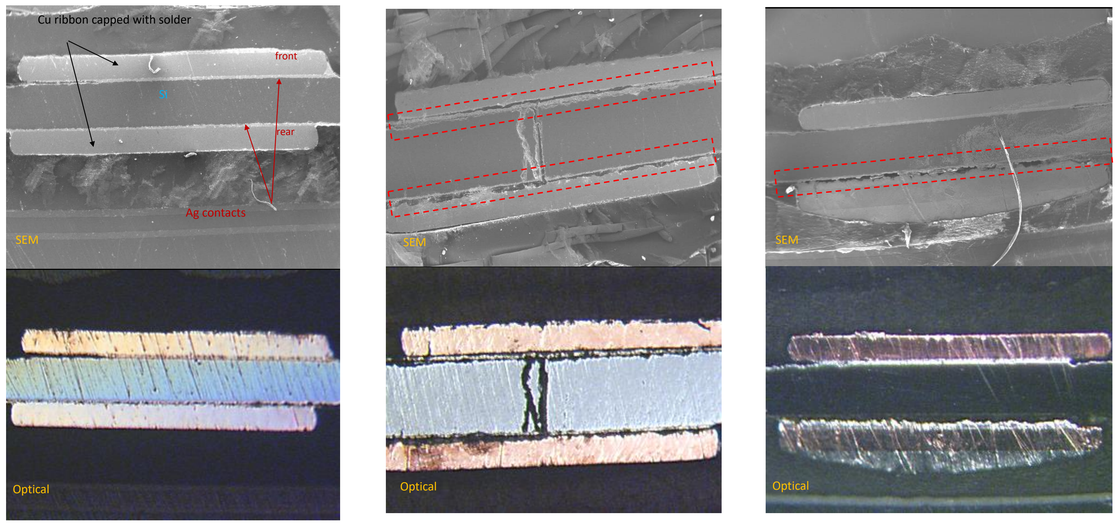


(a) SiC grinding sheet (b) Sample Polishing

(d) Sample in SEM (c) Carbon Coater

SEM IMAGING AND EDS PROFILING

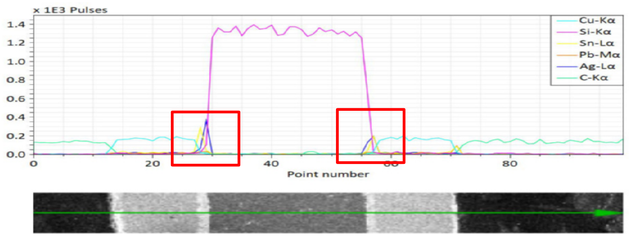
Unexposed module | **Arizona module (18 years)** | **Florida module (10 years)**



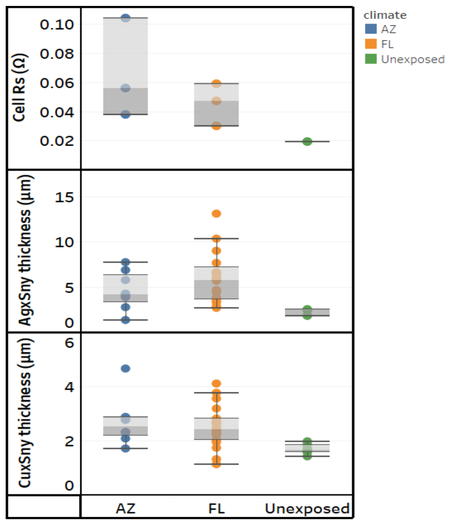
Uniform interface without any contact loss

Deterioration of solder-Ag interfaces at both front and rear contacts → *IMC formation followed by thermomechanical stress under diurnal thermal cycles*

Deterioration of solder-Ag interface, primarily at rear contact → *formation of metal oxides in the presence of moisture (entered through the backsheet)*



- The average thickness of Ag-Sn and Cu-Sn IMCs was calculated from FWHM technique applied on overlapping regions of elements between solder and Ag busbar and Cu ribbon respectively.
- FL module showed thicker Ag_xSn_y layer IMC at rear contacts due to formation of metal oxides in the presence of moisture. AZ module has thicker Cu_xSn_y due to higher diffusivity of Cu in Sn at high operating temperatures over longer exposure in the field.



CONCLUSIONS

- Florida climate induces more degradation at rear cell contacts due to the penetration of moisture though the backsheet, whereas both the front and rear contacts get affected severely in Arizona climate owing to IMC growth followed by thermomechanical fatigue.
- A good correlation between *R*s increase and solder bond fatigue through IMC growth and void formation was established in field aged modules.

REFERENCES

[1] G. TamizhMani and J. Kuitche, "Accelerated Lifetime Testing
[3] T. Geipel, M. Moeller, A. Kraft, and U. Eitner, "A comprehensive study of intermetallic compounds in solar cell interconnections and their growth kinetics," *Energy Procedia*, vol. 98, pp. 86–97, 2016.
[4] T. Laurila, V. Vuorinen, and J. K. Kivilahti, "Interfacial reactions between lead-free solders and common base materials," *Mater. Sci. Eng. R*, vol. 49, pp. 1–60, 2005.

Arizona State University

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Role of Humidity on the Degradation of UV-cut and UV-pass Encapsulants

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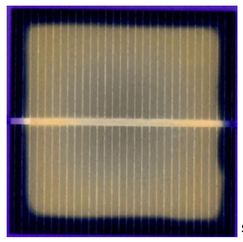
Introduction

- Two common degradation modes in field-aged modules: Encapsulant browning and delamination
- Caused by UV light, elevated temperatures, and humidity

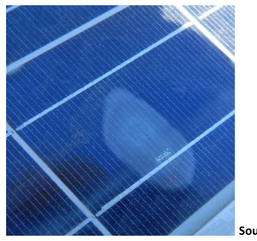
Encapsulant Browning



Source: PRL

- Late-onset degradation mode in PV modules
- Chromophore formation decreases transmission
- Durability issue detected by UV fluorescence (UVF) imaging

Delamination



Source: NREL

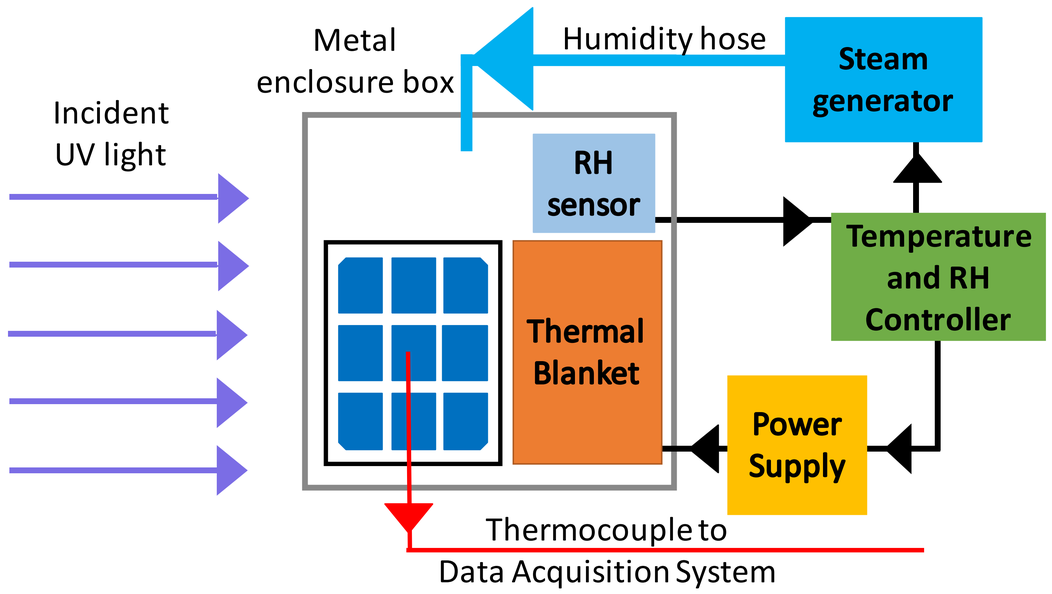
- Adhesion loss between encapsulant and other layers
- Optical decoupling decreases transmission
- Reliability issue leading to other degradation modes

Experimental Setup

Sample Set and Characterizations

- Six mini-modules with glass/backsheet construction were fabricated
  - 3 UV cut (UVC) EVA mini-modules — UVC EVA on both sides of the cell
  - 3 Hybrid EVA mini-modules — UV pass (UVP) EVA above cell and UVC EVA below cell
- Samples simultaneously exposed to accelerated **UV light, elevated temperatures, and humidity**
- Samples were characterized intermittently with
  - UVF imaging to highlight are of browning
  - Light IV via solar simulator to track cell operation
  - Reflectance to detect spectrum changes due to browning
  - Yellowness Index (YI) measurements to quantify extent of browning

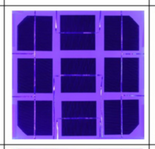
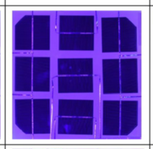
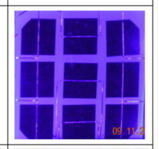
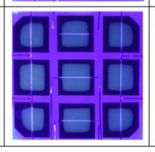
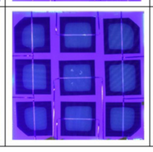
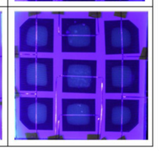
Results and Discussion

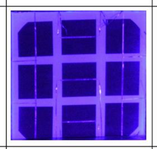
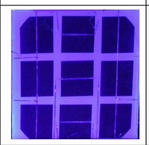
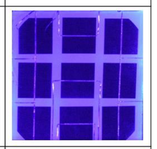
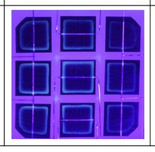
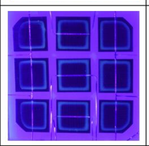
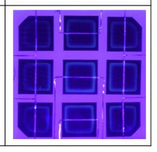


Schematic of setup placed inside the walk-in UV chamber

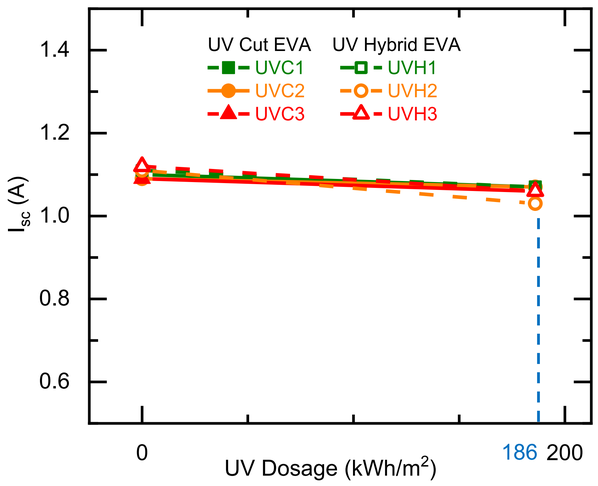
- Samples were exposed to
  - Accelerated UV light: 171 W/m² for a total dosage of 186 kWh/m²
  - Elevated temperatures: 56.7°C – 67.1°C
  - Multiple humidity levels: 11.2% – 54.4%

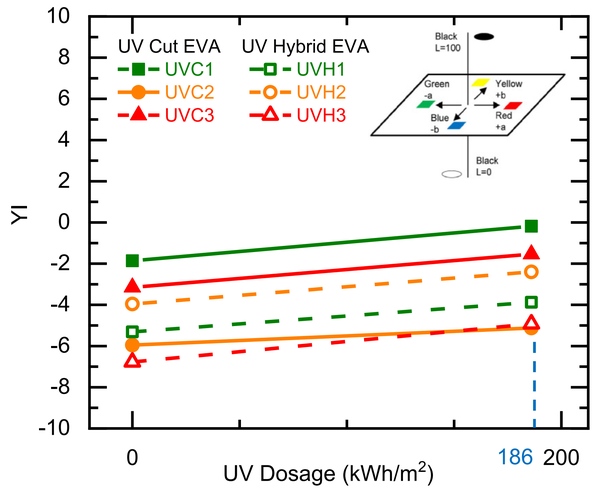
Detecting the encapsulant browning and delamination through UVF imaging

Coupons	UVC 1	UVC 2	UVC 3
Temperature	64.4°C	60.3°C	63.1°C
% RH	11.2	54.4	28.9
0 kWh/m²			
186 kWh/m²			

Coupons	UVH 1	UVH 2	UVH 3
Temperature	60.7°C	56.7°C	67.1°C
% RH	11.2	54.4	28.9
0 kWh/m²			
186 kWh/m²			

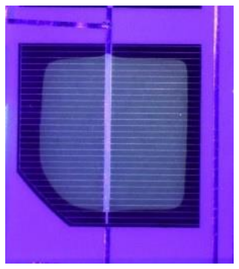
- Encapsulant browning is seen in UVC mini-modules
- Ring-like pattern seen in UVH mini-modules



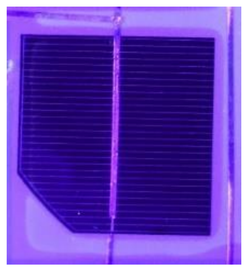


- I_{sc} drop measured is within the measurement error
  - Greater UV dosage would result in higher I_{sc} drop
- The change in YI indicates a decrease in the blue component of the sample color and an increase in the yellow component

UV-T exposure – 200 kWh/m²



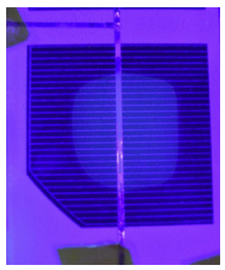
UV Cut EVA 3
T: 78.4°C
RH: 0%



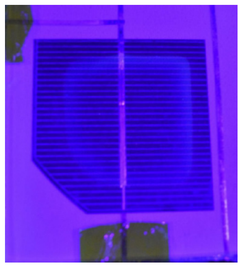
UV Pass EVA 3
T: 77.9°C
RH: 0%

Al tape on the backsheet: No oxygen photobleaching

UV-T-RH exposure – 186 kWh/m²



RH-UVC 3
T: 63.1°C
RH: 28.9%



RH-UVP 3
T: 67.1°C
RH: 28.9%

No Al tape on the backsheet: Photobleaching

Conclusions

- Setup described enables samples to be exposed to humidity and elevated temperatures inside a walk-in UV chamber
- Sealed box prevents humidity from escaping and adversely affecting the lifetime of the UV lamps
- UVC mini-modules show increasing browning with higher humidity
- UVH mini-modules show a ring-like pattern possibly due to delamination

Construction Mishaps and Long Term Problems

The Learning Curve

- Lack of engineering experience
- Bad procurement motives
- Subpar material acceptance process
- Poor storage & handling decisions

The Issues

- Electrical damage / corrosion
- Rodent infestation
- Water infiltration
- Site drainage / deterioration

How would you change things next time?

- What civil & geotechnical standards do you specify?
- How do you assess these standards?
- What accountability is there post completion?
- Does the “solution” fit your long term needs?

Invenergy

Evening Stow Angle Impact on Soiling Rate

Abstract

Soiling losses can represent significant production loss depending on local climate. At a certain solar site, different soiling rates were visually observed in flat-stow framed panels vs angle-stow framed panels. A production-based analysis was performed to determine the impact of evening stow angles on soiling rates for single-axis tracking modules.

Methodology

Data from December 2018 through February 2019 was analyzed. The dataset was filtered for timesteps above 100 W/m^2 irradiance, when all strings were producing within 25% of each other, and binned by days since last precipitation. Production at the inverter level was compared in each timestep to estimate the impact of soiling loss. Production was normalized via flash test results.

System details

- Two configurations of modules used (Group A, B)
- Each group consists of subsets configured both in 1-high and 2-high portrait orientation single-axis tracking system
- Torque tubes at same ~6' height

Conclusion

Despite the visual observation of soiling, it does not appear that evening stow angle significantly impacts production by way of soiling rates.

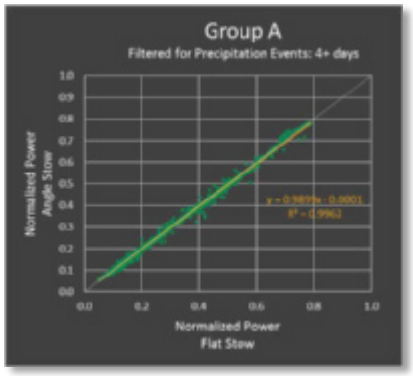
Limitations

- Different Trackers, both present in Groups A & B
- Different racking configurations
- Limited dataset
- No dedicated soiling station for each group

Future Work

- Decrease independent variables
- Test varying stow angles
- Longer data collection
- Use 2 fixed panels as a soiling station
- Set up clean and dirty panels on tracker to compare soiling rates

Figure 1: Angle-stow tracker



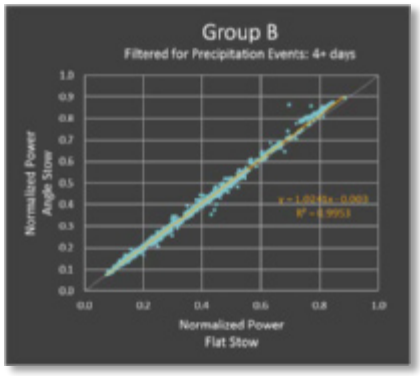
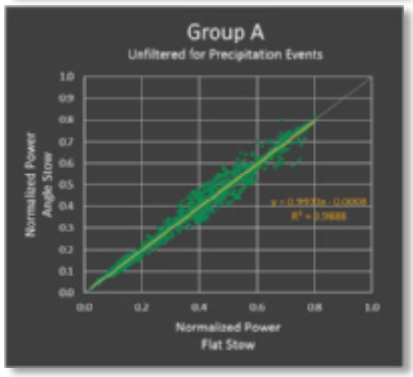
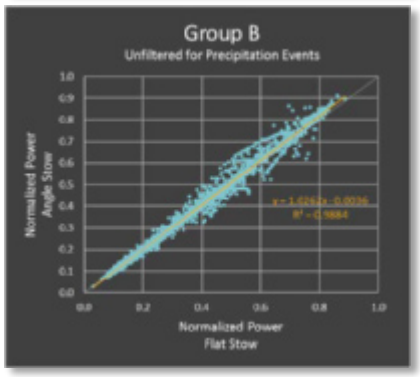


Figure 2: Flat-stow tracker





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Update on IEC 63209: Why a Predictive Scientific Basis is Both Essential and Impossible

Tony Sample, European Commission, Joint Research Centre (JRC), Ispra, Italy
Sarah Kurtz, Ingrid Repins, Michael Kempe (NREL)

Problem: How to standardize testing to inform decisions such as:

- ***Set interest rates for PV transactions***
- ***Set insurance rates for PV systems***
- ***Select best hardware for a given project***

Solution: Standardized extended-stress testing: IEC 63209

IEC 63209: Extended Stress Testing of PV Modules

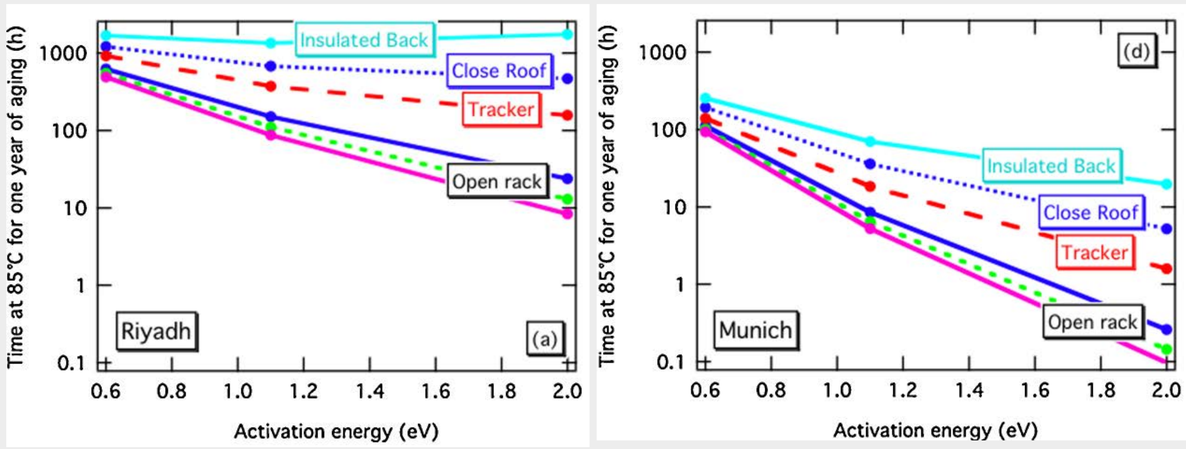
- **Unifies extended-stress testing that is already happening**
- **Is at Committee Draft stage**
- **Is planned as a Technical Specification**
- **Will provide a starting point for improvements in future years**

Why a Scientific Basis for IEC 63209 is Essential

- ***PV industry is now ~$100 billion/y: need to reduce and assess risk using accurate tools***
- ***IEC strives to be technical experts and to base standards writing on that technical expertise***
- ***In the past, poorly-designed standards have sometimes set the industry back by flagging a problem that wasn't a problem, or missing a problem that was a problem: we need to "get it right"***

Why a Scientific Basis for IEC 63209 is Impossible

- ***Acceleration factors vary, so the ideal stress level/sequence for one failure mechanism is likely to be too little or too much for another***
- ***Stress varies by location and mounting configuration (graphs below show how test times can vary by >1000)***



IEC 63209 – Five proposed test legs

Test Leg 1
Failure issues: Thermal fatigue

- ***200 Thermal cycles***
- ***200 Thermal cycles***
- ***200 Thermal cycles***

Test Leg 2
Failure issues: Mechanical (e.g., cracked cells)

- ***Static load (as in IEC 61215)****
- ***1000X 1000 Pa Cyclic load ****
- ***200 Thermal cycles ****

**** Still under discussion***

Test Leg 3
Failure issues: Backsheet cracking, encapsulant discoloration, etc.

- ***200 h Damp heat***
- ***60 kWh/m² UV per IEC 61730***
- ***10 Humidity freeze***
- ***60 kWh/m² UV per IEC 61730***
- ***200 Thermal cycles***

Sequence applied to front of one module and back of second module

Test Leg 4
Failure issues: Package integrity, corrosion

- ***1000 h Damp heat***
- ***1000 h Damp heat***

Test Leg 5
Failure issues: Potential induced degradation

- ***96 h Damp heat with voltage***
- ***96 h Damp heat with voltage***

Characterization

- ***No pass-fail criteria applied***
- ***Record results of IEC 61215 characterization***
- ***Also include EL imaging***
- ***All results reported***

Thank you to Solar Energy Technology Program for supporting this work

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