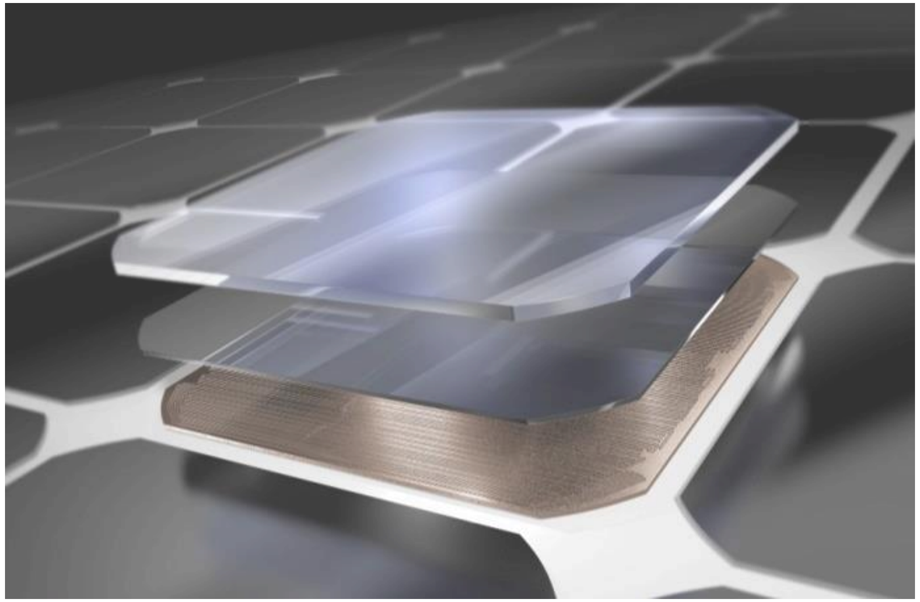
Field Failures and Accelerated Tests

David H. Meakin, SunPower Corporation

BAPVC/DuraMAT Workshop, Stanford University

May 21st , 2017



Safe Harbor Statement

This presentation contains “forward-looking statements” within the meaning of the Private Securities Litigation Reform Act of 1995, including, but not limited to, statements regarding (1) our technological evolution and research and development activities; and (2) estimates regarding the future performance and reliability of our products. These forward-looking statements are based on our current assumptions, expectations and beliefs and involve substantial risks and uncertainties that may cause results, performance or achievement to materially differ from those expressed or implied by these forward-looking statements. Factors that could cause or contribute to such differences include, but are not limited to: (1) competition in the industry and downward pressure on average selling prices; (2) our liquidity, substantial indebtedness, and our ability to obtain additional financing for our projects and our customers; (3) our ability to meet our cost reduction targets; (4) regulatory changes and the availability of economic incentives promoting use of solar energy; (5) challenges inherent in constructing and maintaining certain of our large projects, such as the Solar Star projects; (6) the success of our ongoing research and development efforts and commercialization of new products and services; (7) fluctuations in our operating results; (8) manufacturing difficulties that could arise; and (9) challenges managing our joint ventures. A detailed discussion of these factors and other risks that affect our business is included in filings we make with the Securities and Exchange Commission (SEC) from time to time, including our most recent reports on Form 10-K and Form 10-Q, particularly under the heading “Risk Factors.” Copies of these filings are available online from the SEC or on the SEC Filings section of our Investor Relations website at investors.sunpowercorp.com. All forward-looking statements in this presentation are based on information currently available to us, and we assume no obligation to update these forward-looking statements in light of new information or future events.

Reliability Value Chain

Design

- Failure Modes and Effects Analysis (FMEA) to prioritize effort
- Highly Accelerated Stress Screening or Life Testing to discover new failure modes
- Physics of Failure research
- Design Verification Testing
- Accelerated Lifetime Testing

Manufacture

- Critical Nodes
- Reliability Monitoring Program (RMP)
- Quality: Supplier quality, incoming material QA, in-line and statistical process control, Out-of-the-Box Audit.

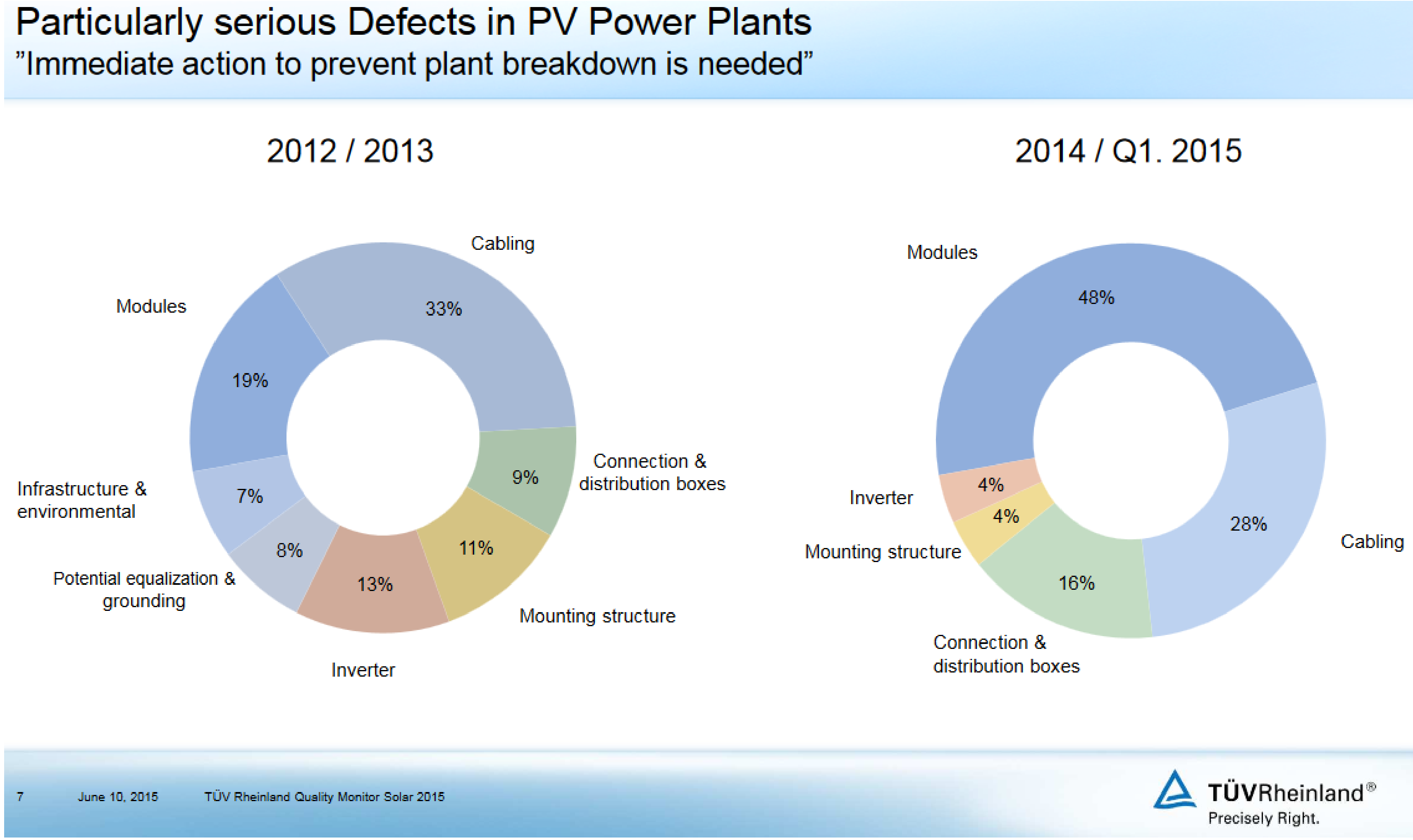
Go to market

- Third Party Certification
- Warranty design
- Competitive differentiation
- Bankability

Closed-Loop Learning

- Field Monitoring
- Site Inspection
- RMA Monitoring
- Pro-active site inspection and Failure Analysis

TUV Study: Modules can be a large % of "particularly serious" defects in PV power plants



[1] "Quality Monitor 2015" by TÜV Rheinland, June 10, 2015, accessed 3/23/2017. http://www.tuv-e3.com/fileadmin/user_upload/Downloads/2015-Quality_Monitor_Solar_16_9.pdf

Field Findings

2016 Study (partial list of Failure Modes)	c-Si type 1	c-Si type 2	SunPower	Comments
Backsheet yellowing	~35%	0	0	Indicative of mfr lack of understanding of failure physics and/or test methods
Snail trails	~2%	0	0	
Hotspot + backsheet bubble	0.28%	0	0	Variation indicative of quality control processes. SolarBuyer 2015 study[2] found poor correlation between quality control and manufacturer size
Faulty bypass diode	0.05%	0	0.05%	SunPower cells have low reverse bias voltage, which gives low temperature in reverse bias. A failed bypass diode is not critical for SunPower[3,4]

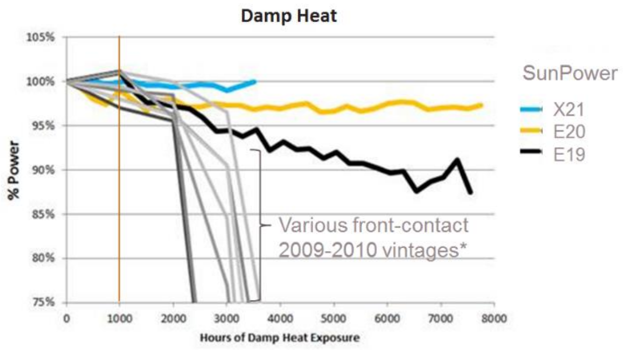
NREL STUDY [1]	Moderate		Hot and humid		Desert	
Years of field exposure	0-10	11-20	0-10	11-20	0-10	11-20
Number of reports	21	6	14	4	13	9
Number of modules	457	1626	2718	170	1451	4103
Encapsulant discoloration	0	0	9.9%	100%	3.3%	23.2%
Major delamination	0	46.7%	0	57.6%	0.3%	2.2%
Internal circuitry discoloration / resistance increase	4%	0.6%	9.9%	1.5%	2.8%	19.5%
Internal circuitry failure	0	0	0.9%	0	0.6%	2.2%
Hot spots	11.7%	0.1%	26.1%	2.9%	1.1%	5.2%
Fractured cells	0.5%	0.1%	5%	10.6%	1.7%	1.9%
Diode / JBox	0	0	21.7%	0	0.1%	0.7%
Potential induced degradation	9.7%	0	0.2%	0	0	0

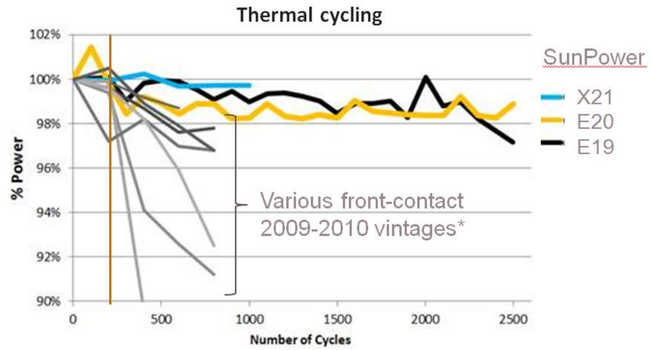
Variation due to climate variations can be significant too

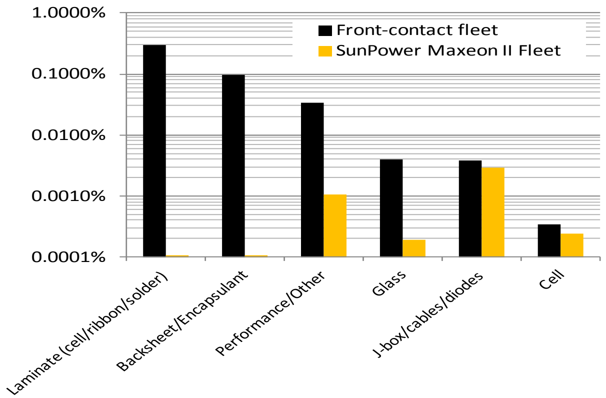
[1] D. Jordan, et al., “Photovoltaic failure and degradation modes”, *Prog. Photovot: Res. Appl.* (2017) DOI: 10.1002/pip 2866
[2] I. Gregory, Photovoltaic Module Reliability Workshop, Feb 24-27, 2015 Golden Colorado.
[3] E. Kam-Lum et al., “Effects of Solar Cell Reverse-Bias Voltage on PV Module’s Partial Shade Performance”, PV Module Reliability Workshop 2016
[4] A. Brooks et al, “PV System Power Loss and Module Damage Due to Partial Shade and Bypass Diode Failure Depend on Cell Behavior in Reverse Bias”, IEEE PVSC 2015.

SunPower Reliability Performance

- SunPower's IBC panels have lower field degradation and failure rates than conventional panels, validated by both accelerated testing and field performance.
- Superior reliability is the result of specific design and materials choices:
  - **Unique architecture** provides uniform current density in reverse bias – no hot spots.
  - **Thick backside metal** reduces cell cracking; high finger density harvests power even when cracking does occur.
  - **No front surface metal** = no corrosion
  - **Engineered strain relief** in interconnects
  - **Superior materials** for encapsulant and backsheet

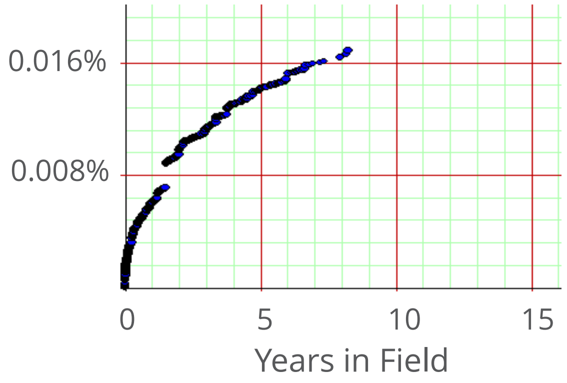






SunPower E19, E20, X-series Panels

Post-commissioning Warranty RMA Rates*



>$30M of reliability R&D invested our product … and many times that in product development, qualification and validation

* Based on 18M modules, Includes all customer-initiated warranty returns. Excludes cosmetic and any customer satisfaction returns initiated by SunPower.

Higher areas of interest due to trends in the industry

Area of Interest	Trend	Comments
Electrically Conductive Adhesives (ECA)	New applications in tiled-cell-interconnects and standard ribbon stringing	ECAs are used in many long-life applications, but limited experience in PV. Improved PoF models would decrease risk and allow additional types of ECAs to be used.
Backsheet Adhesion	Increased use of monolithic back sheets	Improved understanding of contributors to change in adhesion over time should lead to improved AESTs. Can be a complex problem because new back sheets offer a range of quality and adhesion properties
AR glass	The vast majority of modules now have AR glass	For residential, aesthetics is important but there has not been a lot of work on it (e.g., change in off-angle appearance with time). There has been work done on the interaction of AR glass properties with soiling type, but additional work would be useful.
Glass/glass modules	More producers and more volume	Evolution of environment within a glass/glass panel with modern materials may be high value. Some producers using glass/glass as justification for 30 year warranty, even though some use EVA (e.g., Trina).
Polymer Front Sheet	New applications for flexible and lightweight panels	Improved understanding of degradation, including with new materials, would be useful to some companies.

Other areas

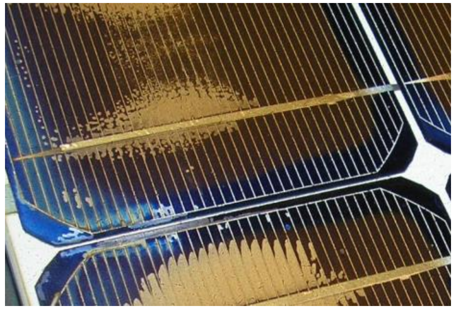
The following mechanisms continue to show up as large percentages of module failure on system level surveys. However they are not as obviously suitable for academic research.

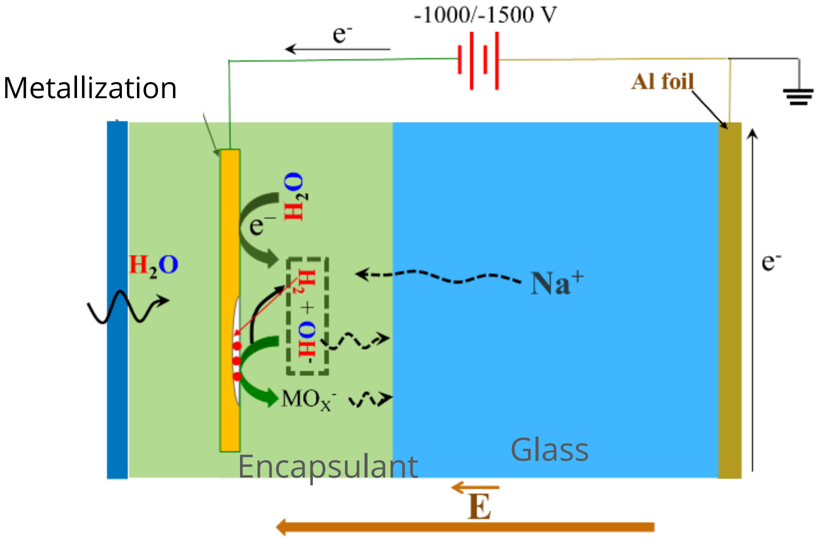
Area of Interest	Trend	Comments
Electrochemical Corrosion	Modern encapsulation materials decrease impact and risk, but still an important failure mode for some cell-module combinations	Changes in cell processing and encapsulation approach can increase or decrease the risk, so improved understanding of PoF (especially interactions) still useful.
Solder Joint Failure	Still a common failure mode in some modules	Consensus that 25 years is more likely represented by >500 (and possibly 800+) Thermal Cycles depending on environment
Hot Spots	Appears to be an increasing problems for front-contact cells	Some modules can have severe problems, with temperatures high enough to burn the backsheet
Potential Induced Degradation (PID)	Modern encapsulation materials and cell treatments are decreasing the problem	A lot of work around the world – would be difficult to contribute much.
Diode & Junction Box Failures	Can be severe, but frequency not likely increasing (except in extremely price sensitive markets such as India)	Persistent problem that must be improved by design changes and diodes or bypass controlling schemes – but may not be suited to DURAMAT resources.
EVA browning	The percentage of modules that use EVA is decreasing	The physics of EVA browning are understood.
Cables, other parts		Mechanisms are largely understood. Problems are generally the result of use of inferior materials.

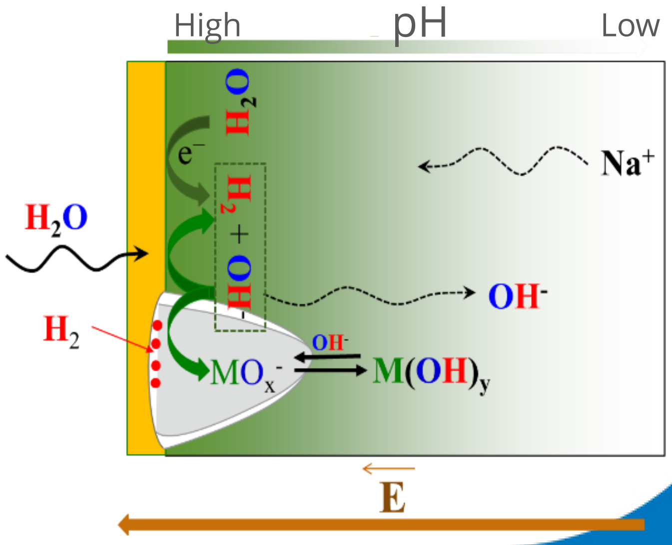
Predicts II: Electrolytic Corrosion

Jichao Li, Yu-Chen Shen, Kat Han, Mike Kempe (NREL), Peter Hacke (NREL)

- When under bias, a leakage current pass between the frame to/from the cell
- Water diffuses to the metallization; at a negatively-biased cell that water undergoes a reduction reaction with by-products H_2 and OH^-.
- Basic conditions can lead to corrosion and delamination.
- Preliminary values of activation energies and humidity dependencies have been measured; “total accumulated charge” appears to correlate time to failure.







Closing Remarks

- Government laboratories and Academia can not solve quality problems but they can contribute significantly to the improvements in the area of reliability.
- There are plenty of opportunities for DuraMAT to contribute to the improvement of PoF models, accelerated testing, and the understanding of field failures.

Thank You

Let’s change the way our world is powered.

Partial List SunPower Reliability Publications

R.A. Sinton, and A. Cuevas, "A Quasi-Steady-State OpenCircuit Voltage Method for Solar Cell Characterization," 16th European Photovoltaic Solar Energy Conference, Glasgow, May 1-5, 2000.

W. Mulligan, D. Rose, M. Cudzinovic, D. DeCeuster, K. McIntosh, D. Smith, and R. Swanson, "Manufacture of Solar Cells with 21% Efficiency," Proc. 19th European Photovoltaic Solar Energy Conference, Paris, 7-11 June, 2004.

W. Durisch, J. Mayor, K. Lam and J. Close, "Efficiency of SunPower's SPR-90 Module and Output at a Sunny Site in Jordan," Proc. 20th European Photovoltaic Solar Energy Conference and Exhibition, Barcelona, June 6-10, 2005.

D. Rose, S. Daroczi, "Development and Manufacture of Reliable PV Modules with > 17% Efficiency," Proceedings of the 20th European Photovoltaic Solar Energy Conference, Barcelona, Spain (2005).

R. Swanson, M. Cudzinovic, D. Deceuster, V. Desai, J. Jürgens, N. Kaminar, W. Mulligan, D. Rose, D. Smith, A. Terao, K. Wilson, S. Corporation, and I. Way, "The Surface Polarization Effect In High-Efficiency Silicon Solar Cells," in IEEE Photovoltaic Specialists Conference, 15th, 2005, pp. 1–4.

R. Swanson, D. DeCeuster, V. Desai, D. Rose, D. H. Smith, and N. Kaminar, "Preventing Harmful Polarization of solar Cells," 7,554,031 B22009.

Y. Meydbray, K. Wilson, E. Brambila, A. Terao, S. Daroczi , "Solder Joint Degradation in High Efficiency All Back Contact Solar Cells," Proceedings of the 22th European Photovoltaic Solar Energy Conference, Milan, Italy (2007).

D. Degraaff, S. Caldwell, R. Lacerda, G. Buena, A. Terao, and D. Rose, "Qualification, Manufacturing, and Reliability Testing Methodologies for Deploying High-Reliability Solar Modules," in European Photovoltaic Solar Energy Conference and Exhibition, 25th, 2010.

M. Mikofski, M. Anderson, S. Caldwell, D. DeGraaff, E. Hasselbrink, D. Kavulak, R. Lacerda, D. Okawa, Y.C. Shen, A. Tedjasaputra, A. Terao and Z. Xie, "A dynamic cell-by-cell PV system model to predict lifetime performance and reliability," 26th European Photovoltaic Solar Energy Conference and Exhibition, pp. 105-112, 2011.

G. Bunea, N. Boitnott, D. Kim, E. Gacho, L. Abra, O. Koehler, J. Peurach, "High Volume Production of 20% Efficiency Polarization Free Modules," 26th European Photovoltaic Solar Energy Conference and Exhibition, pp. 3165-3168, 2011.

L. Abra, S. B. Rim, S. D. Kim, S. Corporation, S. Jose, and U. States, "Temperature of Solder Contact in Back-Contact Si Solar Cells and Its Effect on Reliability of Modules under Localized Shading Environments," in IEEE Photovoltaic Specialists Conference, 38th, 2012, no. 1.

M. A. Mikofski, D. F. J. Kavulak, D. Okawa, Y. Shen, A. Terao, M. Anderson, S. Caldwell, D. Kim, N. Boitnott, J. Castro, L. Ann, L. Smith, R. Lacerda, D. Benjamin, and E. Hasselbrink, "PVLife : An Integrated Model for Predicting PV Performance Degradation over 25 + Years," in IEEE Photovoltaic Specialists Conference, 38th, 2012, no. 3, pp. 1744–1749.

E. Hasselbrink, M. Anderson, Z. Defreitas, M. Mikofski, Y.-C. Shen, S. Caldwell, A. Terao, D. Kavulak, Z. Campeau, and D. DeGraaff, "Validation of the PVLife Model Against 3 Million ModuleYears of Live Site Data," in IEEE Photovoltaic Specialists Conference, 39th, 2013.

M. Anderson and Z. Defreitas, "A SunPower Fleet-Wide System Degradation Study using Year-over-Year Performance Index Analysis," 2012.

E. F. C. Hasselbrink, D. Ph, C. Mark, D. F. J. Kavulak, D. Okawa, Y. Shen, A. Terao, M. Anderson, W. Caldwell, D. Kim, N. Boitnott, L. Ann, L. Smith, and R. Lacerda, "Module Lifetime Prediction through Integrated Modeling of Known Failure Modes," in PV Module Reliability Workshop, 2012, pp. 1–18.