A Framework for a Comparative Accelerated Testing Standard for PV Modules

Preprint

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Abstract — **As the photovoltaic industry has grown, the interest in comparative accelerated testing has also grown. Private test labs offer testing services that apply greater stress than the standard qualification tests as tools for differentiating products and for gaining increased confidence in long-term PV investments. While the value of a single international standard for comparative accelerated testing is widely acknowledged, the development of a consensus is difficult. This paper strives to identify a technical basis for a comparative standard.**

Index Terms — **photovoltaic modules, accelerated testing, service lifetime, wear-out mechanisms, field failures.**

I. INTRODUCTION

Since 2009, the prices of photovoltaic modules have fallen by almost a factor of three [1], putting pressure on manufacturers to develop lower cost products or to justify a higher selling price. As customers wish to gain confidence in the long-term performance of PV modules and to differentiate those products that will last longer, the interest in differentiation of products through more thorough, accelerated testing has increased. Building on the definition proposed by TamizhMani and Kuitche [2], we define "comparative" tests as accelerated tests that differentiate products according to their long-term durability in the field for a specific use environment (Table I). In contrast, qualification tests identify design flaws that lead to early failures; lifetime tests predict service life in the desired location and application. While lifetime prediction is desired, we do not currently have enough information about PV module reliability to define a service-life prediction test.

Many test laboratories now offer comparative accelerated testing, as summarized in Table II. These test programs generally apply the same tests as the qualification tests, but apply them for a longer duration or combine existing tests in a test sequence. The primary themes we observed in a review of this collection of tests include 1) extended-duration, 2) sequential tests, 3) quantification of module condition after each test, 4) additional measurements (e.g., electroluminescence), and 5) addition of voltage bias during damp heat.

TABLE I. THREE TYPES OF ACCELERATED TESTS [2]

	Qualification	Comparative	Lifetime
Purpose	Minimum design requirement	Comparison of products	Substantiation of warranty
Quantification	Pass/fail	Relative	Absolute
Climate or Application (Mounting)	Not differentiated	Differentiated	Differentiated

TABLE II. ACCELERATED TEST PROGRAMS

DH: Damp heat, TC: Thermal cycling, DML: Dynamic mechanical load, DHWB: Damp heat with bias, HF: Humidity freeze, HS: Hot spot.

Program Name	Extra Test Sequences*	Key Features	Test Length (Months)**
Holistic QA [3,4]	DH, TC, DML	Extended 61215	~4
Thresher [5]	DHWB, TC, HF	Document degradation after each test cycle	~6
Reliability Demonstration [6]	DHWB, HS	Comprehensive	~6
Durability Initiative [7]	DHWB, Outdoor, UV, HS, DML, TC	Durability assessment	~6+
Test to Failure [8,9]	DHWB, TC	Test to failure	>12
Long-Term Sequential [10]	UV, DH, TC, HF	Sequential (pass-fail)	~12+
PV+Test [11]	DHWB, TC, ML	Assign rating	~4
Weather [12,13]	Multiple***	Simulates weather	~12

* Beyond IEC 61215 or IEC 61646 test sequences
** A "+" indicates additional testing in the field
*** Not based on IEC 61215/61646 test sequences

There are few data directly indicating the value of these longer tests for predicting field performance. The comparison of accelerated test results with field data is challenging because of the different time scales. However, early PV systems have now been in the field for > 30 years, and each year more data become available from veteran systems [14].

The current qualification tests [15-17] have the stated scopes: to show "that the module is capable of withstanding prolonged [or long-term] exposure in…general open-air climates." These standards do not quantify the meaning of the terms "long-term" and "prolonged," but IEC 60721-2-1 defines the "general" climate, providing a basis for further standards.

This paper briefly summarizes what is known about correlations between field and accelerated testing, and uses this information to formulate recommendations for a comparative accelerated test standard. We start by reviewing what was learned from a somewhat similar effort more than 30 years ago, and then review newer field data to provide a basis for the types of mechanisms that need to be prioritized. Based on this prioritization and on principles the community agrees upon, a rating system for a comparative accelerated test standard is proposed as a starting point for standards that will evolve toward better meeting the needs of the community. The intent of this paper is to introduce a rating system built on objective technical evidence and reasons and input from stakeholders. Examples are shown of how the rating system can be communicated with differing levels of detail for the various stakeholders.

II. LEARNING FROM HISTORY

In the late 1970s, the Jet Propulsion Lab (JPL) executed a series of block buys of PV modules that passed successively harsher accelerated tests [18-23]. A dramatic reduction in early failures occurred between Block IV and Block V [18,24]. The primary differences between these tests are highlighted in bold in Table III [21-23] and included:

- Increase in the number of thermal cycles
- More stressful humidity freeze test
- Addition of a hot-spot test.

TABLE III. COMPARISON OF JPL BLOCKS IV AND V TESTS

Test	**Block IV**	**Block V**
Thermal Cycling	50 cycles (-40 to +90°C)	**200** cycles (-40 to +90°C)
Humidity (Freeze)	5 cycles 54°C/90%RH to -23°C	**10** cycles **85°C**/85%RH to **-40**°C
Hot Spots	**None**	3 cells, 100 h
Mechanical Load	10,000 cycles, ± 2400 Pa	10,000 cycles, ± 2400 Pa
Hail	9 impacts 20 mm @ 20 m/s	10 impacts 25 mm @ 23 m/s
High Pot	< 50 μA @ 1500 V	< 50 μA @ 2*Vs+1000
Reported Field Failures	> 50% [24]	~ 1% [24]

The thermal-cycling test queries mechanical fatigue, which is the mechanism that causes failures of interconnect ribbons, solder bonds, and multiple other interfaces. A hard freeze after exposure to high humidity causes the expansion of water as it freezes, stressing interfaces and promoting delamination; the Block V version of the Humidity (Freeze) test caused more stress than the Block IV version. The hot-spot test motivated manufacturers to use bypass diodes, which protect the modules during cell mismatch caused by partial shading or cell damage. These three changes helped to avoid important design flaws, decreasing failure rates. It is notable that the 1000-h damp heat test that is viewed as a critical element of today's qualification test was not included in Block V testing. Nevertheless, the changes between the Block IV and Block V tests dramatically improved the test's ability to identify infant mortality [18,24]. This experience may be useful toward developing comparative tests.

III. IDENTIFICATION OF FAILURES OBSERVED TODAY

A. Field Data Summary

Field experience with PV is increasing exponentially with the recent corresponding increased production volume. Although information is often lacking about the testing used to qualify a design and about the manufacturing quality control, researchers have assembled some statistical data (Table IV) indicating an opportunity for improvement: we strive to identify tests that will avoid these failures in the future.

TABLE IV. SUMMARY OF SELECTED FIELD STUDIES

Observation	Sample Size	Reference
Laminate internal electrical circuit 36% of failures (~2% of modules failed after 8 years); glass 33%; j-box and cables 12%; cells 10%; encapsulant and backsheet 8%	21 manufacturers; ~60% of fleet of > 1.5 GW	DeGraaff [25]
16% of systems required replacement of some or all modules because of a variety of failures, with many showing breaks in the electrical circuitry	483 systems	Kato [26,27]
3% developed hot spot after < 7 years; 47% had non-working diodes	1232-module system	Kato [26,27]
External wiring shattered, failed	~70,000 modules	Rosenthal [24]
Early degradation linked to optical transmission losses (through glass and encapsulant) and light-induced degradation; later degradation is more from increased series resistance	204 modules from 20 manufacturers	Skoczek [28]
Encapsulant discoloration 66%; delamination 60%; corrosion 26%; glass breakage 23%; j-box 20%; broken cells 15%*	~2000 reports	Jordan [29]
200 thermal cycles corresponded to ~10 years in the field	> 10 years of manufacturing	Wohlgemuth [30,31]

* Fraction of papers reported these visual defects

DeGraaff summarized data from SunPower's > 1.5 GW of installations, including PV modules from 21 manufacturers [25]. The most common failure type involved failed solder bonds or other internal electrical interconnection issues. Delamination of the anti-reflective coating on the glass was the second most common failure. About 12% of the failures were related to the junction boxes or cabling, often causing arcing that could lead to fires.

Kato [26,27] reported the need for replacement of modules after 5-12 years in ~16% of systems studied, with most of those cases showing electrical failures (interconnects or bypass diode failures). Rosenthal reported on Block IV and V modules, some of which were in the field, for a full 10 years [24] with minimal (< 1.3%) failures, implying that 200 cycles of thermal cycling may be adequate for a 10-year lifetime. Jordan's literature review [29] showed that discoloration and delamination were most frequently reported; corrosion, glass breakage, cell breakage, and many other problems were also observed.

Four themes from the data in Table IV are:

1. Degradation or safety issues caused by failure of cell interconnects, solder bonds, or the bypass diodes that protect in case of shading.
2. Early degradation in the short-circuit current related to light-induced degradation and changes in transmittance associated with changes in anti-reflection coatings, encapsulation discoloration, and delamination.
3. Corrosion (often associated with delamination).
4. Junction-box failures.

Reports of early failures from manufacturing defects and/or potential-induced degradation motivate improvements in quality control and improved qualification testing. These issues are being addressed by Task Group 1 of the International Quality Assurance Task Force and the IEC Technical Committee 82 (TC82), Working Group 2 (WG2), respectively. Glass and cell breakage are also frequently reported, meriting prioritization if resources can be found to address these. It could be argued that glass breakage should be prioritized above corrosion based on Table IV, but as PV markets move into more tropical areas, corrosion may become more apparent, increasing its priority.

B. Evidence of Value of Extended Testing

Correlation of field failures reported in historical studies with accelerated testing provides a basis for proposing a new test standard. According to the studies of Wohlgemuth [30], ~500 thermal cycles are needed to screen for 25-year lifetime in the field for thermal-fatigue type failures, motivating an increase in the number of thermal cycles from 200 to 500. The value of dynamic mechanical loading before applying thermal cycling has also been demonstrated [32].

As indicated in Table IV, discoloration and delamination of encapsulants are frequently reported to contribute to module degradation. The current qualification tests apply only a few months equivalent of field UV (less than 3 months in sunny locations), which is grossly inadequate for exploring the effects of long-term UV exposure. Longer UV exposure has been shown to correlate with improved durability [33]. A test developed by STR and successfully used as a guide for selecting ethylene-vinyl acetate (EVA) formulations would provide a rapidly implementable improvement [33].

Jordan's summary of ~2000 studies found that 26% reported corrosion. To our knowledge, the community has not identified an improved corrosion test to be implemented in the near term. A number of reports have suggested that extending damp-heat testing beyond 1000 h (e.g., to 1250 h) uncovers failures that are observed in the field [30,34,35].

Thus, based on correlations between accelerated and field testing, we conclude that harsher stress tests for thermal fatigue, UV exposure, and corrosion can identify designs that last longer in the field. In addition, the large number of diode failures reported for a few systems [26,27] and the frequent reporting of junction-box issues motivate additional testing.

Using existing publications, it may be possible to quickly define new tests for:

- Thermal fatigue (additional cycles or combined tests)
- Dynamic mechanical load*
- Encapsulant discoloration (e.g., STR test)
- Corrosion
- Junction box detachment
- Bypass diode (extended test)
- Extended hot-spot test
- Potential-induced degradation.*

* Drafts of these tests have been submitted to WG2 of TC82.

Standardizing test methods that have proven to be useful to manufacturers during the product-development phase is a wise strategy for quickly bringing benefit to the community and can form a starting point for defining comparative test sequences.

IV. PROPOSAL FOR CREATION OF COMPARATIVE RATING SYSTEM

The complexity of relating the results of multiple accelerated tests to a multitude of use conditions challenges us to construct a comparative rating system that: 1) requires an acceptable testing time, 2) is easy to understand and use, and 3) still retains enough information to correlate with field experience as a function of climate/application. We next discuss guiding principles that apply to the creation of the tests and a rating system, and then propose the system and how to communicate it to the various stakeholders.

A. Guiding Principles

Although defining the test sequences and the rating system is highly controversial, the guiding principles for the tests and rating system are more generally accepted. They must:

- Aim to differentiate products according to their durability for the desired deployment conditions.
- Be relevant (give confidence in warranty period).
- Be carried out within a reasonable timeframe making it applicable for industrial and commercial use.
- Have acceptable cost.
- Be communicated in useful ways (both simple and detailed for different audiences).

TABLE V. CLIMATES PROPOSED FOR RATING SYSTEM

	New Tests Will Require Additional Stress	Differentiation of Durability		
IEC 60721-2-1 Climate Designation	**Proposed Changes**	**C**	**B**	**A**
Moderate	Tests listed in section III B	Comparable to qualification test	Better than qualification test	Most durable
Warm Damp, Equable	Tests for delamination & moisture ingress in humid climates	Comparable to qualification test	Better than qualification test	Most durable
Extremely Warm Dry	Tests for higher temperatures	Comparable to qualification test	Better than qualification test	Most durable

- Include options to accommodate design and material differences.
- Be designed to learn from the results and be dynamically updated, when required (its application will help to improve the standard).
- Specify that when there is insufficient information to evaluate the usefulness of a proposed test, we will estimate and communicate the uncertainty.
- Define clear responsibility and accountability for communicating the ratings to consumers.

In general, basic qualification tests duration should be ~ 3 months or less if they are used as a basis for entering the market. However, we expect that meaningful comparative tests may require more than 3 months.

B. Proposal of Rating Categories Related to Climate

We propose a comparative rating system based on three climate zones (Table V) according to IEC 60721-2-1:

- Moderate
- Warm damp, equable
- Extremely warm dry.

These might also be labeled as temperate, tropical (or hot-humid), and desert (or hot-dry).

Additionally, just as a module is tested according to its system voltage, the rating is made in the context of a module intended to be deployed in an open-rack or roof-mount configuration. Depending on the classification of the mounting configuration, the test conditions will be adjusted.

C. Additional Stresses Included in Rating System

For a rating system to have predictive value, it must encompass all primary failure modes and all associated stresses. We propose a comprehensive rating system that considers all stresses including:

- UV, temperature, and humidity experienced in locations associated with the climate definitions in IEC 60721-2-1
- Temperature variability (thermal cycling)
- Salt spray
- System voltage with specified bias polarity and in conjunction with temperature and humidity
- Mechanical damage caused by snow
- Mechanical damage caused by wind
- Hail
- Ammonia.

D. Differentiation of Durability

A primary goal of the new rating system is to differentiate products according to their durability. Given that we do not yet fully understand what differentiation is useful, we propose that within each climate rating, an A, B, or C rating may be ascribed (as described in Table V). As the accelerated test procedures are defined, the A, B, and C ratings will be defined either because the tests are completed at a higher level of stress or because the module retained a higher performance/safety rating after completion of the stress test.

The meanings of other stresses may be defined more quantitatively, as in the case of hail testing in which the size and velocity of the ice balls are specified. There is a need to more effectively communicate the meanings of the snow, wind, and other tests, as indicated in Table VI.

The proposed rating system will provide a means for comparing the expected durability of new products and will help customers to gain confidence in their upfront investments for each use environment. Confidence in long-term investments is becoming increasingly important as incentive programs are scaled back [36]. The continued growth of the industry relies on confidence that the products will last for the full warranty period; a comparative test standard is the first step toward assessing durability commensurate with the warranty.

TABLE VI. OTHER STRESSES

Stress	Existing test	Comment
Snow	IEC 61215 or 61646, 10.16 mechanical load test	Test is not currently effective at identifying some types of damage
Wind	IEC 61215 or 61646, 10.16 mechanical load test	Test does not identify problems with uplift
Hail	IEC 61215 or 61646, 10.17 Hail test	Results could be more effectively communicated
Salt	IEC 61701 Salt mist	Results could be more effectively communicated
Ammonia	IEC 62715 Ammonia test	Results could be more effectively communicated

E. Creation of Test Protocols

The test protocols used as the basis for the rating system will be developed by careful scientific evaluation of failures that have been observed in the field and how these have been successfully duplicated in accelerated tests. Whenever possible, rate equations and related simulations will elucidate the meanings of the tests. We anticipate that the test protocols will use combinations of stresses. As more understanding is gained, the tests will be updated.

F. Three Ways to Communicate Rating System

The ratings proposed using Tables V and VI must be communicated to:

- Customers who want an in-depth analysis for a large purchase of modules
- Customers who want to quickly screen a large number of modules and/or who desire a high-level summary without in-depth analysis (e.g., for a small purchase)
- Future researchers or insurance companies who want to correlate the rating tests with field experience for lifetime prediction.

To address the needs of all users, we recommend communicating the test results in three ways (Table VII).

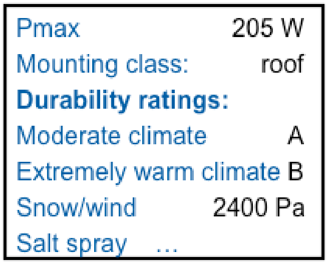
TABLE VII. PROPOSED COMMUNICATION OF RATINGS

Communication Vehicle	Purpose	Defined by Standard?
Test Report	Provide details for in-depth analysis	Yes
Nameplate	Screening of many modules; easy to understand; high-level summary to correlate with field performance	Yes
Maps, Tables, or Graphs	Interpret meaning of test for each location	No

For customers wishing to do an in-depth analysis, a test report should be defined in the standard, including the data that were measured at each stage of the testing.

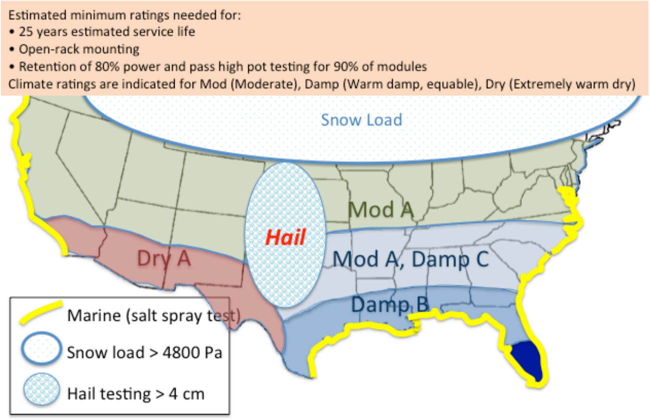
For customers seeking a high level summary, a rating should be derived from the complicated test results using a formula constructed by the tests' authors. For purposes of illustration, we suggest that an A, B, or C be assigned, as indicated in Table V. To aid future researchers, a high-level summary will be required on the name plate for easy reference when field results are studied decades from now (Fig. 1). At the manufacturer's discretion, test results can also be included in marketing information (e.g., datasheets).

Finally, the meaning of the rating can be summarized in maps, tables, or graphs as research projects outside of the test standard, to the extent that the information is available. These visual aids could indicate the number of years of service life expected for a product in a specified use environment. More generally, a map could show the recommended minimum rating needed for a desired lifetime and application (e.g., rack mounting) as shown in Fig. 2 or similar information could be presented in a table for every location. The multiple stress ratings could be compared with the desired ratings for a specific location in a spider graph. In some regions, only one rating might be needed; in other regions, multiple requirements might apply, including ratings for hail, salt, etc. It may take many years to advance the understanding of the tests far enough to be able to create these maps, but the vision of how they could be used by the community can guide us as we create the rating system.



Pmax 205 W
Mounting class: roof
Durability ratings:
Moderate climate A
Extremely warm climate B
Snow/wind 2400 Pa
Salt spray …

Fig. 1. Example of how the new rating system could be communicated on a nameplate.



Estimated minimum ratings needed for:
• 25 years estimated service life
• Open-rack mounting
• Retention of 80% power and pass high pot testing for 90% of modules
Climate ratings are indicated for Mod (Moderate), Damp (Warm damp, equable), Dry (Extremely warm dry)

Fig. 2. Example map illustrating how the meaning of the ratings could be communicated once the information is available. Mod, Damp, and Dry refer to the climate zones indicated in Table V.

V. CONCLUSIONS

As a basis for creating comparative test standards, we note that there is evidence of benefit in adding harsher tests for:

- Thermal-fatigue (e.g., solder bond failures)
- UV-induced degradation
- Corrosion
- Diode and junction-box failures.

The effects of temperature and humidity can be assessed relative to three climate zones defined in IEC 60721-2-1:

- Moderate
- Extremely warm dry
- Warm damp, equable.

These should be assessed in the context of classification according to the mounting configuration:

- Open rack mounted
- Roof mounted.

We propose a comprehensive rating system that considers stress from wind, snow, salt, and hail in addition to the tests related to the temperature and humidity aspects of climate.

When creating these new tests, we must apply stresses in combinations to duplicate the types of failures seen in the field. The results of the comparative tests may be summarized with ratings A to C and communicated by:

- Detailed report
- Nameplate
- Interpretive maps, tables, or graphs.

In the future, we may correlate long-term performance with the comparative test results toward validating a service life prediction. In the meantime, this rating system will increase confidence in long-term performance and provide customers with a tool to differentiate products.

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REFERENCES

[1] D. Feldman, et al., "Photovoltaic (PV) Pricing Trends: Historical, Recent, and Near-Term Projections", National Renewable Energy Laboratory, DOE/GO-102012-3839, (2012).

[2] G. TamizhMani, and J. Kuitche, "A Literature Review and Analysis on: Accelerated Lifetime Testing of Photovoltaic Modules", Solar ABCs, (2013).

[3] B. Jaeckel, et al. "A New Standard for Holistic Quality Assurance." 26th European PVSEC, Hamburg, 2011 pp 3484-3490.

[4] D. Cunningham, B. Jaeckel, and A. Roth "A New Approach for Holistic PV Module Quality Assurance by Extended Stress Testing and Production Monitoring." PV Module Reliability Workshop, Golden, CO 2012.

[5] A. Funcell "'The Thresher Test' Crystalline Silicon Terrestrial Photovoltaic Modules Long Term Reliability and Degradation." PV Module Reliability Workshop, Golden, CO 2012.

[6] J. Meydbray "Reliability Demonstration Test." PV Module Reliability Workshop, Golden, CO 2012.

[7] [1] D.H. Meakin, et al. "Fraunhofer PV Durability Intiative for solar modules", Photovoltaics International, 20, 2013, p. 77.

[8] P. Hacke, et al. "Test-to-Failure of Crystalline Silicon Modules." 35th IEEE PVSC, Honolulu, pp. 244-250, 2010.

[9] P. Hacke, et al. "Application of the NREL Test-to-Failure Protocol for PV Modules", 19th Crystalline Silicon Workshop, Vail, CO 2009.

[10] G. TamizhMani "Long-Term Sequential Testing (LST) of PV Modules." PV Module Reliability Workshop, Golden, CO 2012.

[11] "Introducing "Best of modules" Quality assurance", PV Magazine, 2011, (02), 2011, pp. 92-107.

[12] K.P. Scott and A. Zielnik "Atlas 25plus - Long Term Durability Test for PV Modules." PV Module Reliability Workshop, Golden, CO 2012.

[13] A. Zielnik 'PV Durability and Reliability Issues', Photovoltaics World, Nov/Dec pp. 10-14, 2009.

[14] D. Jordan and S. Kurtz "Photovoltaic Degradation Rates—an Analytical Review", Prog.Photovolt:Res.Appl., 2013; **21** : 12-29.

[15] IEC 61215: "Crystalline silicon terrestrial photovoltaic (PV) modules - Design qualification and type approval," 2005.

[16] IEC 61646: "Thin film terrestrial photovoltaic (PV) modules - Design qualification and type approval," 2008.

[17] IEC 62108: "Concentrator photovoltaic (CPV) modules and assemblies - Design qualification and type approval," 2007.

[18] M. Whipple "The Performance of PV Systems", PV Performance and Reliability Workshop, Golden, CO 1993, p. 453.

[19] A. Hoffman and R. Ross "Environmental Qualification Testing of Terrestrial Solar Cell Modules." 13th IEEE PVSC, Washington DC, pp. 835-842, 1978.

[20] M. Smokler, D. Otth, and R. Ross "The Block Program Approach to Photovoltaic Module Development." 18th IEEE PVSC, Las Vegas, NV, pp. 1150-1157, 1985.

[21] R. Ross "FSA Engineering & Reliability Development Methods - Can They be Applied Today?", InterSolar, San Francisco, CA http://www2.jpl.nasa.gov/adv_tech/photovol/ppr_86-90/Ross_SEMI-VG_07-08-12.pdf, 2012.

[22] "Block V Solar Cell Module Design and Test Specification for Intermediate Load Applications", JPL, (1981).

[23] R. Ross, and M. Smokler, "Flat Plate Solar Array Project Final Report, Volume VI", JPL, (1986).

[24] A. Rosenthal, M. Thomas, and S. Durand "A Ten Year Review of Performance of Photovoltaic Systems." 23rd IEEE PVSC, pp. 1289-1291, 1993.

[25] D. Degraaff, R. Lacerda, and Z. Campeau "Degradation Mechanisms in Si Module Technologies Observed in the Field; Their Analysis and Statistics", PV Module Reliability Workshop, Golden, CO 2011.

[26] K. Kato "PVRessQ!: a research activity on reliability of PV systems from a user's viewpoint in Japan." SPIE, San Diego 2011, 81120K, doi:10.1117/12.896135.

[27] K. Kato "PVRessQ! PV Module Failures Observed in the Field", PV Module Reliability Workshop, Golden, CO 2012.

[28] A. Skoczek, T. Sample, and E. Dunlop "The Results of Performance Measurements of Field-aged Crystalline Silicon Photovoltaic Modules", Prog.Photovolt:Res.Appl, 17, 2009, pp. 227-240.

[29] D. Jordan, J. Wohlgemuth, and S. Kurtz "Technology and Climate Trends in PV Module Degradation." 27th European PVSEC, Frankfurt, Germany 2012, pp 3118 – 3124.

[30] J. Wohlgemuth, et al. "Using Accelerated Tests and Field Data to Predict Module Reliability and Lifetime." 23rd European PVSEC, Valencia, Spain, 2008, pp 2663 – 2669.

[31] J. Wohlgemuth, D. Cunningham, A. Nguyen, and J. Miller "Long Term Reliability of PV Modules." 20th European PVSEC, Barcelona, Spain, 2005, pp. 1942-1948.

[32] J. Wohlgemuth "The effect of cell thickness on module reliability", 33rd IEEE PVSC, San Diego, CA, 2008, paper 420.

[33] J. Wohlgemuth, M. Kempe, and D. Miller "Discoloration of PV Encapsulants." 39th PVSC, Tampa, FL, 2013.

[34] W. Eerenstein, et al. "Climate Chamber Test Results of MWT Back Contact Modules." 25th European PVSEC, Valencia, Spain, pp. 3854-3847, 2010.

[35] D. Degraaff, et al. "Qualification, Manufacturing, and Reliability Testing Methodologies for Deploying High-Reliability Solar Modules." 25th European PVSEC, Valencia, Spain, pp. 3722-3734, 2010.

[36] M. Bazilian, et al. "Reconsidering the economics of photovoltaic power", Renewable Energy, 53, (May), 2013, pp. 329-338.