Reliability Testing Beyond Qualification as a Key Component in Photovoltaic's Progress Toward Grid Parity

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Reliability Testing Beyond Qualification as a Key Component in Photovoltaic's Progress Toward Grid Parity

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***Abstract*— This paper discusses why it is necessary for new lower cost PV modules to be tested using a reliability test sequence that goes beyond the Qualification test sequence now utilized for modules. Today most PV modules are warranted for 25 years, but the Qualification Test Sequence does not test for 25-year life. There is no accepted test protocol to validate a 25-year lifetime. This paper recommends the use of long term accelerated testing to compare now designs directly with older designs that have achieved long lifetimes in outdoor exposure. If the new designs do as well or better than the older ones, then it is likely that they will survive an equivalent length of time in the field.**

Keywords-Photovoltaic module reliability, Reliability Testing, Qualification Testing, Levelized Cost of Electricity (LCOE), Grid Parity

I. INTRODUCTION

The photovoltaics market has been growing rapidly. Fig. 1 shows the annual growth rate in worldwide shipments of PV modules from 2004 to 2009 as reported by Navigant [1] and EPIA [2]. Over this timeframe (which includes the financial crisis of 2008) worldwide PV module shipments grew by an average of 50% per year. In late 2010 both SolarBuzz [3] and Renewable Energy World [4] are predicting that the total shipments for 2010 will be approximately 16 GW, which represents more than 100% growth over the 2009 volume.

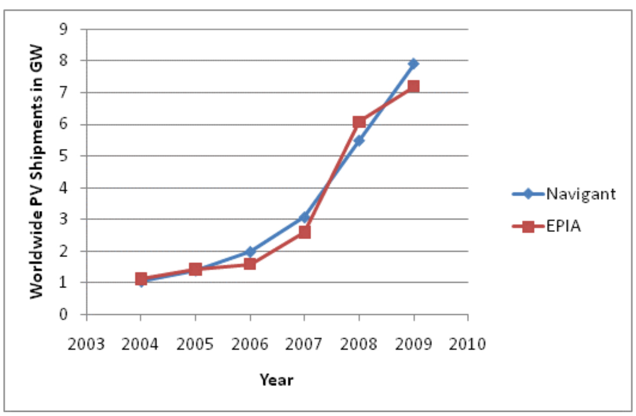

Figure 1: Annual Worldwide Shipments of PV Modules

Since the end of the poly-Si shortage in 2007-2008, the selling price of PV modules has decreased appreciably. SolarBuzz [3] estimated that the retail price of PV modules for residential applications dropped by 27% from late 2007 to late 2010. SEIA and a Lawrence Berkeley 2010 study of the PV industry gave similar estimates for PV module price reductions over this time period. So progress is being made in reducing the cost of PV modules.

Whether you look at the SolarBuzz module retail selling price of $3.50/Watt peak or at the SEIA average module selling price for large systems of $2.21/Wp, the cost of PV generated electricity is still higher than the utility costs in most parts of the US and the world. Using the System Advisor Model (SAM) [5] with a retail module cost of $3.50/Wp from SolarBuzz, an overall systems cost of $7.00/Wp and a module lifetime of 30 years installed in Phoenix, AZ yields a Levelized Cost of Electricity (LCOE) of $0.17/kWh with the 30% tax credit and $0.24/kWh without the tax credit. Neither of these costs can match the local utilities' residential electric rate. EIA reports that average retail electricity prices have been running about $0.12/kWh. [6] The rapid growth in PV shipments is being driven by incentive programs, particularly the feed-in-tariff programs in Germany and other European countries.

Lower module prices and lower system costs are required in order to reach grid parity and therefore stimulate dramatic growth in PV shipments without the need for incentive programs. Lower module manufacturing costs and selling prices must be achieved without adversely affecting the PV module reliability both in terms of overall module lifetime and in terms of continual performance degradation. Increases in the annual degradation rate will have a negative impact on the LCOE while an increase in premature module failures can potentially damage PV's reputation as a reliability electrical source.

So how can PV module manufacturers determine that the changes they make in design, materials and/or processes do not adversely affect the module reliability? They cannot wait 20 or 25 years to see what happens to the lower cost modules when they are deployed in the field. So they must utilize accelerated reliability tests to evaluate the potential for these lower cost modules to survive without increased degradation of output power. However there are no accelerated stress tests that we know of today that can show whether a module type will survive 25 years anywhere it is deployed.

This paper proposes a process that utilizes the past experience of a module type using both field and accelerated stress test results as a baseline for testing of a new module type. The new module type can then be evaluated against the older design using accelerated stress tests that go beyond those utilized in the Qualification Test Sequence. Comparison of the performance between the old and the new module types can give an excellent indication of how the new design is likely to perform outdoors compared with the previous design.

II. Qualification Testing

Qualification tests are a set of well-defined accelerated stress tests developed out of a reliability testing program. Qualification tests incorporate strict pass/fail criteria. Such tests are used by customers to qualify modules for purchase and by manufacturers as a means of demonstrating a degree of product reliability. Good examples of these tests are IEC 61215 [7] and IEC 61646 [8] for performance qualification and IEC 61730 – 1 and 2 [9] for safety qualification. These test sequences were developed based on the identification of field failure mechanisms.

A. Failure Modes

Identification of field failure modes has been ongoing since the JPL Block Procurement program in the 1970's and 1980's. [10] A list of major failure mechanisms for crystalline silicon modules is given in Table 1. [11, 12]

TABLE 1
Common Failure Modes for Crystalline Silicon Modules

Failure Modes
Broken Interconnects
Broken Cells
Corrosion
Delamination of Encapsulant
Encapsulant loss of Elasticity or Adhesion
Encapsulant Discoloration
Solder Bond Failure
Broken Glass
Hot Spots
Ground Faults
Junction Box Failures
Connection Failures
Structural Failures
Bypass Diode Failures
Open circuits leading to arcing

Several additional failure modes have been identified for thin film PV modules. These are given in Table 2.

TABLE 2
Common Failure Modes for Thin Film Modules

Technology	Failure Mode
Glass Superstrate Designs	Electrochemical corrosion of TCO
Integrated Modules	Shunts at the scribe lines
Any thin film	Loss of Interlayer Adhesion
Thin Films on Glass	Inadequate edge deletion

The next important step was the identification of accelerated stress tests that would duplicate these failure modes in a reasonable short amount of time. The initial steps in this work were undertaken by JPL in the Block Program [10, 13]. Table 3 provides a brief summary of the stress tests developed to address the identified failure modes. [14] The list in Table 3 was utilized to establish the initial qualification tests that grew into IEC 61215. [14]

TABLE 3
Accelerated Stress Tests for PV

Accelerated Stress	Failure Mode
Thermal Cycle	Broken Interconnect Broken Cell Solder Bond Failures Junction Box Adhesion Module Connection Open Circuits Open Circuits leading to Arcing
Damp Heat Exposure	Corrosion Delamination of Encapsulant Encapsulant loss of adhesion & elasticity Junction Box Adhesion Electrochemical corrosion of TCO Inadequate edge deletion
Humidity Freeze	Delamination of Encapsulant Junction Box Adhesion Inadequate edge deletion
UV Test	Delamination of Encapsulant Encapsulant loss of adhesion & elasticity Encapsulant Discoloration Ground Fault due to backsheet degradation
Mechanical Load	Broken Interconnect Broken Cell Solder Bond Failures Broken Glass Structural Failures
Dry and Wet Insulation Resistance	Delamination of Encapsulant Ground Faults Electrochemical corrosion of TCO Inadequate edge deletion
Hot Spot Test	Hot Spots Shunts at the scribe lines
Hail Test	Broken Cells Broken Glass
Bypass Diode Thermal Test	Bypass Diode Failures

B. IEC 61215 and IEC 61646 Qualification Tests

IEC 61215 and IEC 61646 include the following stress tests:

- 200 Thermal cycles from -40°C to +85°C with peak power current flow above room temperature.
- Damp heat exposure at 85°C and 85% relative humidity for 1000 hours.
- A combined leg of UV Preconditioning (15 $kwhm^{-2}$), 50 thermal cycles from -40°C to +85°C, and 10 humidity freeze cycles from +85℃, 85 % RH to -40℃.
- Wet leakage current test at the rated system voltage.
- Mechanical load test of 3 cycles of 2,400 Pa uniform load, applied for 1 hour to front and back surfaces in turn.
- Hail test with 25 mm diameter ice ball at 23 m· s -1, directed at 11 impact locations.
- A bypass diode thermal test, with one hour at short circuit current and 75 °C and one hour at 1.25 times short circuit current and 75 °C.

- Hot spot test with 3 lowest shunt resistance cells subjected to 1 hour exposure to 1000 $W \cdot m^{-2}$ irradiance in worst-case hot-spot condition and highest shunt cell subjected to 5 hours exposure to 1000 $W \cdot m^{-2}$ irradiance in worst-case hot-spot condition

While Qualification Tests like IEC 61215 and IEC 61646 are important and valuable, they have limitations because the stress levels are by design limited and the goal is to have most commercially available products capable of passing the test sequence. So passing the qualification test means the product has met a specific set of requirements but doesn't say anything about which product is better for long term performance. Most of today's commercial modules pass the qualification sequence with minimum change, meaning that they suffer almost no degradation in power output from the test sequence. This means that the Qualification test itself is not a good tool for determining whether a change in materials, processing or design is likely to reduce the module's lifetime or increase the annual degradation rate. However, the Qualification Test sequence can be utilized as a starting point for developing a methodology to evaluate the impact of new lower cost designs, materials and processes on the modules long term reliability.

III. RELIABILITY TESTING BEYOND QUALIFICATION

The testing required for evaluation of the impact of changes in module construction on the reliability, lifetime and degradation rate must address the observed failure modes and must cause degradation of the product.

A. Establishing Reliability Tests

Since the accelerated stress tests from the Qualification Tests are designed to address the identified field failure modes, these are a good starting point for developing reliability tests for evaluating the impact of changes to the product. How can the Qualification Tests be turned into reliability tests? The following methods may all contribute to the final test plan:

- Increase the test duration, for example do more thermal cycles or expose the modules to damp heat for a longer time.
- Use higher stress levels, but making sure that the higher stress levels don't cause failures that are not seen in the field.
- Combine stress, for example applying voltage to the module during damp heat.
- Utilize step stresses, where the initial stress starts with the stress level from the Qualification Test and increases until failures are seen. Once again care must be taken to insure that the failures seen are the same failure modes identified from field exposure.
- Evaluate new methods to accelerate the failure modes identified in the field, for example using the Dynamic Mechanical Load Test to accelerate cell breakage caused by wind-induced vibrations. [15]
- Use material or coupon tests in situations where it would be too expensive to test full modules. For example long term UV testing at high temperature to evaluate material discoloration and degradation is better performed on small coupons of the same cross-sectional construction as the module.

B. Measurement Tools

In the Qualification Tests pass/fail measurements include peak power at Standard Test Conditions (STC) and the dry and wet leakage currents. There are additional measurement tools that can be utilized to observe problems before they impact the power or leakage currents. The following measurement tools can be valuable tools to use for identifying failure modes before they are serious enough to cause measureable power loss.

- Visual inspection can be used to observe discoloration of encapsulant, corrosion of metals and delaminations.
- Infrared cameras show heat dissipation, so can be used to determine areas where collection of current has been disrupted (higher series resistance) or where current is flowing where it shouldn't (shunting). An IR camera can also be used to show whether the current path through a string of cells is intact and whether the module bypass diodes are carrying current during normal operation and during shaded operation.
- Electroluminescence looks at the Near IR light generated by carriers transitioning across the cell p-n junction. So electroluminescence can be utilized to see discontinuities in the junction such as cracks in the cell or breaks in the junction itself.
- Testing for adhesion of the package layers, the junction box and the frame.
- Dark I-V curves that can identify small changes in series and shunt resistance before they are large enough to change the light I-V curve.

C. Developing specific reliability tests for specific changes

The first step in this process is to understand which failure modes the proposed change is likely to impact. A guideline for this has been established by Working Group 2 – Modules of IEC Technical Committee TC-82 on PV. These guidelines have been published as an IECEE Decision Sheet [16]. It is now planned for them to be incoporated directly into the third editions of IEC 61215 and IEC 61646. Table 4 provides a summary of these guidelines. These guidelines are utilized to define what retests are necessary in order to maintain product certification under IEC 61215 or IEC 61646.

These guidelines for retest should be used as a starting point for the analysis described in Subsection A. So for example if the change involves the encapsulation system, the test sequences should be based on:

- UV/50 thermal cycles,/10 humidity freeze cycles,
- Damp heat, 1000 hours at 85°C/85% RH
- Hail impact, if not tempered glass, and
- Hot spot, if material composition changes.

So the question becomes "Do these tests need to be modified from the qualification test to assess the ability of the change to survive 25 years without impacting failure rate or degradation rate?" The answer to this question depends upon which test is under discussion. Finally we must decide whether additional tests could be helpful in assessing the ability of the new product to perform as well as the old product throughout the warranted lifetime.

TABLE 4

Guidelines for Retest Requirements for IEC 61215 and IEC 61646

Modifications To	Tests to Repeat
Cell Technology	200 Thermal Cycles 1000 hours of Damp Heat Hot Spot Mechanical Load (for reduction in cell thickness)
Encapsulation System	UV/TC 50/HF 10 1000 hours of Damp Heat Hail Impact (if not tempered glass superstrate) Hot Spot
Superstrate	UV/TC 50/HF 10 Mechanical Load Hail Impact 1000 hours of Damp Heat (if non-glass) Hot Spot (if non-glass) Outdoor Exposure
Increase in Module Size (> 20%)	200 Thermal Cycles Mechanical Load Hail Impact
Backsheet	UV/TC 50/HF 10 Robustness of Termination 1000 hours of Damp Heat Hail Impact (if substrate design) Mechanical Load (if mounting depends on backsheet)
Frame or Mounting Structure	Mechanical Load Outdoor Exposure (if plastic) UV/TC 50/HF 10 (if plastic) 1000 hours of Damp Heat (if adhesive used) 200 Thermal Cycles (if adhesive used)
Junction Box/Electrical Termination	TC 50/HF 10 Robustness of Termination 1000 hours of Damp Heat By-pass Diode Thermal Test (if diodes are in J-box)
Interconnection between Cells	200 Thermal Cycles 1000 hours of Damp Heat Hot Spot
Electrical Circuit	Hot Spot (if more cells per diode) By-pass Diode Thermal Test (if current level increases) 200 Thermal Cycles (if internal conductors behind cells)
Higher or lower output (by > 10%)	Hot Spot By-pass Diode Thermal Test (if higher)
By-pass Diode	By-pass Diode Thermal Test

D. Establish a Baseline

Since we do not have accelerated stress tests that can show that a module type will survive 25 years outdoors where ever it is deployed, a baseline must be established for the proposed reliability tests. This baseline can be established using modules with similar construction that have proven long term service life. These baseline modules must be of the same PV technology (i.e. crystalline silicon, CdTe, CIGS, etc.) and preferably have similar packaging (i.e. glass superstrate design or glass-glass construction). Baseline modules should then be tested through all of the accelerated stress tests proposed in Section E along with the new module type.

E. Proposed changes to Qualification Tests to assess long term reliability after a change in product design

In this section each of the accelerated stress tests from IEC 61215 /61646 will be discussed and recommendations made as to whether it is necessary to modify them in order to use them for assessing long term reliability of lower cost PV modules.

<u>Thermal cycling:</u> Two hundred (200) thermal cycles have been equated to 10 to 11 years of outdoor exposure via comparison to field data [17 and 18] and via modeling of weather data [19]. Therefore more thermal cycling stress is required to assess a 25 year lifetime. The thermal cycle stress can be increased by cycling faster, using a wider temperature cycle or using more cycles. Cycling faster is limited both by the test chamber capability and the need to avoid thermal shock. Cycling at the fastest rate allowed by IEC 61215 is probably the best compromise. Expanding the temperature range is possible but once again is limited by equipment capability and the potential to cause failures not seen in the field (phase changes at low temperature and polymer damage at higher temperatures. If the test chamber can achieve 90°C a small degree of acceleration can be achieved.

This leaves increasing the number of cycles as the best approach. If 200 cycles equals 10 years of field exposure then 500 cycles would represent 25 years [17 and 18]. If after 500 thermal cycles the control construction and the new, lower cost modules have similar power loss and do not exhibit detrimental changes (i.e. broken interconnects) then the two constructions should have similar field performance for failure modes caused by thermal cycling.

<u>Damp Heat:</u> The 85°C/85% relative humidity exposure is as accelerated as necessary. These conditions probably never happen in the real world as the modules tend to dry out at their highest temperatures, but absorb moisture at lower temperatures. It is difficult to judge what outdoor exposure the 1000 hour exposure at 85/85 represents. In a recent experiment 10 crystalline silicon modules qualified to IEC 61215 were exposed to 1250 hours of 85/85. Only 2 of the 10 types successfully passed the extended test. [18] On the other hand some glass-glass encapsulated modules can easily endure more than 2000 hours of damp heat exposure. So rather than specify a particular length of time, it seems appropriate to test the control technology and the new technology through enough hours of damp heat that both begin to lose some power (say to 90% of the original) in order to verify that the new

technology is no worse and has no additional failure modes than the old module technology it will replace.

UV/TC50/HF10: This sequence of tests is mainly a test for the package. If the module fails this test it indicates inadequate adhesion between layers or inadequate cure level in the encapsulant. It is not a lifetime test so typically does not need to be enhanced for reliability testing. So the recommendation is to test both the new module construction and the old module construction to the sequence defined in IEC 61215/61646, but with the addition of the Dynamic Mechanical Load Test discussed below.

Mechanical Load: In the test a specified (wind) load is applied to the front and the back of the modules 3 times. If the module is to be used in a snowy location the load is increased during the last front cycle. The wind load (2400 Pa) and snow load (5400 Pa) are average values from around the world. If modules are to be used in windy or snowy locations higher values should be tested. In addition, mechanical loading can cause cells (especially thin ones) to crack. Modules measured immediately after wind or snow loading may not have degraded power, but if these modules are thermal cycled (say 25 to 50 cycles) significant cell breakage will then cause power loss.

Hail Test: The hail test is only required for changes in non-tempered glass superstrate modules. In this case the test should be run as specified in IEC 61215/61646.

Bypass Diode Thermal Test: No change in this test is recommended for assessing long-term reliability. The bypass diodes will be stressed by the other accelerated tests (thermal cycle, damp heat, etc.) so it is extremely important to ensure that each diode is working correctly after completing the reliability test procedures. In addition, it is important to set up a production line test to ensure that each bypass diode has been installed correctly and is operational before the module is shipped to the customer.

Hot Spot Test: The Hot Spot test in IEC 61215 edition 2 is not a particularly good test. It will be modified in edition 3. In the meantime use the ASTM E 2481-06 Hot Spot Test. [20]

Other tests to consider in the assessment of new products:

Dynamic Mechanical Load Test: The only mechanical test in IEC 61215 is a static mechanical load test that is performed after the accelerated stress tests. A Dynamic Mechanical Load test followed by 50TC/10HF does a much better job of identifying modules with cells that are prone to breakage and would cause subsequent power loss. [15] There is an available DIN Standard (EN12211) that can be utilized for this test. [21] Ultimately it is likely that a similar dynamic mechanical load test (DML) will be incorporated into IEC 61215 as part of the sequence UV/DML/50TC/10HF.

Transportation Testing: PV modules are usually shipped to the installation site. If improperly packaged significant damage and power loss can occur during the shipment. Changes in module construction and/or changes in packaging design can influence this result. Use of a standard transportation test such as ISTA Procedure 3 [22] is recommended until an IEC PV transportation test can be completed.

UV Material Test: While IEC 61215 contains a UV test, this is only meant as a pre-screening test to address UV sensitive bonding issues. This test is not long enough to assess whether the polymeric materials utilized in a module are capable of surviving the UV exposure expected during the lifetime of the module. Long term UV exposure of full sized modules is difficult and expensive. Therefore most long-term UV exposures have been made on coupons with the same cross sectional construction as the modules to be evaluated. STR developed a long term UV exposure protocol during their work evaluating the causes of EVA yellowing. [23] BP Solar reported the use of a similar UV exposure protocol for 26 weeks to verify a 25-year lifetime. [24] A similar UV testing protocol should be used to evaluate any new polymeric material for use in a PV module. The material should be exposed to the UV within the standard package in which it will be used. Since there is no agreement between UV dose and years in the field, it would be best to perform the test with the new material side-by-side with the material it is to replace. The test should proceed for at least the proposed 26 weeks or until one or both of the materials begin to discolor or degrade. At that point a comparison between old and new material will indicate whether the new material will perform as well as that which it is to replace.

IV. CONCLUSIONS

A method for assessing the long term reliability and durability of new lower cost PV modules has been presented. Because the new approach compares the results of the accelerated testing with modules that have a known long lifetime, a new module type qualified through this procedure has a high likelihood of also surviving in the field. The recommendations given in this paper can serve as a guideline for the establishment of a specific program of reliability testing for each major cost reduction proposed. Use of this methodology will reduce the risk that a change made to reduce cost will have a major, negative impact on module lifetime or degradation rate.

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