A novel climate-specific field accelerated testing of PV modules

Preprint

Sai Tatapudi, Joseph Kuitche, GovindaSamy TamizhMani

2018 SPIE 10759, Optical Engineering + Applications
A Novel Climate-specific Field Accelerated Testing of PV Modules

Sai Tatapudi, Joseph Kuitche, GovindaSamy TamizhMani
Arizona State University Photovoltaic Reliability Lab (ASU-PRL), 7349 E Innovation Way South, Mesa, Arizona, USA 85212

ABSTRACT

Failure modes and degradation rates of PV modules in a specific climate are primarily dictated by the module design and field-specific climate stressors such as temperature, UV and humidity. To identify the long-term design issues and predict lifetime of PV modules, the plant owners, investors and researchers typically utilize long-term indoor accelerated tests such as extended/modified IEC 61215 tests. Though the indoor accelerated tests can appropriately be designed for the environmental stressors of a specific climate, several challenges are encountered and they include: capital and operating costs of multiple walk-in environmental and weathering chambers for commercial size modules; only statistically insignificant number of commercial modules can be tested at a time due to size limitation of the chambers, and; multiple climate-specific temperatures and multiple humidity profiles used in the long-term accelerated tests prevent performing conventional IEC 61215 test profiles inside the same chamber. All the above-mentioned challenges can be adequately addressed using a novel climate-specific field accelerated testing setup presented in this work. This test program has been designed specifically for the hot-dry desert climate where the environmental stressors are temperature and UV with little or no influence from humidity. This program can easily be modified for the other climatic conditions, e.g. test setup for a hot-humid condition can include temperature, UV and humidity. In the current outdoor accelerated test program for hot-dry desert climate, the temperature acceleration is achieved by inserting heavy thermal insulators on the backside of the modules and the UV acceleration at higher operating temperatures are achieved by using a V-trough solar concentrator on the thermally insulated PV modules installed on a 2-axis tracker. An acceleration factor of about 12-15 is expected depending on the activation energy of the climate-specific degradation mechanism, e.g. encapsulant browning and solder bond degradation.

Keywords: Accelerated testing, predict lifetime, climate-specific field accelerated testing

1 INTRODUCTION

Due to market pressure, the photovoltaic (PV) modules are sold at an incredibly low price of less than $0.32/watt. To get to this price level, most manufacturers utilize low cost encapsulant and backsheet materials. In addition, new transparent backsheets are being explored by the manufacturers to replace the back glass of bifacial glass/glass modules. All these new packaging materials need to be independently evaluated for long-term failure and degradation rate predictions using accelerated test methods. Conventionally, these accelerated tests are performed using indoor environmental and UV chambers. The indoor environmental chambers are very expensive to own, maintain and operate. Moreover, these chambers can accommodate only very limited number of commercial modules (less than 10) for each of the required accelerated stress tests. In this paper, we propose to reduce the accelerated testing costs by using low-cost outdoor accelerated test setups and by accommodating large number of test modules, which would require only some additional racking materials and outdoor test space. This paper presents an inexpensive, real-time, outdoor accelerated test setup to perform long-term reliability tests of PV modules.

1.1 Challenges of Indoor Accelerated Test Methods

The accelerated tests of PV modules are traditionally performed using indoor environmental and UV chambers. The indoor environmental chambers are very expensive to own, maintain and operate. Moreover, these chambers can accommodate only very limited number of commercial size modules for each of the required accelerated stress tests. To provide an objective evidence on the cost and sample limitation of indoor environmental accelerated testing chambers, we would like to utilize our own data which have been gathered over 20 years at ASU-PTL (Arizona State University Photovoltaic Testing Laboratory) and ASU-PRL (ASU Photovoltaic Reliability Laboratory). ASU-PTL was the first PV module certification testing laboratory (founded in 1992) and the first accredited (in 1997) PV certification testing
laboratory in the United States. ASU-PTL and ASU-PRL have purchased, maintained and operated five walk-in environmental chambers, three small environmental chambers, three small UV chambers (UV + temperature), one walk-in UV chamber (UV + temperature) and two UV weathering chambers (UV + temperature + humidity). The walk-in environmental chambers typically cost about $250,000 each (including installation and commissioning) and can accommodate only up to twelve 250-300 watts modules. Similarly, the walk-in UV chambers available in the market typically cost very high and accommodate only up to eight 250-300 watts modules. In addition, the maintenance cost and the operating cost (especially, electricity cost) would exceed several tens of thousands of dollars each year for each chamber. Similarly, the UV lamps of UV chambers are expensive to replace, and their lifetime is very limited as well. These capital, operational and maintenance costs data clearly indicate that the long-term reliability testing (typically, 6-12 months) using indoor environmental chambers is very expensive for the manufacturers, testing labs and other interested stakeholders of the industry. This paper proposes utilizing a disruptive outdoor approach for the long-term accelerated testing of PV modules for the long-term reliability evaluations determining the acceleration factors and wear-out failure modes. This disruptive approach is based on the use of a real-time outdoor field stressing setup utilizing test racks (fixed and 2-axis), thermal insulators on the substrates of modules (solar gain), and optical reflectors (to increase the irradiance level on the modules). This outdoor accelerated testing approach is expected to cost only less than 30% of the indoor accelerated testing cost. This paper does not attempt to provide post-stress test results but aims to describes an innovative test setup to perform inexpensive, real-time, outdoor accelerated testing methodology. The outdoor accelerated test setup presented in this paper is designed to accelerate the dominant stressors and failure/degradation modes specific to the hot-dry desert climate of Arizona.

1.2 Dominant Failure/Degradation Modes

Before initiating any long-term indoor or outdoor accelerated tests, one should be aware of the dominant failure/degradation modes existing in a specific climate, so the appropriate mode-specific stressors can be identified and accelerated. Two of the topmost degradation modes of PV modules in hot-dry desert climates are the encapsulant discoloration and solder bond degradation. Therefore, the outdoor accelerated test setup presented in this paper is primarily designed to accelerate these two specific degradation modes (though other degradation modes may also concurrently occur due to the stressors used in this test setup). A brief description of these two dominant degradation modes along with the required accelerated tests is provided in sections 1.2.1 and 1.2.2.

1.2.1 Encapsulant Discoloration

Encapsulant provides the structural support, optimum optical coupling, and physical as well as electrical isolation for PV modules. Ethylene vinyl acetate (EVA) is the most commonly used encapsulant in the wafer-based c-Si modules. A variety of optimal properties coupled with low cost make EVA a popular encapsulant choice over many decades. The freshly-laminated, transparent EVA—susceptible to degradation with prolonged exposure of UV radiation, temperature and humidity—typically starts to turn yellow and eventually brown in the field. Encapsulant discoloration is one of the topmost field degradation modes occurring in PV modules [1-4]. The discoloration is often attributed to be the result of chromophore generation due to the degradation of UV absorbers/additives in EVA and/or due to the polyene formation with UV radiation at elevated temperatures with or without humidity [5, 6]. The browned EVA absorbs some of the incident visible light, lowering the light reaching the solar cell, which in turn, reduces the cell short-circuit current (Isc) and hence the module power output. An accelerated test method of consistently replicating the wear-out mechanism of encapsulant degradation along with a physical model would be useful to predict the degradation rate and acceleration factor for a specific construction type and a specific climate condition. To predict the degradation rate and determine acceleration factor for any degradation mode, one needs to first obtain the activation energy for the specific degradation reaction. The activation energy can be determined using the Arrhenius model if a specific reaction is accelerated at two or more temperatures and the corresponding affected reaction/performance parameter is measured. In the current outdoor test approach, a test setup is designed to accelerate the encapsulant discoloration by maintaining the operating temperatures of the test modules at three different levels along with an increased daily UV dose.

The IEC 61215 qualification testing of photovoltaic modules encomasses a set of well-defined short-term (about two-three months) accelerated stress tests with strict pass / fail criteria based on the functionality / performance, electrical and mechanical safety, and visual requirements [7]. The qualification testing per IEC 61215 standard requires an UV exposure of PV modules at an UV dose of 15 kWh/m² only. Assuming an UV content of about 5% in the global irradiance, the total UV-dose in the desert condition of Arizona is calculated to be about 120 kWh/m²/year or about 3,000 kWh/m² over 25 years. This calculation clearly indicates that the UV dose utilized in the qualification testing is not sufficient for the lifetime testing of PV modules and it is only a preconditioning test equivalent to about 45 days of
exposure in the field. Therefore, passing the UV testing of IEC 61215 doesn’t say anything about the long-term performance of PV modules in the field [8]. BP Solar reported the use of a UV-exposure at 90°C for 26 weeks (6.5 months) to verify a 25-year lifetime of PV modules [9]. A long-term outdoor accelerated test method for the encapsulant degradation mode is presented in this work.

1.2.2 Solder Bond Fatigue/Failure
Solder bond degradation is one of the common field degradation modes occurring in PV modules [10, 11]. Solder bond degradation can be caused by a combination of high static operation temperature and/or cyclic thermal stress of components surrounding the interconnect and metallization system. High temperature operation can lead to the phase segregation within the solder material and intermetallic compounds (IMC) formation between copper ribbon and solder and silver metallization and solder. The cyclic temperature condition can be caused by the daily, seasonal and cloud thermal cycles. The difference in the coefficients of thermal expansion (CTE) between the materials of copper ribbon, semiconductor, silver metallization, phase segregated solder, IMC and encapsulant etc. induces the thermo-mechanical fatigue (TMF) on the solder bonds during thermal cycling, leads to the micro-cracks which in turn increase the series resistance (Rs) and decreases fill factor (FF). The TMF exacerbates if the solder material experiences phase segregation and IMC formation. The IMC is formed when the thin silver metallization diffuses into the solder and/or copper in the copper ribbon diffuses into solder. The new compounds formed are brittle in nature. These reactions accelerate at higher temperatures. Increase in IMC thickness and phase segregation in the solder material make the solder bonds brittle which are prone to cracking during thermal cycling (TC). This leads to Rs increase, and eventually a decrease in fill factor (FF) and output power (Pmax). As described in section 1.2.1, to predict the degradation rate and determine acceleration factor for any degradation mode, one needs to first obtain the activation energy for the specific degradation reaction. In the current outdoor test approach, the same test setup described in section 1.2.1 is designed to accelerate the solder bond degradation by maintaining the operating temperatures of the test modules at three different levels.

The IEC 61215 qualification testing calls for 200 thermal cycles from -40°C to +85°C with injected current flow above room temperature [7]. This thermal cycling test with thermal 200 thermal cycles has been demonstrated to identify the interconnect design flaws leading to early failure of the modules. However, this thermal cycling test has been reported to be inadequate for giving confidence in the warranty of ~ 20 year for many climatic conditions [9, 12]. A long-term outdoor accelerated test method for the solder bond degradation mode is presented in this work.

2 METHODOLOGY

2.1 Outdoor Accelerated Test Setup
Due to expensive indoor accelerated testing costs, we propose using a disruptive real-time outdoor approach for the accelerated testing of PV modules for the long-term reliability evaluations determining the acceleration factors and wear-out failure modes. This approach is based on the use of an outdoor field stressing setup utilizing test racks (fixed and 2-axis), thermal insulators on the substrates of modules (solar gain) and optical reflectors/concentrators (to increase the irradiance level on the modules). This outdoor accelerated testing approach is expected to cost only less than 30% of the indoor accelerated testing cost, can accommodate statistically significant number of modules by simply expanding the space for the test racks and can be performed right at the PV plant site or climate of interest.

The proof-of-concept test setup designed and built at ASU-PRL consists of nine commercial modules from three manufacturers (3 modules per manufacturer) as shown in Figure 1 and Figure 2. On a fixed, latitude-tilt rack (Figure 1), three of these modules (one per manufacturer) were installed without any thermal insulation on the backside of the modules and another three (one per manufacturer) were installed with thermal insulations on the backside of the modules to increase the temperature but at the same insolation level as the modules without insulations. On a 2-axis tracker (Figure 2), the last three modules (one per manufacturer) were installed with thermal insulations on the backside of the modules to increase the temperature and with diffuse reflectors (above 75% reflection including the UV spectrum) to increase the irradiance level to about 1.4 time compared to the fixed tilt irradiance. The expected insolation/time increase would be about 1.3 times for the 2-axis trackers (8.5 sunhours per day) compared to the latitude tilt rack (6.5 sunhours per day). If the 2-axis tracker modules gain a daily average temperature of about 30°C higher than the un-insulated modules on the latitude tilted modules and a typical activation energy of 0.5-0.6 eV is assumed for a life-determining degradation/failure mode, then the total calculated acceleration factor, based on the Arrhenius equation, would be about 12-15. This means one-month testing on a 2-axis tracker, with thermal insulation and front light reflection, would be
equivalent to one-year testing on a fixed tilt rack, which in turn is equivalent to one-year field exposure of PV modules in large plants. Therefore, in about 2 years of outdoor accelerated testing, one should be able to determine the lifetime (over 25 years) degradation rate and wear-out failure modes (in addition to the infant mortalities and midlife failures) of the actual/specific PV modules installed in a specific climatic condition. This accelerated testing can be halved if the increased temperature is about 40°C higher than the actual modules operating in the plant.

The plane of array (POA) irradiance of both fixed tilt rack and 2-axis tracker are continuously monitored using pyranometers and reference cells. The temperatures of all nine modules are also continuously monitored using thermocouples. The modules can be maintained at the short-circuit condition for the worst-case acceleration or at the MPPT (maximum power point) condition for the normal operating condition.

![Visual Image of Fixed Tilt Rack](image1)

**Figure 1.** Visual image of fixed tilt rack with first three modules (manufacturers 1 through 3) operating at low temperature (T1) and next three modules with back thermal insulators (manufacturers 1 through 3) operating at mid temperature (T2).

![Visual of 2-axis Tracker](image2)

**Figure 2.** Visual of 2-axis tracker modules (manufacturers 1 through 3) operating at high temperature (T3).

This proof-of-concept study has demonstrated that we can attain three different temperatures at any specific instance in the daytime. In the nighttime, all the 9 modules operate at about the same temperature with a small temperature difference of less than 3°C between all nine modules. This small difference is caused by the difference in the sky and ground radiations of the modules depending on the tilt-angle of the fixed tilt rack and stow-angle of the 2-axis tracker in the nighttime. For statistical significance, the test racks can be increased to accommodate several dozens of modules instead of just nine modules presented in this work.

### 3 CHARACTERIZATIONS

The following key characterization tests have been performed on the nine modules before they were installed in the field. The modules are periodically monitored and characterized in the field itself to determine the degradation and failure
modes without removing the modules from the test racks. The eventual goal of this work is to predict lifetime of PV modules using the acceleration factor determined based on the periodical degradation data measured at each of the three temperatures. To obtain quantitative degradation data for a specific degradation mode, the researchers can use one or more characterization data. For example, the periodical degradation data of encapsulant degradation can be obtained by periodically monitoring the short-circuit current loss, measuring yellowness index, measuring spectral reflectance or measuring UV fluorescence intensity of every module. These techniques can also be used as complimentary techniques to validate one measurement versus the other.

3.1 Visual Inspection

Visual inspection is periodically performed according to a visual inspection checklist. This checklist identifies 86 different types of degradation and failure modes. Of these, 61 defect types are categorized as performance defect types that affect PV module power output and 25 defect types are categorized as safety failures that affect safety (mechanical/electrical safety or fire hazard) [13-15]. The visual inspection is needed to identify all the degradation modes of a module type specific to the construction and climate. This work currently focuses only on two degradation modes of encapsulant discoloration and solder bond degradation, but the collected visual inspection data could be applied to the other degradation modes as well. The visual inspection is scheduled to be obtained every 3 months in the field.

3.2 Infrared (IR) Imaging

Like the visual inspection, the IR imaging is also periodically performed on all the test modules on clear sunny (> 700 W/m²) and low wind speed (< 2 m/s) days. These images are useful to monitor the progress of hotspot and temperature non-uniformity issues over the test period. The IR images would be greatly useful to explain and correlate the other test results obtained in this work. The example shown in Figure 3 provides the average, maximum and minimum operating temperatures of PV modules of manufacturer 1 with and without back insulators. The IR images are scheduled to be obtained every 3 months in the field.

![Figure 3. IR images of manufacturer 1 modules without (left) and with (right) thermal insulations on the rear side of the modules after 60 days of field exposure.](image)

3.3 Electroluminescence (EL) Imaging

The EL images are useful to monitor the cell cracks and the deterioration of metallization/contact fingers. Since the cracks at the cell centers can allow oxygen reaching the front encapsulant layer at the centers of the cells, the encapsulant browning rate would be heavily influenced by the cell cracks which can be observed in the EL images. These images can be used to explain the anomalies in the performance test result. As an example, Figure 4 shows an EL image obtained for one of the test modules before the field exposure. The EL images are scheduled to be obtained every 3 months in the field.

![Figure 4. EL image of a module from manufacturer 1 showing on cell cracks before exposure in the field.](image)
3.4 Ultraviolet Fluorescence (UVF) Imaging

An array of UV light (~390 nm) sources is being used to perform UV fluorescence imaging and to analyze encapsulant discoloration, and possible cell crack development after significant field exposure. Figure 5 shows an UVF image of a 2-axis tracker mounted module right after installation in the field. Since UVF imaging technique is a very powerful method to detect the encapsulant browning issues very early in the field, it is anticipated that the UVF images can be directly correlated with short-circuit current degradation and yellowness index changes in future when the encapsulant start discoloring in the field. The UVF images are scheduled to be obtained every 3 months in the field.

![UVF Image](image)

Figure 5. UV fluorescence (UVF) image of a module of manufacturer 3 on a 2-axis tracker with thermal insulations on the backside before field exposure.

3.5 I-V Measurement

The periodical I-V measurement is the most important characterization to determine the impact of degradation modes on the performance parameters, Isc, FF or Voc. In the current work, we primarily focus on the short-circuit current (Isc) degradation and the fill factor (FF) (or series resistance, Rs) degradation as these are two parameters affected by encapsulant discoloration and solder bond degradation, respectively. The initial I-V measurements are obtained outdoor on a cloudless sunny day when irradiance is above 800 W/m² and windspeed is under 2 m/s. Figure 6, presents the initially measured Isc data along with the nameplate rated Isc data. The performance measurements are scheduled for every 3 months as well.

![Isc vs. Nameplate Rated Isc](image)

Figure 6. Initial measured Isc vs. nameplate rated Isc of all nine modules
4 CHALLENGES IN CURRENT OUTDOOR ACCELERATED TEST SETUP

4.1 Non-uniform Temperature

An acceptable uniform temperature can be obtained on the latitude-tilted modules with and without back insulators. However, obtaining a uniform temperature on each module installed on the 2-axis tracker has proven to be a challenge due to non-uniform reflection of light from the reflectors to the modules as can be seen in Figure 7. This challenge can be addressed by adjusting the reflector angle and/or increasing the reflector size.

![Figure 7. Non-uniform temperature distribution of the 2-axis installed modules due to non-uniform reflected light.](image)

4.2 Uncontrolled Temperature

The current test setup is unable to maintain a fixed temperature throughout the daytime. This issue can be alleviated using nine controlled heating blankets below the backsheets of the nine modules investigated in this proof-of-concept study. The primary focus of the future work is to improve the test setups to control and maintain the PV modules at three fixed temperature ranges of 65°C +/- 5°C (latitude-tilt), 75°C +/- 5°C (latitude-tilt) and 85°C +/- 5°C (2-axis tracker).

4.3 Wind Load Issues

The current test setup on the 2-axis tracker needs to be improved for the heavy wind loads existing at the site in the month of July every year. To minimize the wind load issue in the month of July, we made the reflectors flat and kept the tracker platform in a stowed mode in the night times. Still, the reflector structure was not strong enough to withstand the gusty wind storms experienced in July 2018 even at the stow mode and the reflectors were ripped apart from the 2-axis tracker platform and fell on the ground as shown in Figure 8. New mechanical options to install the reflectors on the tracker platform are being explored so they can withstand future wind storms.
5 FUTURE WORK

In the future work, we aim to obtain uniform reflected light by adjusting the reflector angle and size. To control and maintain the PV modules at three fixed temperature ranges of $65^\circ C \pm 5^\circ C$, $75^\circ C \pm 5^\circ C$ and $85^\circ C \pm 5^\circ C$, a combination of thermal insulation and fiberglass reinforced silicone rubber heating blankets will be used on the back of the modules. The temperature of the individual modules will be fixed using an inbuilt temperature controller comes with each blanket. In summer time when the ambient temperature exceeds $45^\circ C$ and irradiance exceeds $1000 \text{ W/m}^2$ at our desert site (Phoenix/Mesa, Arizona), the lowest temperatures of the modules can exceed $70^\circ C$ for a few hours if the modules are tilted to the latitude angle. This would warrant installing expensive cooling units to keep the modules at $65^\circ C \pm 5^\circ C$. To avoid this additional cost, the tilt angle of the rack mounted PV modules can be adjusted to $45^\circ C$ during summer months (or use neutral density mesh/bug screens), so the solar gain can be minimized, and the module temperature can be maintained at the required temperature of $65^\circ C \pm 5^\circ C$. Similarly, during summer months, the highest temperature of $85^\circ C \pm 5^\circ C$ will be maintained through the off-axis tracking (or change the reflector angle or use neutral density mesh/bug screens) option available in the controller of the 2-axis tracker. New mechanical options to install the reflectors on the tracker platform are being explored so they can withstand future wind storms. All the modules will be operated at MPPT using module level power electronics (MLPE) or a multi-curve I-V tracer with MPPT tracking capability.

6 CONCLUSION

The work presented in this paper demonstrates a new real-time approach to perform outdoor accelerated testing of statistically significant number of modules at a dramatically reduced testing cost. The usefulness of each periodical outdoor characterization is described. Based on the known operating conditions (temperatures and UV dosage) and the periodical characterization data, the mode- and climate-specific degradation rate can be predicted, and the acceleration factor can be determined. The technical challenges encountered in the current test setup and the planned future works are also briefly presented.
REFERENCES


