Robust Measurement of Thin-Film Photovoltaic Modules Exhibiting Light-Induced Transients

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ABSTRACT

Light-induced changes to the current-voltage characteristic of thin-film photovoltaic modules (i.e. light-soaking effects) frustrate the repeatable measurement of their operating power. We describe best practices for mitigating, or stabilizing, light-soaking effects for both CdTe and CIGS modules to enable robust, repeatable, and relevant power measurements. We motivate the practices by detailing how modules react to changes in different stabilization methods. We also describe and demonstrate a method for validating alternative stabilization procedures, such as those relying on forward bias in the dark. Reliable measurements of module power are critical for qualification testing, reliability testing, and power rating.

Keywords: Photovoltaic, Solar, Testing, Metastability, Transient, Thin-film

1. INTRODUCTION

Thin-film photovoltaic modules (here we consider CIGS and CdTe) are known to exhibit a range of transient changes in performance upon exposure to light.[1,2] Many such changes are metastable in that they are reversed upon storage in the dark. These changes pose a challenge to repeatable and relevant measurements of module power. It is useful to collect current-voltage (IV) curve measurements at the standard test conditions (STC) of one-sun illumination at 1000 W m^{-2} and module temperature of 25°C, which are representative of a module's outdoor-realized electrical performance state. Such measurements are critical for many applications, including reliability and qualification testing. To ensure these measurements are relevant to outdoor performance, thin-film modules frequently undergo light exposure (often called light-soak) prior to measurement. The results of the STC measurement are however often dependent on conditions during light exposure, necessitating a well-controlled method to achieve repeatable and reproducible results. Here, we review our findings on conditioning modules for measurement and document our best practices.

Though the electrical performance states realized under various conditions are not indefinitely stable, we use the term "stabilization" to refer to procedures designed to bring about a particular metastable state, even if only temporarily. It is also important to note that there is, in general, no single "light-state" of a module, and any light-induced electrical performance state is representative of conditions under which a module was exposed.[3] This is discussed in more detail in Section 3.1, but raises the point that there is inherently a trade-off between repeatability and outdoor-relevancy. Since there is a continuum of outdoor-realized electrical performance states and no one procedure could hope to target all of these states, we recommend a well controlled stabilization protocol using reasonable conditions to produce an outdoor-relevant (but not necessarily outdoor-equivalent) state.

Here, we document and support such a stabilization protocol. Section 2 provides an overview of our experimental methods. We then motivate features of the recommended stabilization procedure in Section 3 with both prior and new experimental results; we focus on several critical aspects of stabilization including methods for determining light-exposure duration, controlled conditions during exposure, and best practices for cooling the module to measurement temperature. In Section 4, we provide detailed documentation of our best practices for thin-film module stabilization. Before concluding, we also present results and make recommendations regarding validation protocols for possible alternative procedures (including procedures that do not make use of light) in Section 5.

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2. GENERAL EXPERIMENTAL METHODS

2.1 Simulator-based light exposure

Indoor, simulator-based light exposures were carried out in a light-exposure chamber providing class BBA illumination.[4] one-sun illumination was supplied by an array of metal-halide lamps with closed-loop intensity control. Modules were actively maintained at their maximum power point except when in situ IV curves were automatically collected every five minutes. A temperature set-point of 50°C was used for back-of-module temperature, maintained by closed-loop control of forced-air cooling using room-temperature air. Back-of-module temperature was monitored with thermocouples adhered in the centers of the modules.

2.2 STC IV curves

STC IV curves were collected with a long-pulse class AAA solar simulator.[4] Back-of-module temperature was measured with a thermocouple at the center of the module. Maximum power points determined from these IV curves were temperature-corrected to 25°C according to manufacturers' recommendations. All reported power measurements were made at 25±2°C.

2.3 Bias at elevated temperature (BET)

We tested a light-free stabilization method, namely the application of bias at elevated temperature.[5] BET was carried out by placing modules in a dark environmental chamber and ramping the air temperature to 85°C at a rate of at least 3°C/min. Once the ramp was complete, we applied forward bias to the modules at 90% of V_{oc} for 1.5 hours. We then ramped the chamber temperature down at the same rate. To aid in module cooling the chamber air temperature was ramped down to approximately 0°C. The modules were removed when their temperature approached 25°C. Finally, the modules' STC IV curves were measured between 30 and 60 minutes after the chamber temperature passed through 25°C. These bias steps were repeated until the STC light IV curves indicated the module's were stable to within 2%.

3. CONSIDERATIONS FOR LIGHT-BASED STABILIZATION

Repeatable and reproducible measurements of a module's outdoor-relevant performance require careful control of the stabilization procedure. In this section, we discuss our findings surrounding the importance of module temperature during light exposure and different methods for determining when the modules are stable.

3.1 Importance of temperature during light exposure

We have previously shown that module temperature during light exposure can affect the final light-stabilized state of thin-film modules.[3] An important implication of this finding is that there is no well-defined "light-state" of a thin-film module. Instead, there is a continuum of light-stabilized states that depend on the light-exposure conditions. Thus for repeatable and reproducible measurements, we must select a specific set of of exposure conditions. We have chosen a module temperature of 50°C and one-sun illumination. This temperature is chosen because we have found it can be reliably achieved indoors in a continuous simulator while still being relevant to real-world outdoor operation.

It is important to distinguish these recommended light-exposure conditions (RLEC) from real-world conditions. In practice, modules operating in the field will be exposed to variable temperatures and illuminations implying that a module's metastable performance will be dependent on the particular environment in which it is deployed. Thus there is no single outdoor performance state. It is important to note that we do not consider the RLEC-achieved state to be equivalent to an outdoor state. Instead it represents a compromise between outdoor-relevancy and repeatability.

Figure 1 illustrates the difference between RLEC- and outdoor-stabilized efficiency. It shows the relationship between STC power measured for four CdTe modules (two different products). Four modules were exposed outdoors, actively tracked at maximum power, until the infrequent measurement stability criterion described in Section 4.2 was met. The outdoor exposure was interrupted to measure STC IV curves for the stability criterion. The P_{mp} from the final STC measurement was taken as the resulting stabilized power. Next, we exposed the modules in a continuous simulator under RLEC until the stability criterion was met and once again measured the STC IV curves. The mean back-of-module temperature for irradiances above 500 W m^{-2} for one module type (red in Figure 1) during outdoor exposure was 39°C, and for the other module type (blue in Figure 1) it was 42°C.

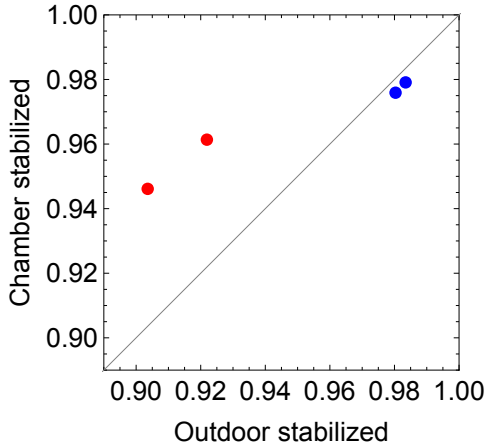

Figure 1. Comparison between the measured STC power of four CdTe modules after chamber (RLEC) and outdoor stabilization. A tie line is also shown in gray. Different colors indicate different module types. Power measurements are normalized to rated nameplate power.

For one product, the discrepancy between the two stabilized efficiencies is approximately 4% as shown in Figure 1. This highlights the distinction between a RLEC- and outdoor-stabilized state. It also demonstrates the importance of using tightly-defined light-exposure conditions in order to achieve repeatable and reproducible results, thus supporting the narrowly defined RLEC parameters.

3.2 Use of forward bias during cool-down

In order to make STC IV measurements at 25°C after a light exposure, modules must be cooled down from the light-exposure temperature. This cool-down period introduces a challenge in that the modules' electrical states may begin to relax from the light-induced state. We have previously found that the application of forward bias during this stage can aid in the maintenance of the light induced state.[6] However, the success of this approach is product-specific. For example we have also observed that for some products, the bias can boost module performance over time.[6] In other cases, we have seen no strong evidence that maintenance bias provides any benefit.[5] Given the product-specific nature of the success and relevancy of maintenance bias during cool-down, we generally recommend against its use. However we note that it may be considered for internal tests after careful validation.

3.3 Determining stability

The timescale and character of light-induced performance changes in thin-film modules are product-specific. Therefore, it is useful to use a prescribed criterion on power changes, as opposed to a set exposure duration, to decide when a stabilizing light exposure should be ended. The light-based stabilization procedure in the existing qualification standard IEC 61646[7] calls for measurements to be made every 43 kW h m^{-2} of insolation. In a pending update to the IEC 61215 qualification standard, which will incorporate thin-film module qualification and silicon qualification into a single standard, this interval is expected to be 20 kW h m^{-2}. In both cases, the stabilization criterion is based on three measurements. Note that if the light exposure is carried out with simulated light and temperature is controlled to within ± 2°C, the measurements can be made in situ during light exposure. In this section we demonstrate that frequent measurements of power made in situ during a light exposure under controlled conditions can establish stability with higher certainty than three infrequent measurements.

We exposed a CdTe module in the light-exposure chamber with a back-of-module temperature of 47 ± 0.6°C and measured IV curves at five-minute intervals. We then compared the power change over 40 kW h m^{-2} intervals calculated in two different ways (both described in Section 4.2). First with the standard method of three infrequent P_{mp} values from IV curves collected every 20 kW h m^{-2}, and second with a regression of all the P_{mp} values from IV curves on the same 40 kW h m^{-2} interval. We repeated both calculations for 48 different 40 kW h m^{-2} intervals, beginning between 17 and 21 kW h m^{-2} of insolation. An example is shown in Figure 2. In this case, the change calculated with regression was 0.36% over the 40 kW h m^{-2} interval, while that calculated with infrequent measurements was 0.71%.

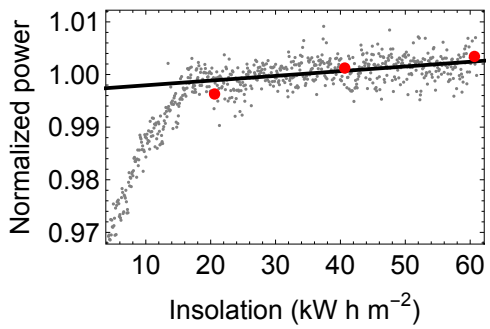

Figure 2. Comparison between the regression and infrequent measurement methods for determining stability during light exposure of a CdTe module. The gray points are P_{mp} values calculated from IV curves taken at 5-minute intervals during exposure. The red points indicate three points, separated by 20 kW h m^{-2} (starting at 20.6 kW h m^{-2} total insolation). The black line shows the linear regression to all the P_{mp} values (gray points) on that same interval. The regression indicates a change in power of 0.36% over the 40 kW h m^{-2} interval, while that calculated with infrequent measurements was 0.71%. This illustrates how noise in a few infrequent measurements can obscure the underlying trend.

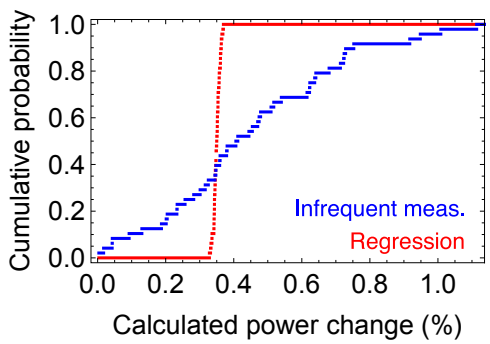

Figure 3. Cumulative distribution functions of the power change over various 40 kW h m^{-2} intervals calculated with three infrequent measurements (blue) and with regression of frequent measurements (red) for the light exposure shown in Figure 2. The results are shown for 48 different intervals beginning between between 17 and 21 kW h m^{-2} of insolation. The results show that regression of frequent measurements provides a more precise way to determine stability.

We find that the regression method gives a more precise result than the infrequent measurements. The cumulative distribution functions for power change calculated with the two methods are shown in Figure 3. While both methods indicate that the module is stable (<2% change) for all of the considered 40 kW h m^{-2} intervals, the regression method gives a more precise result. Thus we recommend that the regression method for determining stability be used when possible.

4. RECOMMENDED STABILIZATION PROCEDURE

Here we present a detailed light-based procedure for the stabilization of thin-film modules.

4.1 Procedure

1. Light exposure

   (a) Expose the module to simulated sunlight under the following recommended light-exposure conditions (RLEC):

      i. Irradiance between 800–1000 W m^{-2}

      ii. Back-of-module temperature of 50±2°C.

      iii. Class CCC or better simulator as per IEC 60904.[4]

iv. Either fixed-resistance load or active maximum power tracking can be used. Fixed-resistance load should be selected so that the module voltage at 1000 W m^{-2} is within ±5% of the nominal maximum power voltage. Active maximum power tracking should have an uncertainty in the maximum power voltage of ±5% or better.

(b) Determine when this exposure is complete according to either of the "methods for determining stabilization" detailed below.

(c) Additional exposure of up to 100 kW h m^{-2} is permitted to enable parallel testing of multiple modules or accommodate scheduling constraints.

2. Cool the module to measurement temperature

(a) Cool the module to a back-of-module temperature of 24.5–25.5°C.

(b) This step must take 0.5–1 h.

3. Measure the final IV curve

(a) Must be completed within 0.5–1 h after the end of the final light exposure

(b) Module temperature must be 24.5°C–25.5°C.

(c) Measure an IV curve with class AAA illumination[4]

(d) Measure, record, and report:

i. Full IV curve points

ii. P_{mp}, I_{sc}, V_{oc}, FF

iii. Module temperature

iv. Date and time of curve

4.2 Methods for determining stabilization

1. Regression of in situ measurements

(a) This method is applicable only if the simulator used for stabilization is class BBA or better.

(b) Obtain a measurement of P_{mp} at least once every five minutes, either through active tracking or from an IV curve. If measurements from active tracking are used the associated uncertainty should not exceed ±2%.

(c) Compute the total insolation (Q) from points measured when irradiance and back-of-module temperature are in the specified range (irradiance: 800–1000 W m^{-2}, module temperature: 50±2°C):

$$Q = \sum_{i=1}^{N} E_i t_i \tag{1}$$

where N is the number of observations meeting the specified criteria, E_i is the ith measurement of irradiance and the t_i is interval between the measurement and those immediately preceding and following it. Q should be calculated for each measurement of P_{mp} to enable regression.

(d) Temperature- and irradiance-correct each measurement of P_{mp} according to:

$$P_r = P \frac{1000}{E} \frac{1}{1+\gamma(T-T_r)} \tag{2}$$

where P (W) is the module power measured at irradiance E (W m^{-2}) and temperature T, γ (1/°C) is the fractional power temperature coefficient, P_r (W) is the power at reference temperature T_r (typically 25°C) and reference irradiance (1000 W m^{-2}).

(e) Perform a least-squares linear regression on P_r *vs.* Q for any interval ≥40 kW h m^{-2}.

(f) Measure, record, and report:

i. Start and end time and date
ii. All in situ P_{mp} measurements, irradiance, back-of-module temperature (single-point, center of module), and time and date of measurement (data collected at least once every five minutes)
iii. Report the start and end date and time of the interval over which the data was regressed along with the slope of the linear fit.

2. Infrequent measurements

(a) At intervals of no less than 20 kW h m^{-2} of insolation, measure the module's IV curve under repeatable conditions, within the specifications below, to determine if P_{mp} is stable. Compute the total insolation (Q) according to Equation 1 from points measured when the irradiance and back-of-module temperature are in the specified range (irradiance: 800–1000 W m^{-2}, module temperature: 50±2°C).

(b) These power measurements must be done with a solar simulator, class BBA or better at an illumination intensity of between (700–1100) W m^{-2}.

(c) The IV curve can be collected at any convenient back-of-module temperature between 25–50°C, but this temperature must be repeated within 2°C for consecutive measurements.

(d) the P_{mp} calculated from this IV curve should be corrected for irradiance and temperature according to Equation 2

(e) The light exposure can either be interrupted for measurement or an in situ measurement can be made. If the exposure is interrupted, the IV measurement must be made 0.5–1 h after the interruption and the light exposure must be restarted as soon as possible and within 2 h of the original interruption.

(f) The light exposure is considered complete after three consecutive measurement of P_{mp}, separated by at least 20 kW h m^{-2} of insolation satisfy $\frac{P_{max}-P_{min}}{P_{ave}} \leq 0.02$ where P_{max}, P_{min}, and P_{ave} are the extreme and average values of the three consecutive power measurements separated by at least 20 kW h m^{-2}.

(g) Measure, record, and report

i. Start and end time and date
ii. Whether the measurements are made in situ, or the exposure in interrupted
iii. all P_{mp} measurements including date and time of measurement
iv. Irradiance and back-of-module temperature (single-point, center of module), and time and date of measurement (data collected at least once every five minutes)

5. VALIDATION OF ALTERNATIVE PROCEDURES

For some products it may be appropriate to use an alternative to the procedure described in Section 4. For example it has been suggested that the application of forward bias at elevated temperature (BET) can be used to stabilize CdTe modules.[5] Such procedures may be advantageous in that they provide a way to put modules into an outdoor-relevant electrical performance state more quickly and less expensively than a controlled light exposure. However, before such alternative procedures are used with any product, we recommend that they be validated to prove they produce an electrical performance state that is light-stable under the RLEC described in Section 4.

The importance of validation is highlighted by Figure 4. Which shows the change in measured power during several steps of BET followed by exposure in the light soak chamber. In agreement with previous results,[5] we find that the state produced by BET is not stable under illumination at a module temperature of 50°C for two different types of CdTe modules.

A simple validation procedure to screen alternative stabilizations is to:

1. Perform the alternative stabilization
2. Measure the STC IV curve
3. Perform the light-based stabilization as described in Section 4
4. Measure the STC IV curve

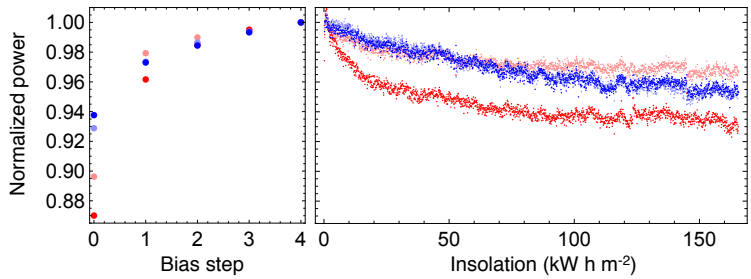

Figure 4. Change in power during application of BET intervals (bias steps, left) and subsequent light exposure (right). The BET measurements were taken at STC and the light-exposure measurements were made in situ. The BET measurements are normalized to the final bias step measurement and the light-exposure measurements are normalized to the start of the exposure. The results indicate that BET is successful in affecting a transient change in power, but that this change is partially relaxed upon exposure to light.

If the power determined from the IV curves in steps 2 and 4 differ by less than 2%, then the alternate procedure is accepted, otherwise it is rejected. We note that this should be applied on a product-by-product basis, as some procedures may be appropriate for certain modules but not others.

We demonstrated this validation procedure on four CdTe modules (two each of two different products) which were first subjected to BET and then light exposure as shown in Figure 4. We interrupted the light exposure at several points to measure STC IV curves. This allowed us to attempt validation on two different alternative procedures: BET only and BET followed by 53 hours of light exposure (BET+light). BET+light could be useful as the BET phase quickly saturates large changes (which could take much longer with light alone) while the final light exposure ensures the resulting state is light-stable.

The variation between STC IV curves (steps 2 and 4) for the two procedures are shown in Table 1. Based on these results, BET only is rejected for these modules, but BET+light is successfully validated. Figure 5 provides a visualization of the validation on one of the modules, and shows that the STC-measured power reflects the trends observed from in situ IV curves during light exposure.

Table 1. Relative variation in STC power between alternatively-stabilized and subsequently light-stabilized measurements. BET is rejected for these modules based on the observed variation $\geq$2%, while BET+light is successfully validated.

	Variation (%)	
Module	BET	BET+Light
A1	2.2	0.1
A2	3.8	0.7
B1	3.1	1.0
B2	3.3	1.0

6. CONCLUSION

We have motivated and described our best practices for the stabilization of transient performance changes in CIGS and CdTe PV modules prior to STC measurement. Because a module's performance is sensitive to the exact light-exposure conditions, it is important to have a tightly defined stabilization procedure such as that documented here, to achieve repeatability and reproducibility. We also emphasize that alternate procedures may be useful for some products, but that they must be carefully validated to ensure they produce a light-stable condition under reasonable conditions.

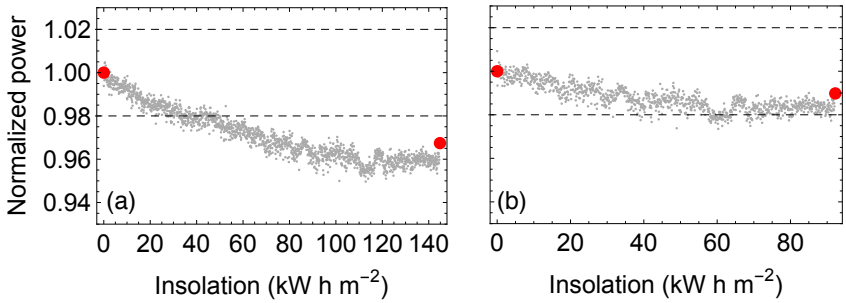

Figure 5. Example validation of BET (a) and BET+light (b) on module B2. Red points indicate STC measurements and gray points indicate in situ measurements during light exposure. Insolation is calculated from the end of the alternate procedure, and both the STC and in situ powers are normalized to the beginning of the validating light exposure. Dashed lines indicate the criterion for accepting the alternate procedure. Here, BET+light is validated and BET only is not.

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