Reliable Power Rating of Perovskite PV Modules

Preprint

Tao Song, Larry Ottoson, Josh Gallon, Daniel J. Friedman and Nikos Kopidakis

National Renewable Energy Laboratory

Presented at the 48th IEEE Photovoltaic Specialists Conference (PVSC 48)
June 20-25, 2021

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Conference Paper
NREL/CP-5900-80309
July 2021

Reliable Power Rating of Perovskite PV Modules

Preprint

Tao Song, Larry Ottoson, Josh Gallon, Daniel J. Friedman and Nikos Kopidakis

National Renewable Energy Laboratory

Suggested Citation
Song, Tao, Larry Ottoson, Josh Gallon, Daniel J. Friedman and Nikos Kopidakis. 2021. *Reliable Power Rating of Perovskite PV Modules: Preprint*. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5900-80309. https://www.nrel.gov/docs/fy21osti/80309.pdf.

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Conference Paper
NREL/CP-5900-80309
July 2021

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

NOTICE

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office (SETO) Agreement Number 34351. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

NREL prints on paper that contains recycled content.

Reliable Power Rating of Perovskite PV Modules

Tao Song, Larry Ottoson, Josh Gallon, Daniel J. Friedman and Nikos Kopidakis

PV Cell and Module Performance Group, National Renewable Energy Laboratory, Golden, Colorado, 80401, USA

***Abstract*—As the perovskite technology is ramping up into commercialization, reliable and accurate power rating of large-size perovskite modules becomes a prominent aspect for its future deployment in the PV market. It is known that the performance calibration of perovskite PV devices is very challenging due to its complex dynamic response during a conventional current-voltage (IV) measurement. PV researchers have previously proposed several steady-state performance calibration methods to reliably extract PV efficiencies, but mostly focus on small area research-type cells. In this paper, we emphasize the importance of reliable performance calibration on large-size perovskite modules. Extending the NREL Cell and Module Performance (CMP) group's steady-state performance calibration protocol (i.e., Asymptotic P_{MAX} Scan) for perovskite cells to modules, we justify the necessity of reporting steady-state efficiencies for perovskite cells and discuss the challenges of applying this protocol to modules. We also present our protocol for Maximum Power Point Tracking (MPPT), which is a technique often used for performance calibration of perovskite cells and modules, and show a comparison between MPPT and Asymptotic P_{MAX}. Using MPPT we demonstrate the interplay between metastability and degradation in perovskite modules, and emphasize the necessity to develop preconditioning protocols for stabilizing these devices. Our aim is to promote development of consensus protocols for performance calibration of perovskite modules, and to advance their credible power ratings, which will be beneficial to the growth of perovskite technology in the PV market.**

Keywords—Power rating, Perovskite, PV modules

I. Introduction

With the rapid growth in efficiencies [1,2] and continuous improvement in device stability [3], the perovskite technology has been transitioning from lab-scale research devices to larger prototype modules. As a number of perovskite startup companies target on introducing perovskite modules into commercial market, accurate and reliable power rating of these products is increasingly important for PV investors and customers to make financial decisions on advancing perovskite deployment in the renewable energy portfolio. In this contribution we present the application of the Asymptotic P_{MAX} method, that our group has developed for perovskite PV cells [4,5] to perovskite PV *modules*. After a brief justification for the need to measure stabilized performance for perovskite PV devices, we present our choice for such a method, discuss some of the challenges of applying it to modules and show initial results collected on monolithically integrated, series-connected perovskite modules. Maximum Power Point Tracking (MPPT) is another currently more common stabilization method for perovskite modules [6]. Here we also present our MPPT protocol and a comparison between MPPT and Asymptotic P_{MAX}. We note that the PV testing community has not yet arrived at a consensus protocol for the performance characterization of perovskite PV, and while our group has so far developed and adopted the Asymptotic P_{MAX} method, other major independent PV testing laboratories are using MPPT to obtain the stabilized performance. Our paper aims to contribute to the ongoing discussion on consensus protocols for perovskite testing in the firm belief that it should be reached by intercomparisons between the various methods currently employed.

The power rating of a conventional Si PV module is determined by a current versus voltage (I-V) scan of the device under illumination, typically measured over relatively short scanning time scales of hundreds of milliseconds to seconds. In particular, when a flash simulator is used for testing, a typical flash duration of 100 ms or less is sufficient for measurement of an IV curve on a Si module (note that some types of Si modules, e.g., high-capacitance PERC and HIT, may require longer pulses to avoid capactive errors [7]). However, it has been shown that such I-V scans at these short time scales are unreliable for perovskite PV devices due to their dynamic device responses to changes in measurement conditions (e.g., I-V scan rate/direction and pre-conditioning requirement) and a method to stabilize the output of the device under defined light and voltage bias conditions is needed for reliable performance calibration [4-6, 8, 9].

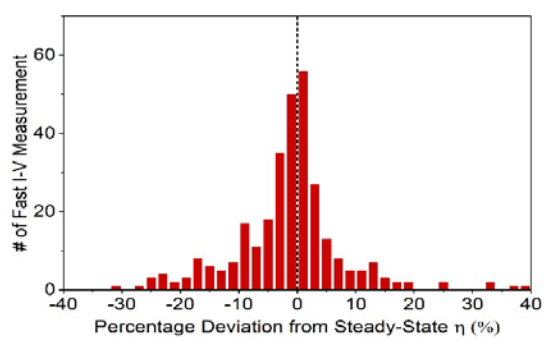

Figure 1 Histogram of efficiency deviation in a relative scale from the fast I-V scans (100 mV/s scan rate) over the asymptotic P_{MAX} scans on nearly 100 perovskite solar cells. These cells were independently submitted to NREL CMP group from independent customers all over the world.

Fig. 1 shows the performance deviation histogram of nearly 100 perovskite cells extracted with over 300 conventional ("fast", typical scan rate 100 mV/s) I-V scans compared to their efficiency obtained by the asymptotic P_{MAX} method [4, 5]. Note that all the cells were independently submitted to the NREL Cell and Module Performance (CMP) group for performance calibration since 2016. The "transient" efficiencies from the fast I-V scans are normalized to their respective steady-state values obtained using the Asymptotic P_{MAX} method, and then subtracted from unity. In Fig. 1, the measured efficiencies from fast I-V scans scatter around the steady-state efficiency baseline; however a significant number of efficiencies calculated from the fast IV vary by more than 10% (relative) and some by up to 30%, from its stabilized value. As a result, it is very difficult to conduct meaningful performance comparisons between perovskite PV architectures and between perovskites and other PV technologies when efficiencies are measured with conventional I-V scans at typical scan rates.

While data comparable to Fig. 1 do not, to our knowledge, exist yet for perovskite modules, there is no reason to expect that a module will show a stable response to a conventional IV scan when a cell doesn't. Our approach to improving accuracy on reporting the performance of perovskite modules, which is to apply steady-state efficiency measurement protocols on perovskite modules, should be a better way to serve as a benchmark for perovskite PV commercialization. In the following, we will detail NREL's steady-state efficiency measurement protocols, first the Asymptotic P_{MAX} Scan followed by MPPT, and discuss the challenges for measuring perovskite modules. We note that this work only focuses on single-junction perovskite thin film modules and does not discuss other important module approaches such as perovskite on silicon.

II. CHALLENGES OF MEASURING PEROVSKITE MODULES

The P_{MAX} calibration of a commercial Si or thin film PV module is typically carried out on a flash simulator. For our Spire5600 flash simulator the flash duration is around 100 ms. Figure 2 shows an attempt at measuring an IV of a perovskite module on our flash simulator and demonstrates, as expected from the discussion above, how invalid such a flash test is.

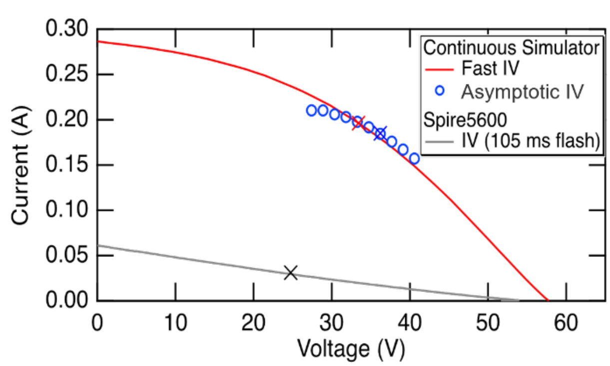

Figure 2. IV curves of a perovskite module obtained using a Fast IV (red curve, 5 s scan time) and asymptotic IV (blue circles, total duration 1122 s) on a Large-Area Continuous Module Simulator, and an IV curve carried out during a single flash on a Spire5600 flash tester (gray curve, 105 ms flash duration). Maximum power points are indicated by crosses. During the asymptotic scan the module temperature was controlled to (25±1) °C, as in all other IV measurements.

Figure 2 also shows a fast IV, collected in 5 s, which is a typical setting for conventional modules in our continuous module simulator. The asymptotic IV points around P_{MAX} are also shown (discussed in the following section). Figure 2 clearly illustrates that continuous illumination is needed for IV measurement on this perovskite module. We note that the behavior shown in Figure 2 is an extreme case of a module that does not respond to the flash, but is not what we *always* observe in perovskite modules; there are other modules for which the flash IV is much closer to that measured on the continuous simulator. More work is needed to determine a solution for high throughput testing of devices in a production line. As Figure 1 demonstrates, a conventional IV is unreliable as a calibration method, implying that a flash IV is unreliable as well. On the other end of time scales for an IV calibration, performing an Asymptotic IV that exceeds 15 minutes of scan time per module will also be highly impractical on a production line. However, is there at least a *correlation* between conventional IV or flash IV with the more reliable stabilized performance of the device that can provide the manufacturing community with a high throughput inline evaluation tool? This question remains open and more results on more perovskite modules are needed to try to answer it.

As already discussed, obtaining a stabilized output from a perovskite device requires long scan times (1122 s in the example of Fig. 2) during which the device has to be kept at Standard Test Conditions (STC), i.e., irradiance of 1000 W/m^2 and device temperature of 25 °C. This temperature requirement for an STC calibration, monitored by a sensor attached to the device, is easy to achieve on small perovskite cells of typical size of a few cm^2; however it is much more difficult for larger devices and presents a major challenge of applying the Asymptotic P_{MAX} or MPPT to perovskite modules. The Asymptotic P_{MAX} and MPPT protocols we describe below do not require specialized equipment beyond a standard continuous large area simulator and IV scanning electronics that a typical module testing laboratory already uses. It does however require a method, such as the temperature-controlled chamber we use, to keep the module temperature to 25 °C during measurement.

III. ASYMPTOTIC P_{MAX} SCAN AND MPPT

To conduct an Asymptotic P_{MAX} scan, we begin with a conventional fast IV scan (such as the one shown in Figure 2, red curve) to obtain approximately the voltage V_{MAX} corresponding to the maximum power point P_{MAX} of a module. We then select 10 (or any predefined number of) voltages around V_{MAX} and start the Asymptotic IV scan by applying a constant voltage from this voltage set and monitoring the current of the module. When the current changes less than 0.1%/minute for >30 s, we record the average current for the last 30 s and move to the next voltage [5]. This process produces the Asymptotic IV results shown in Figure 3 and they correspond to a partial IV scan around P_{MAX}. After the stabilized current for all voltage points has been obtained, we convert the current vs. voltage to power vs. voltage, shown in the insert of Figure 3, and apply a standard algorithm [5, 12] to obtain the P_{MAX} of the module.

The criteria for accepting the current measurement as stabilized, a change of less than 0.1%/minute for 30 s, provides a balance between measuring the current long enough for stabilization to occur, but not too long to initiate irreversible degradation in typical perovskite cells [5]. To date, about 75% of perovskite modules submitted to our group for performance characterization reach stabilized current under this criterion. For the remainder, continuous degradation, manifested by a monotonic decrease in current, sets in during the asymptotic P_{MAX} scan preventing the 10-point scan from completing. Currently the perovskite modules under development are smaller than other commercial thin film technologies, for example the current record perovskite module has a designated area of 804 cm^2 [2, 13]. Optimizing the choice of stabilization criteria, and in fact the testing method itself (more below), is therefore work in progress and will be reassessed as larger perovskite modules become available.

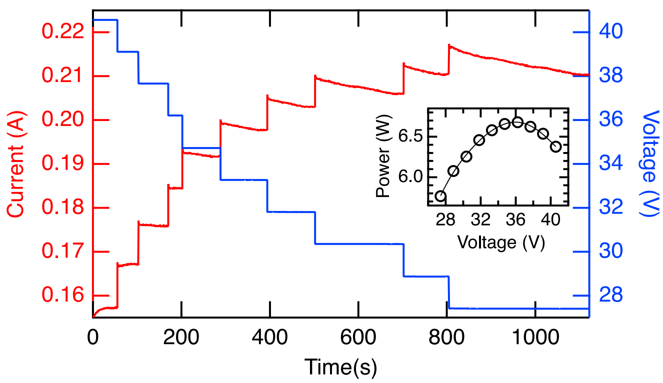

Figure 3. Current (red, left axis) and Voltage (blue, right axis) versus time for an Asymptotic P_{MAX} scan on a perovskite module. The stabilized current values correspond to the blue circles in Figure 2 and the corresponding Power vs. Voltage is shown in the insert, along with a standard polynomial fit to obtain P_{MAX}.

The challenge of maintaining the module temperature to as close to 25 °C as possible for power rating at STC is met in our group by using a continuous AAA+ module simulator that has a temperature-controlled environmental chamber, the Eternalsun Spire High-Performance Light Soaker (HPLS) [14]. In a rather extreme case of an asymptotic P_{MAX} measurement that lasted over 1 hour, the temperature of the module was still kept at (25±1) °C as shown in Figure 4.

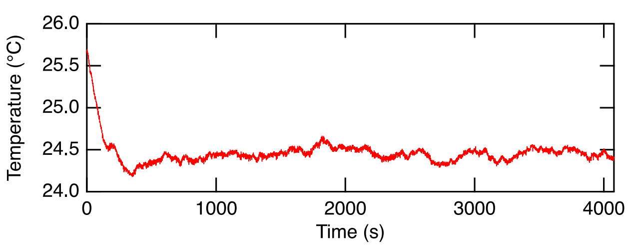

Figure 4. Temperature vs. time, monitored by an RTD temperature sensor attached to the back of a perovskite module, during an unusually long measurement of an asymptotic P_{MAX} in the HPLS simulator.

Another commonly used measurement technique for perovskite (and other emerging) cells and modules is MPPT. This method actively tracks the P_{MAX} of the device using a "perturb-and-observe" algorithm. Essentially, the voltage applied to the module in every step is changed by a preset ΔV (and adjustable) and the change of the output power, ΔP, is measured. If ΔP>0 the next ΔV step will be in the same direction; if ΔP<0 the sign of ΔV is changed [6]. Figure 5 shows a typical MPPT measurement for a perovskite minimodule. In this case, we accept the power as stabilized if it changes by <0.1%/min for at least 30 s. This stop criterion is applied after a minimum measurement time of 5 minutes. The power over the last 30 s is then averaged to give the rated power of the device, also shown in Figure 5. Comparison of this power measurement to the P_{MAX} extracted from conventional IVs (triangles in Figure 5) once again demonstrates the unreliability of conventional IVs for power-rating the module.

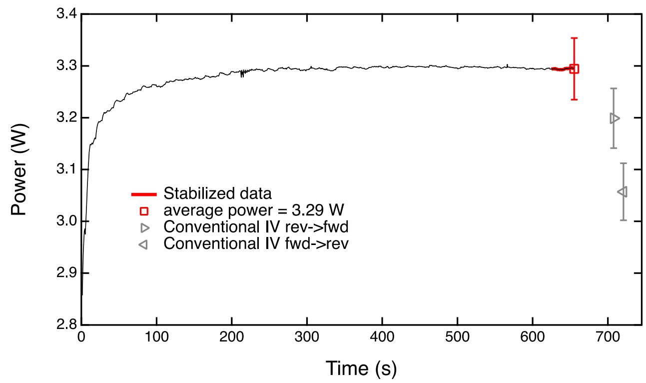

Figure 5. Power vs. time during an MPPT scan of a perovskite module. The scan conditions are: after an initial time window of 5 min, accept the power as stabilized if it changes less than 0.1%/min for 30 s. The thicker red line indicates the last 30 s of the scan, that are averaged to give the P_{MAX} (red quare). The trianges indicate the P_{MAX} extracted from conventional IVs (both directions, 5 s duration) immediately after the MPPT measurement.

Figure 6 shows a comparison between sequential MPPT and Asymptotic P_{MAX} measurements on this device, labeled MPPT1,2,3, compared to asymptotic scans labeled Asy1 and Asy2 conducted after the first and second MPPT scans. The discrepancy between the P_{MAX} obtained with the asymptotic method and MPPT is 3.1% in the first scan and down to 1.9% (and marginally in agreement within the estimated uncertainty of each measurement) for the second scan. The device was then placed in dark storage at room temperature in air for 4 days, after which three MPPT scans labeled day4-MPPT1,2,3 were carried out. A considerable recovery of P_{MAX} is observed in the MPPT scans of day 4, indicating metastability in this device. However, while the power did stabilize for each scan according to our 0.1%/min criterion, a steady decline of P_{MAX} over consecutive MPPT scans is observed on both days. These measurements were conducted as an initial step toward determining a preconditioning protocol that would result in repeatable P_{MAX} measurements in perovskite modules, which however still remains work in progress as the data of Figure 6 indicates.

Finally, we emphasize that for an accurate performance characterization of PV modules, an accurate measurement of the spectral response, usually given as the Quantum Efficiency (QE), is also crucial since it is used to derive the spectral mismatch factor M under simulator spectrum and then to translate the I-V measurement to STC for meaningful comparisons with other PV technologies. Here we note that the QE of emerging PV cells including perovskites sometimes cannot be measured correctly using the same protocol for Si or

CIGS devices due to the complex non-linear current response. Chopping frequency and light bias level can have a strong effect on the QE shape and magnitude [5,15,16]. Therefore, it is important to scrutinize these effects when setting up a QE measurement on perovskite PV devices.

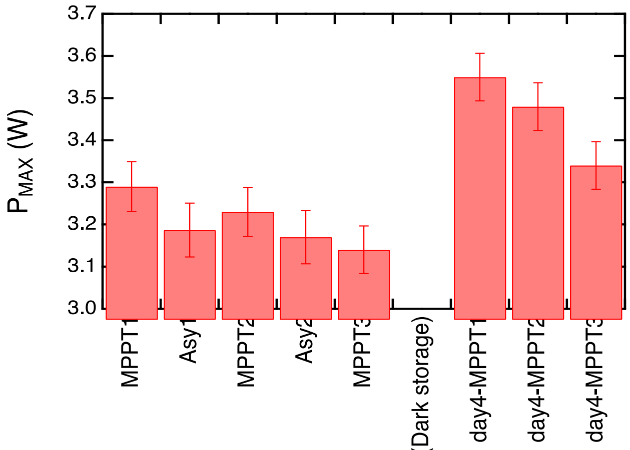

Figure 6. Comparison of P_{MAX} from sequential MPPT and Asymptotic P_{MAX} measurements, followed by dark storage in air for 4 days, followed by 3 consecutive MPPT scans (no asymptotic comparison on day 4). The stop criteria is the same as in the measurement of Figure 5.

IV. Summary and Perspectives

As shown in the previous sections, the criteria for accepting "stabilized" power output are a very important part of any steady-state efficiency calibration protocol. Without a conformity of the stabilization criteria, the extracted device performance for perovksite PV devices may vary with different I-V scan conditions. As a result, it has motivated us to adopt some generalized stabilization thresholds when performing steady-state performance measurements. For instance, to establish when a measured current has reached the short-term stability at each voltage bias, the NREL CMP group has thoroughly studied stabilization criteria for current acquisition during the asymptotic P_{MAX} scan, including what current change rate versus time should be adopted and how to report stabilized current during the asymptotic P_{MAX} scan [5]. However, the situation becomes complicated when metastability and/or degradation cause changes in perovskite devices during the measurement process. The performance of some perovksite PV devices can change with pre-conditioning, e.g., depending on whether they are stored in dark condition or light-soaking before testing. Furthermore, the steady-state measurement must take a much longer time than the conventional fast I–V scan to capture the stabilized device performance, but device degradation is commonly seen in perovskite devices. So far, there is no agreement of pre-condition procedure and stabilization criteria reached in the perovskite PV community. Therefore, it is difficult to have a meaningful performance comparison if different measurement procedures are adopted.

In this paper, we emphasize the need for the PV testing community to continue the discussion of best practices for reliable performance characterization of perovskite modules. The Asymptotic P_{MAX} and MPPT methods discussed here are two commonly proposed method. Their merit will have to be evaluated and compared with other similar methods that other testing laboratories around the world have chosen to use. Arriving at a consensus protocol for perovskite module P_{MAX} rating at STC will improve the accuracy of comparisons between perovskite module architectures and between perovskites and other PV module technologies. In addition, as mentioned above, it will be beneficial to develop more rapid although necessarily less accurate performance measurement methods that can ultimately be applied in a high throughput manufacturing setting.

We also note that the discussion in this paper is focused on single-junction perovskite modules. Perovskite/Si and other perovskite-related tandem modules could be a potential player in the commercial PV market as well. Most measurement procedures discussed above can be transferred to these tandem technologies except that the spectral tuning procedure for tandem devices is more complicated [17,18]. A thorough spectral tuning study on perovskite tandem modules is needed in the future.

Acknowledgment

The authors would like to thank Uni-Test for donating the perovskite modules used in this work. This work was authored in part by Alliance for Sustainable Energy, LLC, the manager and operator of the National Renewable Energy Laboratory for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office (SETO) Agreement Number 34351.

References

[1] NREL Best Research-Cell Efficiency chart. https://www.nrel.gov/pv/cell-efficiency.html.

[2] M. Green et al,. "Solar cell efficiency tables (version 57)." Progress in Photovoltaics: Research and Applications, 29, 31-15, 2021.

[3] M. Khenkin, et al. "Consensus statement for stability assessment and reporting for perovskite photovoltaics based on ISOS procedures." Nature Energy 5, no. 1, 35-49, 2020.

[4] T Moriarty, and D Levi. "NREL's Cell and Module Performance group's asymptotic Pmax protocol for perovskite devices." In 2017 IEEE 44th Photovoltaic Specialist Conference (PVSC), pp. 483-486. IEEE, 2017.

[5] T. Song. D. Friedman, N. Kopidakis, "Comprehensive Performance Calibration Guidance for Perovskites and Other Emerging Solar Cells", Adv. Energy Mater., 2100728, 2021.

[6] N. Pellet, et al. "Hill climbing hysteresis of perovskite - based solar cells: a maximum power point tracking investigation." Progress in Photovoltaics: Research and Applications 25.11, 942-950, 2017.

[7] R. A. Sinton, H. Wilterdink, J. Dinger, A. L. Blum, W. Dobson, C. Sainsbury, In 44th IEEE Photovoltaic Specialist Conf. (PVSC), IEEE, Washington, DC, pp. 2765–2770, 2017.

[8] H. Snaith, et al., "Anomalous hysteresis in perovskite solar cells," J. Phys. Chem. Lett. 5(9), 1511–1515, 2014.

[9] E. Unger et al.,. "Hysteresis and transient behavior in current–voltage measurements of hybrid-perovskite absorber solar cells." Energy & Environmental Science 7.11: 3690-3698, 2014.

[10] R. Dunbar et al., "How reliable are efficiency measurements of perovskite solar cells? The first inter-comparison, between two accredited and eight non-accredited laboratories." J. Mater. Chem. A (5): 22542–22558, 2017.

[11] E. Zimmermann et al., “Characterization of perovskite solar cells: Towards a reliable measurement protocol.” APL Mater. 4: 091901, 2016.

[12] ASTM E948-15 Standard Test Method for Electrical Performance of PV Cells Using Reference Cells Under Simulated Sunlight, 2015.

[13] NREL Champion Module Efficiency Chart. https://www.nrel.gov/pv/cell-efficiency.html.

[14] ExternalSun Spire high-performance light soaker. https://eternalsunspire.com/.

[15] G. Bardizza, Pavanello, D., Galleano, R., Sample, T. and Müllejans, H., "Calibration procedure for solar cells exhibiting slow response and application to a dye-sensitized photovoltaic device." Solar Energy Materials and Solar Cells 160: 418-424, 2017.

[16] Y. Hishikawa, M. Yanagida, and N. Koide. "Performance characterization of the dye-sensitized solar cells." In 31st IEEE Photovoltaic Specialists Conference, 2005., pp. 67-70. IEEE, 2005.

[17] T. Moriarty, J. Jablonski, and K. Emery. "Algorithm for building a spectrum for NREL's one-sun multi-source simulator." In 38th IEEE Photovoltaic Specialists Conference, pp. 001291-001295. IEEE, 2012.

[18] T. Song, “Critical Steps Towards Accurate Efficiency Measurement of Emerging Tandem Solar Cells”, In 47th IEEE Photovoltaic Specialists Conference, pp, 1941-1943 IEEE, 2020.