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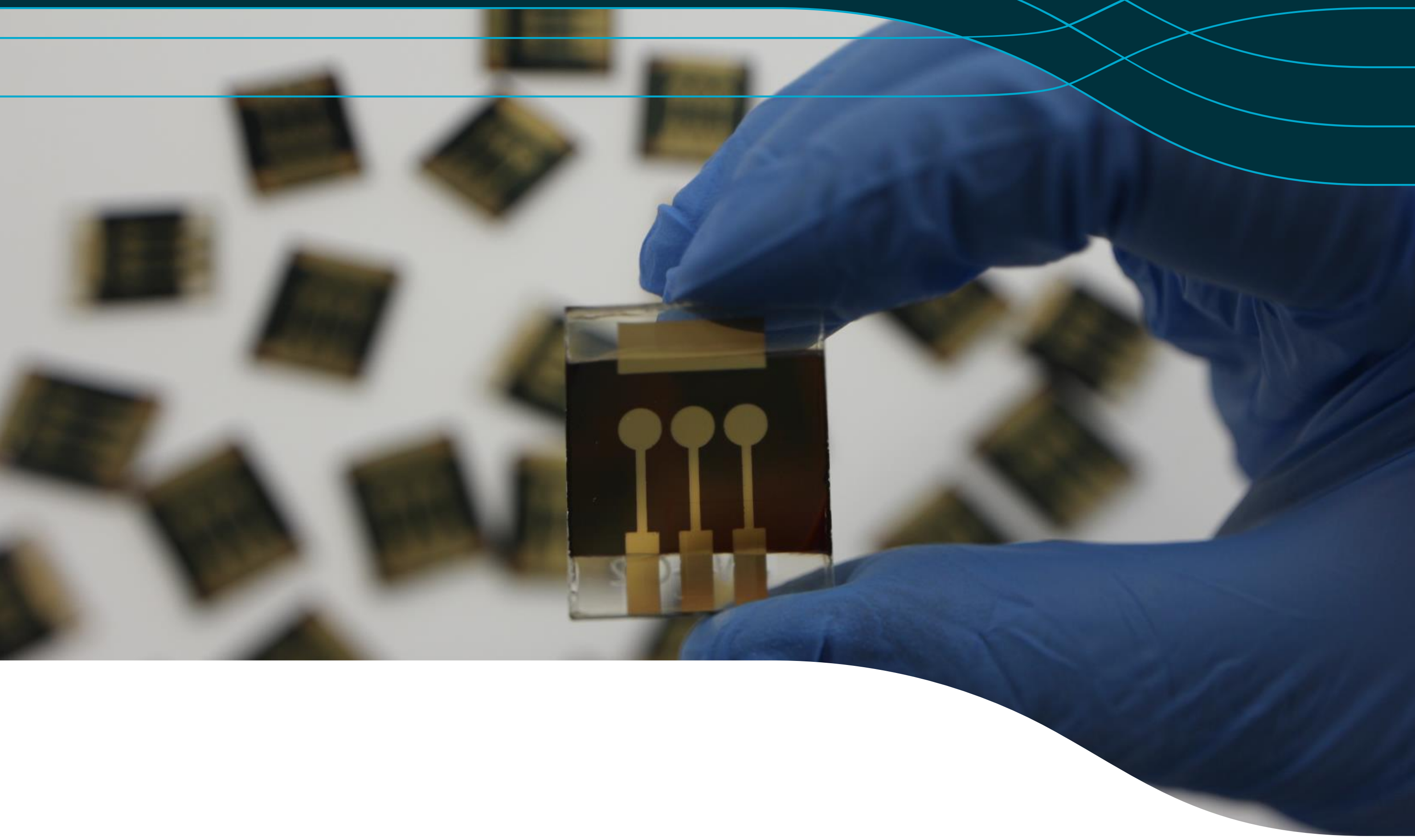
Specifying Guidelines for Assessing Perovskite Solar Cells

Public Impact Report

EP19586
30th July 2019
Prepared for Australian Renewable Energy Agency (ARENA) on project 2015/ERP017



Citation

Dunbar, R., Duck, B. C., Anderson, K. F., Jones, T. W., Wang, J. (T-W), Mihaylov, B., Lin, L., Feenstra, M., Ameri, Lian, C., M., Blakborn, I., Fell, C. J., Duffy, N. W., Wilson, G. J. (2019) "Specifying Guidelines for Assessing Perovskite Solar Cells, Public Impact Report" CSIRO, Australia.

Date	Revision	Details	Prepared	Approved
30/07/2019	A	Issued for client review	G J Wilson	G J Wilson

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Important disclaimer

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Executive Summary

The Report is intended to provide a summary of the outcomes achieved in the delivery of the ARENA funded '*Specifying Guidelines for Assessing Perovskite Solar Cells*' Measure project (2015/ERP017) completed in January 2019. Outcomes for the project have met all agreed objectives including:

Outcome 1: Produce guidelines for assessing perovskite solar cells

The primary objective of the Measure project was to engage with the researcher community in Australia and internationally to assess and develop best practice methodologies for the measurement of emerging photovoltaic technologies, with a focus on perovskite solar cells. Outcomes of the R&D and engagement activities have been captured in peer reviewed publications and disseminated to the broader scientific community through conference and workshop participation.

Importantly, Final Guidelines for the measurement of power conversion efficiency of devices have been developed. Further, these outcomes contributed to the broader international scientific efforts in the field, by inclusion of significant content to a draft standards publication – a Technical Report – entitled *Measurement Protocols for Photovoltaic Devices Based on Organic, Dye-Sensitized or Perovskite Materials*, for the International Electrotechnical Commission (IEC), Technical Committee 82; the international body for standardisation of photovoltaics worldwide. The report, following member countries in IEC TC82 WG2 voted unanimously (with a few abstaining) to endorse the publication of the Technical Report document, now has the identifier IEC TR 63228 ED1 and a publication timeframe on the IEC website.

Outcome 2: Produce recommendations for device packaging

Final methodologies for device fabrication, encapsulation and packaging for devices assessed in the Measure were developed and will be further disseminated in peer reviewed journal publications, in support of the protocols outlined in the Final Guidelines.

Outcome 3: Inter-laboratory researcher exchange

Over the 36 months of the Measure project a total of 9 researcher exchanges were undertaken with the project team, most for an average of 6 months, enabling deep engagement with numerous researcher groups globally. The Measure brought together researchers from Germany (Hamburg University of Applied Science), Netherlands (TU Delft), United Kingdom (University of Bath), China (Huazhong University of Science and Technology) and United States of America (Stanford University).

Outcome 4: Scientific papers and conference presentations

The Measure has delivered important experimental outcomes and translated these to accessible Knowledge Sharing outcomes through publication of no less than three (3) articles in high impact journals. Publications included an invited submission to *Progress in Photovoltaics* and the dissemination of an international Round Robin study in *Journal of Materials Chemistry A*. Further, important dissemination activities included twelve (12) oral and five (5) poster conference presentations as agreed Knowledge Sharing activities during the project lifetime.

1 Introduction and Project Description

CSIRO, with funding support from ARENA, has established the **National Solar Energy Centre (NSEC)** in Newcastle to conduct world class research and development in concentrated solar, thermal processes, components, photovoltaics and grid and network integration. CSIRO is pioneering low-emission technologies that create value for industry and households and provide the knowledge which will help guide Australia towards a smart, secure energy future. Our solar project priorities focus on research at NSEC and examine the technical, economic, environmental and transitional issues for uptake of new energy technologies.

CSIRO was awarded funding support through the Emerging Renewables Program of the Australian Renewable Energy Agency (ARENA) to undertake a Measure to establish Guidelines for measuring the performance of Next Generation Photovoltaics, in particular emerging photovoltaic (PV) technologies such as Perovskite solar cells. This Measure accessed and utilised accredited standard photovoltaic cell measurement facilities at NSEC, as part of the CSIRO PV Performance Laboratory, as a critical aspect of the delivery of this project.

Further details are available on the related ARENA project page.

At the project conception, standard laboratory methods failed to account for the special requirements of these new devices, meaning that practices varied widely and breakthrough results from different groups could not be compared. This project enabled Australian research labs to have access to a best-practice methodology that is reliable, transferable and accurately reflects the true performance of the devices under conditions comparable to a typical environment.

A project repository of Measure outcomes was established:

https://research.csiro.au/solar/arena-measure/

The focus of the Measure was Knowledge Sharing where the development of Guidelines has provided technical guidance for researchers, funding bodies and industry on the potential of new photovoltaic technologies, such as Perovskite solar cells, developing a shared understanding of a standard approach for performance assessment.

1.1 Why Guidelines?

Emerging photovoltaic (PV) technologies such as Perovskite solar cells, although showing extremely encouraging performance, present significant measurement challenges compared to more established PV technologies. Performance characterisation of cells based on the well-established crystalline silicon technology are routinely undertaken at accredited measurement laboratories using methods published in international standards. Emerging technology measurement challenges mean these standards alone are insufficient for accurate performance measurements.

CSIRO established and operates PV Performance Laboratory (PVPL), the only laboratory in the Southern Hemisphere that is accredited for PV cell measurement against required international standards. CSIRO, together with Australian and international partners, undertook the development and dissemination of best-practice guidelines to promote a culture of high accuracy measurement excellence in Australia. Through Knowledge Sharing and researcher placements, CSIRO has endeavoured to build consensus on Guideline suitability with other accredited laboratories worldwide and promote the use of these methods in Australian research laboratories.

Project outcomes are intended to reduce the risk of scientific misinterpretation and misdirected research by addressing significant unresolved challenges in efficiency measurements of Perovskite and related emerging PV devices.

1.2 Project Scope and Outcomes

This project builds on ARENA support for CSIRO's PV Performance Laboratory, the Southern Hemisphere's only accredited facility for standard performance measurement of photovoltaics. The result will be accelerated development and commercialisation pathways for Australian developed PV technologies.

The primary output is a set of Guidelines for accurate device efficiency assessment, which can be used to perform high accuracy measurements at accredited laboratories such as the PVPL. Further, the guidelines will allow for different levels of rigour to suit research laboratories with a range of capabilities:

Basic, requiring only simple instrumentation;

Intermediate, requiring instrumentation found in most research laboratories; and

Advanced, requiring instrumentation and procedures typically only found in accredited labs, such as the PVPL.

Laboratories that intend to follow the Guidelines will then understand the minimum requirements for their desired level of accuracy. In addition, the project assessed processes of fabrication and encapsulation and the resultant effects on device performance.

1.3 Local Knowledge – Global Benefit

This Measure addressed a crucial barrier to reliable assessment of device performance for emerging PV technologies. Through this project, CSIRO has strengthened strategic partnerships between Australia and international researchers at accredited laboratories and facilitated access to critical testing facilities and expertise available through the CSIRO PV Performance Laboratory (PVPL).

The Final Guidelines are intended to provide technical guidance for researchers, funding bodies and industry on the potential of new photovoltaic technologies, such as Perovskite solar cells, using a standard approach for performance assessment.

The outcomes from the Measure are intended to support building capacity and development of important skills for assessing emerging PV device performance, increasing the investment potential for industry into breakthrough technologies, drive innovation and overcome roadblocks for developers of promising compelling PV technologies.

2 Project Outcomes

2.1 Achievements and Lessons Learnt

Over the course of the 3 year project, there has been considerable knowledge gained in both the fabrication, handling and performance assessment of perovskite solar cells, in particular stability of mixed-cation, mixed-halide chemistries. From the extended studies the project team has developed new understanding of fabrication of large-area (and champion cell) devices that are of benefit to the broader scientific community.

A key achievement has been the involvement by members of the Peer Review Committee (PRC) to the IEC committee reviewing measurement protocols for emerging photovoltaic technologies.

2.1.1 Increased stability and durability – stabilised larger area (1 cm^2) perovskite devices

Over the course of delivery of the Measure, improvements in the baseline performance of small area cells (~0.1 cm^2) was achieved to a stable performance exceeding 18% PCE. So called 'Champion' or 'hero' devices (a single cell on a substrate in a batch of cells) has reached 20.1% PCE translating to fabrication of large area cells (>1 cm^2) as an industry acceptable device area, used extensively in the Final Guideline assessment, have achieved verified measurement of 18.1% PCE.

Historical device performance improvement

An outcome from the Measure project has been the progress and statistical improvement in device fabrication and performance – depicted in Figure 1 (below) are the measured efficiency vs. time over a 24 month period, with more than 4000 cells fabricated and tested. Important has been the significant reduction in batch variability over time.

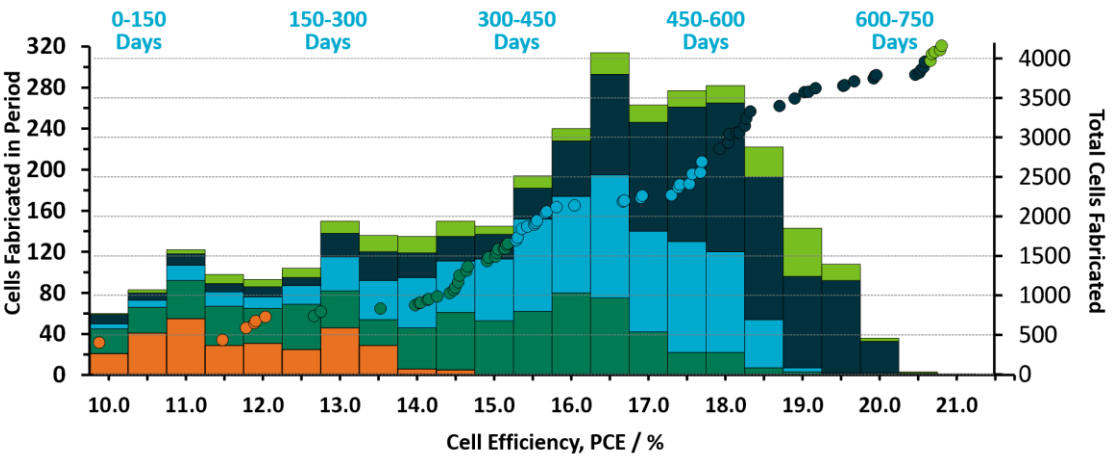

Figure 1. Cell performance history over project lifetime. Different colours represent distinct cell fabrication campaigns where there cell device performance has improved over a 24 month (750 day) period of the project.

2.1.2 International Engagement and Consensus on Guidelines

Early in the project an International Peer Review Committee (PRC) was established to guide the outcomes of the project toward consensus, through engagement in international activities around the core topic area of measurement and assessment of emerging photovoltaic technologies.

Over the course of the Measure project it became apparent that 3 members of the international PRC were involved in drafting a new standards publication – a Technical Report – entitled *Measurement Protocols for Photovoltaic Devices Based On Organic, Dye-Sensitized or Perovskite Materials*, for the International Electrotechnical Commission, Technical Committee 82, the international body for standardisation of photovoltaics worldwide.

In December 2018, member countries in IEC TC82 WG2 voted unanimously (with a few abstaining) to endorse the publication of the Technical Report document, which now has the identifier IEC TR 63228 ED1 and a publication timeframe; this can be found on the IEC website:

This was an important outcome for the Measure where incorporation of methodologies developed in the project to the final Technical Report provides considerable support toward the global objectives of consensus in this emerging area of photovoltaics.

2.1.3 Delivery and Completion of Outcomes

Outcome 1: Produce guidelines for assessing perovskite solar cells

The primary objective of the Measure project was to engage with the researcher community in Australia and internationally to assess and develop best practice methodologies for the measurement of emerging photovoltaic technologies, with a focus on perovskite solar cells. Outcomes of the R&D and engagement activities have been captured in peer reviewed publications (see detailed list) and disseminated to the broader scientific community through conference and workshop participation. Final Guidelines for the measurement of power conversion efficiency of devices have been developed as an output for the Measure, included in Appendix A.

Outcome 2: Produce recommendations for device packaging

Final methodologies for device fabrication, encapsulation and packaging for devices assessed in the Measure were developed and will be further disseminated in peer reviewed journal publications, in support of the protocols outlined in the Final Guidelines.

Outcome 3: Inter-laboratory researcher exchange

Over the 36 months of the Measure project a total of 9 researcher exchanges were undertaken with the project team, most for an average of 6 months, enabling deep engagement with numerous researcher groups globally. This was an important and invaluable aspect of the planned project activities and facilitated two-way deep engagement between the Group of origin and the CSIRO host Group, which enabled sharing of knowledge from the project. By far this was the most appreciated activity by the team and the exchange researchers, with numerous networking and collaboration outcomes achieved.

The Measure brought together researchers from Germany (Hamburg University of Applied Science), Netherlands (TU Delft), United Kingdom (University of Bath), China (Huazhong University of Science and Technology) and United States of America (Stanford University).

Outcome 4: Scientific papers and conference presentations

The Measure has delivered important experimental outcomes and translated these to accessible Knowledge Sharing outcomes through publication of no less than three (3) articles in high impact journals. Publications included an invited submission to *Progress in Photovoltaics* and the dissemination of Roadshow 1 outcomes in *Journal of Materials Chemistry A*. A further four (4) journal manuscripts are under internal and external peer review.

Further, important dissemination activities included twelve (12) oral and five (5) poster conference presentations as agreed Knowledge Sharing activities during the project lifetime.

Full details of the outputs can be found in Section 2.3, p6.

2.2 Conclusions and Recommendations

Observations and Recommendations from Roadshow and Partner Engagement Activities:

1. Two primary sources of error commonly observed during engagement with researcher partners can be traced to correctly setting the illumination level and ensuring the device temperature remains at the reference value. Temperature control is particularly important for any measurements with a significant duration such as Dynamic IV and settled power output (SPO)/settled current at fixed voltage (SCFV). Appropriately calibrated reference cells should be used that have a spectral response similar to the DUT and mismatch corrections should be applied. Lamp characterisation (homogeneity, temporal stability) and correct sample positioning are also required to ensure the illumination level remains correct.
2. The use of Dynamic *I-V* works well for producing hysteresis free I-V curves and is more closely representative of steady-state conditions. Such curves are a requirement to ensure the measured values are representative of the true device performance. Care should be taken to ensure that the appropriate settling time constants and assessment periods are used to achieve truly reproducible results.
3. The use of settled power output (SPO)/settled current at fixed voltage (SCFV) is able to achieve good estimates of device performance when the bias voltage is well chosen.
4. Both careful stabilisation and pre-conditioning steps are required for repeatable stable measurements. Verification of this should be performed through repeated measurement steps for the stabilisation.
5. Regardless of approach all steps (including device history) should be reported. This includes any rest periods and resting voltage bias levels the device is exposed to prior to measurement as well as a steps used for stabilisation and pre-conditioning.
6. Results that are not independently certified may have errors of at least ±10 % when the above conditions are not considered.

2.3 Publications

2.3.1 Journal Publications

- **Invited submission:** Dunbar, R. B., Moustafa, W, Pascoe, A., Jones, T. W., Anderson, K. F., Cheng, Y, Fell, C. J., & Wilson, G. J.; "*Pre-conditioning of perovskite solar cells and its influence on stabilization time*", *Progress in Photovoltaics: Research and Applications* **2017,** *25* (7), 533-544; https://doi.org/10.1002/pip.2839.
- **Published Extended Abstract:** Duck, B. C.; Dunbar, R. B.; Lee, O.; Anderson, K. F.; Jones, T. W.; Wilson, G. J.; Fell, C. J. In *Energy yield potential of perovskite-silicon tandem devices*, Photovoltaic Specialists Conference (PVSC), 2016 IEEE 43rd, IEEE: 2016; pp 1624-1629; https://doi.org/10.1109/PVSC.2016.7749896
- **Accepted Manuscript:** Dunbar, R. B.; Duck, B. C.; Moriarty, T.; Anderson, K. F.; Duffy, N.; Fell, C. J.; Kim, J.; Ho-Baillie, A.; Vak, D.; Duong, T.; Wu, Y.; Weber, K.; Pascoe, A.; Cheng, Y.-B.; Lin, Q.; Burn, P. L.; Bhattacharjee, R.; Wang, H.; Wilson, G. J., *"How reliable are efficiency measurements of perovskite solar cells? The first inter-comparison, between two accredited and eight non-accredited laboratories"*, *Journal of Materials Chemistry A* **2017**, *5*, 22542: http://xlink.rsc.org/?DOI=c7ta05609e

2.3.2 Conference Presentations (chronological order)

- **Oral Presentation** – Asia-Pacific Solar Research Conference, Brisbane 2015
  - Dunbar, R. B., Moustafa, W., Jones, T. W., Anderson, K. F., Yao, Z., Fell, C. J., & Wilson, G. J.; "*Performance measurements of PV devices subject to metastability and degradation: efficiency of perovskite solar cells under standard test conditions*".
- **Oral Presentation** – Proceedings of the 32nd European Photovoltaic Solar Energy Conference and Exhibition in Munich Germany 20th-24th June 2016
  - Dunbar, R. B., Moustafa, W, Duffy, N. W., Duck, B. C., Jones, T. W., Anderson, K. F., Fell, C. J., & Wilson, G. J.; "*Pre-conditioning of perovskite solar cells and its influence on stabilization time*".
- **Poster Presentation** – 43rd IEEE Photovoltaic Specialists Conference, Portland Oregon, 5th – 11th June 2016
  - Duck, B. C., Dunbar, R. B., Lee, O., Anderson, Jones, T. W., Fell, C. J., & Wilson, G. J.; "*Energy Yield Potential of Perovskite-Silicon Tandem Devices*".
- **Oral Presentation** – Hybrid Organic Photovoltaics, Swansea UK, 28th June – 1st July 2016
  - Dunbar, R. B., Moustafa, W, Duck, B. C., Anderson, K. F., Jones, T. W., Fell, C. J., & Wilson, G. J.; "*Pre-conditioning routines for efficiency measurements of perovskite solar cells*".
- **Poster Presentation** – Hybrid Organic Photovoltaics, Swansea UK, 28th June – 1st July 2016
  - Dunbar, R. B., Jones, T. W., Anderson, K. F., Feron, K., Duck, B. C., Fell, C. J., & Wilson, G. J.; "*A light-beam induced current (LBIC) study of perovskite solar cells*".
- **Oral Presentation** – Asia-Pacific Solar Research Conference, Canberra 2016
  - Dunbar, R. B., Duck, B. C., Anderson, K. F., Jones, T. W., Fell, C. J., and G. J. Wilson, "*Comparison .of efficiency measurement methods for perovskite solar cells*".

- **Oral Presentations:** Asia-Pacific Solar Research Conference, Melbourne 5th-7th December 2017
    - G. J. Wilson, *"CSIRO PV Performance Laboratory: challenges in measurement, assessment and development of emerging perovskite semiconductors"*
    - C. J. Fell, *"The Impact of Technique on Measured Efficiency Values for Perovskite Solar Cells"*
    - J. M. Cave, *"Determining the Activation Energy for Hysteresis in Perovskite Solar Cells"*
- **Poster Presentations:** Asia-Pacific Solar Research Conference, Melbourne 5th-7th December 2017
    - L. Lin, *"Effective Interface Engineering in Triple-cation Mixed-halide Perovskite Solar Cells"*
- **Poster Presentation** – European Photovoltaic Solar Energy Conference (EUPVSEC) Amsterdam, The Netherlands 25-29 September 2017
    - Ricky B Dunbar, Timothy W Jones, Kenrick F Anderson, Benjamin C Duck, Christopher J Fell and Gregory J Wilson *"Preliminary guidelines for accurate I-V measurements on perovskite solar cells"*.
- **Oral Presentations:** 4th International Conference on Perovskite Solar Cells and Optoelectronics (PSCO-2018), Lausanne, Switzerland 30th September – 2nd October 2018
    - Benjamin C. Duck, Ricky B. Dunbar, Timothy W. Jones, Kenrick F. Anderson, Jacob (Tse-Wei) Wang, Liangyou Lin, Noel W. Duffy, Bo Chi, Christopher J. Fell, Gregory J. Wilson, "Challenges in measurement, assessment and development of emerging perovskite semiconductors: How reliable are efficiency measurements of perovskite solar cells?".
- **Oral Presentations:** Materials Research Society (MRS) Fall Meeting and Exhibition 25-30 November 2018, Boston Massachusetts USA
    - Liangyou Lin, Jacob Tse-Wei Wang, Timothy Jones, Gregory J. Wilson, "Strategically Construct Bilayer SnO_2 as Electron Transport Layer in Perovskite Solar Cells"
    - Jacob Tse-Wei Wang, Liangyou Lin, Timothy Jones, Mihaela Grigore, Andre Cook, Dane deQuilettes, Roberto Brenes, Benjamin Duck, Kenrick Anderson, Noel Duffy, Vladimir Bulović, Jian Pu, Jian Li, Bo Chi, Gregory J. Wilson, "Facile Recrystallization Process for Efficient Triple-Cation Mixed-Halide Planar-Structure Perovskite Solar Cells"
- **Oral presentation** – Asia-Pacific Solar Research Conference, Sydney Australia 4-6th December 2018
    - Blago Mihaylov, Benjamin Duck, Kenrick Anderson, Giorgio Bardizza, Toshiro Matsuyama, Gregory Wilson and Christopher Fell; "Progress Toward Standardised Measurement Protocols for Perovskite Solar Cells".
- **Poster presentation** – Asia-Pacific International Conference on Perovskite, Organic Photovoltaics and Optoelectronics, Proceedings of International Conference on Perovskite and Organic Photovoltaics and Optoelectronics (IPEROP19), Kyōto-shi, Japan, 27th-29th January 2019
    - Christopher Fell, Blago Mihailov, Benjamin Duck and Gregory Wilson, "Progress Toward Standardised Measurement Protocols for Perovskite Solar Cells".
- **Oral Presentation** – International workshop on evaluation method for perovskite solar cells, Kyoto Research Park, Kyoto, Japan 30th January 2019
    - Christopher Fell, Blago Mihailov, Benjamin Duck and Gregory Wilson, "Progress Toward Standardised Measurement Protocols for Perovskite Solar Cells".

Acknowledgments

CSIRO Energy and the Project Team would like to acknowledge funding support by the Australian Government through the Australian Renewable Energy Agency. This Measure received funding from ARENA as part of ARENA's Emerging Renewables Program.

CSIRO and the Project Team would also like to acknowledge support from participating research institutions in Australia and internationally who have contributed to the project objectives and outcomes through provision of samples and engagement in laboratory studies and research knowledge dissemination. The Project Team is grateful and wish to acknowledge the continued support and in-kind contributions to relevant activities from GreatCell Solar Australia.

Appendix A Final Guidelines

Introduction

The following Guidelines are intended for use in measurements of power conversion efficiency for perovskite solar cells using continuous simulated sunlight, see Note 1. These Guidelines should be considered as a supplement to the existing international PV measurement standards (the IEC 60904 series) to address specific challenges presented by perovskite-based devices. The intent of the Guidelines is to provide direction to enable accurate and repeatable measurements of the photovoltaic efficiency of the device, free of any artefacts of measurement.

The reader is encouraged to refer to existing articles on the topic [1–3], which contain a useful summary of good general practices to follow, most of which apply to measurement of research prototype PV cells in general, not just perovskites.

These Guidelines describe good measurement practices and provide specific direction for the measurement. Due to the large variety of material systems used in perovskite solar cells it is not possible to have one set of measurement parameters that is guaranteed to achieve an artefact-free, reproducible and representative measurement, particularly when the devices are meta-stable. It is possible however to describe protocols for characterising the behaviour of particular types (or batches) of cells, such that one cell from that type/batch can then be measured with high confidence.

Note 1: As it has not yet been demonstrated that measurements with pulsed illumination are appropriate for perovskite solar cells, these guidelines address measurements with continuous illumination only.

Note on device stability and related terminology

An important finding of this work is that usage of the terms *stability* and *stabilisation* in perovskite solar cell measurement is not well standardised, at least among researchers. To help resolve this problem we have elected in these Guidelines to follow the terminology used by the PV industry in relation to all PV devices, as defined in the IEC measurement standards, noting that this is also consistent with usage by the publishers of the solar cell efficiency tables.

To that end, the term *stabilisation* will be used herein to refer only to long-term stabilisation of the device, and not to stabilisation of a measurement reading. When referring to stabilisation of a measurement, e.g. the current at a given voltage point, we will use the term *settling*. This distinction allows short-term transients affecting *I-V* curve measurement to be treated as measurement issues, and clearly distinguishes them from real changes in device performance.

It is presently unclear whether it will ever be possible to stabilise a perovskite PV device to the level of commercial silicon-based products, where degradation rates in the field are typically <1% per year. The IEC standards have a way to deal with this issue, by assigning different stability criteria for the different PV technologies on the market, e.g. Si, a-Si, CdTe, CIGS. It is assumed that when perovskite PV technology reaches a level of stability suitable for commercial applications, a set of appropriate stability criteria will be added to the standards.

Definitions

***Copy test cell*:** A cell that has undergone identical fabrication (same batch), measurement and exposure histories as the test cell. Care should be taken to ensure that the test cell and copy cell are as similar as possible, as differences in properties will lead to errors in the measurement of the test cell.

First measurement point: The first measured value in an efficiency measurement, which depends on the employed method. For dynamic *I-V* curves, settled current at fixed voltage (SCFV) and pre-conditioning for conventional *I-V* curves, the first point is the settled current at the first voltage value. For maximum power point tracking (MPPT), it is the settled current at the determined V_{mpp}.

Hold state: This is the voltage bias, irradiance condition and temperature at which a device is kept in between *I-V* tests.

Forward *I-V* scan: Scan from starting voltage at or below short-circuit to open-circuit or above.

Meta-stability: A device property whereby the device performance changes reversibly in response to a change in its exposure conditions. The reverse pathway (usually a recovery) may or may not occur at the same rate as the forward pathway.

Pre-conditioning: Keeping the device at a set voltage bias, under set temperate and irradiance (or dark) for a short period of time (1 to 20 minutes) immediately before *I-V* measurement, with the aim of removing short to mid-term transient effects and bringing about a reproducible state.

Reverse *I-V* scan: Scan from starting voltage at or above open-circuit to short-circuit or below.

Settled: An *I-V* measurement point has settled if there is a negligible change in the reading on a timescale of at least a few seconds.

Stabilised: A PV device is considered stabilised if a steady-state measurement of its *I-V* characteristic is reproducible over a long period (noting that a brief pre-conditioning step may still be required immediately prior to the measurement). The requirements of the stabilisation procedure can be complicated by the issue of device degradation, hence are yet to be established for perovskites.

Stabilisation: A procedure applied to a PV device, designed to remove long-term transient effects and bring about a state that is representative of the device performance in the field. For example, the device may be kept at a set voltage bias, set temperate and irradiance (or dark) for a some period of time.

STC: Standard Test Conditions, as defined in the IEC 61836 standard.

Steady-state measurement: A measurement where at a given voltage bias, irradiance level and device temperature, the output current of the PV device has settled (see definition below). Note that forward and reverse *I-V* curves measured under steady-state conditions show negligible hysteresis, however a lack of hysteresis does not by itself indicate that the measurement was at steady-state.

Laboratory capability categories

The guidelines contain notes specific to three categories of PV cell measurement capability, defined in Table 1.

Table 1. Suggested classification system for laboratory capability.

	Basic (BAS)	Intermediate (INT)	Advanced (ADV)*
Light source	Non-spectrally matched (e.g. tungsten lamp)	Spectrally matched light source/solar simulator	Spectrally matched light source/solar simulator that undergoes regular characterisation
Irradiance calibration	-	Use of reference devices, typically not spectrally matched. Spectral mismatch typically not accounted for	Range of spectrally matched reference cells, irradiance monitoring during measurement, correction to reference spectrum
Temperature	-	Some consideration of device temperature	Device temperature controlled and monitored, correction to reference temperature according to standard methods
Equipment	Simple	Specialised PV measurement equipment	Specialised PV measurement equipment capable of delivering high accuracy measurements traceable to SI units
Calibration	-	Some items calibrated, typically infrequently	Strict calibration schedule
Methods	Lab developed	Lab developed, typically unverified	Typically international standard methods. Internally validated and externally reviewed during regular technical assessments
Accuracy	Low, unknown	Moderate, unknown	High, and clearly defined. Expression of result to Standard Test Conditions

* accredited laboratory level

Guidelines

1. Temperature

If the response time of the device permits a measurement of the steady-state efficiency under Standard Test Conditions in less than 10 seconds, the considerations of device temperature described in IEC 60904-1 are sufficient. If not, which is typically the case for perovskite cells, additional steps are needed to address the cell heating that will likely occur during the longer measurement.

Good thermal mounting of the cell is critical and all possible steps should be taken to minimise the extent of cell heating during illumination prior to temperature stabilisation (see Notes 2, 3 and 4).

Guidelines specific to each laboratory class are listed below:

ADV: Use a temperature control system to achieve and monitor cell temperature stabilisation. Ensure that the stabilised value is close to the reference temperature at the time of the first (and subsequent) current measurements.

INT: If temperature control is not possible, monitor the cell temperature change with time and record the value of the cell temperature at the time of the current measurement at each voltage.

BAS: If temperature cannot be directly monitored or controlled, ensure that the cell is illuminated prior to the first current measurement for a duration that is consistent for all samples.

Methods for reducing the rate and extent of cell heating during illumination include placing the cell on a stage that is temperature-controlled (ADV) and/or an effective heat sink (all lab classes) e.g. a thick copper plate. Good thermal contact must be achieved between the cell and stage. A jet of cool air (or nitrogen) at a controlled temperature directed at the cell can also be effective (ADV and INT). If this is not possible, a fan can be used (INT and BAS).

Note 2: Temperature stabilisation criteria should be defined in advance. One possible method for doing this is described in Dunbar *et al.* [4]

Note 3: Following the commencement of illumination, the cell temperature increase can vary from a couple of degrees (robust temperature control with excellent thermal contact e.g. a packaged reference cell on a temperature-controlled stage) to tens of degrees if temperature control is poor.

Note 4: The temperature measured outside of the device, typically at the back of the sub/superstrate, can be significantly different, i.e. up to 2 degrees lower, than the junction temperature. One way of assessing this is to package a temperature sensor inside the device and compare the results. For ADV laboratories this temperature differential must be factored into the calculation of measurement uncertainty.

2. Device stability

The stability of perovskite devices is a complex phenomenon and not yet fully understood, especially because observed behaviour is not universal for all device architectures.

Perovskites can exhibit meta-stability effects at various timescales ranging from milliseconds to days. The term meta-stability implies that these effects are fully or partially reversible, however, they may have different time constants, e.g. it may take longer for a device to recover to its baseline performance than it took to degrade.

Unfortunately, coupled with meta-stability there is also irreversible degradation in perovskite devices. Further complicating the analysis, irreversible degradation may also affect the nature of any meta-stability effects. Both meta-stability and degradation may be a function of time, temperature, humidity, voltage bias, irradiance and spectrum.

The combination of the above issues results in a number of challenges:

1. When Forward and Reverse *I-V* curves result in observed hysteresis, the correct output power cannot be taken from either curve, nor can it be taken from the mean of the two curves;
2. Using fast *I-V* sweeps may result in negligible hysteresis, however if the sweep rate is faster than the response time of the device, the measured state is not representative of device performance in the field;
3. To eliminate hysteresis completely, very slow *I-V* scans may be required, which may result in irreversible device degradation during the measurement; see Note 5;
4. A better approach than fast or slow *I-V* scans is to use a Dynamic I-V approach over a limited number of points in the *I-V* curve, possibly including a Maximum-Power-Point-Tracking (MPPT) algorithm. Alternatively, a Settled Current at Fixed Voltage (SCFV) approach has similar benefit, provided the voltage at the maximum power point can be accurately established. These methods are described in more detail in the following sections. These approaches sometimes require prolonged measurement, hence robust temperature measurement and control of the test device is important.
5. To reduce mid- to short-term meta-stability, preconditioning may be used immediately prior to the *I-V* measurement to give more reproducible results. However, care must be taken since it is also possible to induce a state that cannot occur under real operating conditions.
6. A *steady-state* measurement result is not the same as a *stabilised* measurement result, since even a steady-state measurement only captures the performance of the device at the time of measurement, and hence may not be representative of the long-term device performance. This is why the published efficiency tables include an asterisk beside results for perovskite-based devices, indicating they are “not stabilised”.
7. A steady-state measurement of a stabilised PV device should be independent of previous exposure history of the device on a timescale of at least days, and will therefore be representative of the performance of the device in the field over a similar period. At present, stabilisation of perovskite devices is usually impractical, due to the degradation that accompanies the stabilisation process. It is however envisaged that as perovskite solar cells reach developmental maturity, such levels of degradation will be greatly reduced.

Note 5:

If regardless of the method there is a residual hysteresis, an uncertainty component must be assigned to the stated efficiency due to the meta-stability of the device. While strictly speaking this is not a measurement uncertainty, it is indeed a contributor to the range of values that can reasonably be attributed to the device output.

Details on stabilisation, pre-conditioning and steady-state *I-V* measurements are provided in the following sections.

3. Stabilisation

Device stability has been an issue for perovskite solar cells since their discovery. For the purpose of enabling constructive competition between groups worldwide and ultimately the maturing of the technology, efficiencies measured on non-stabilised perovskite devices have been accepted in the world record efficiency tables. However, these measurements are marked in the tables as non-stabilised. As the technology develops and degradation levels improve, the PV community is working toward consensus on criteria that will define stabilisation for perovskite cells.

The Guidelines with respect to perovskite device stability are the same for all levels of laboratory capability. A set of stability experiments should be performed whenever significant changes are made to the materials or structure of the device. This type of experiment requires extended (time) measurements and thus at least some sort of rudimentary temperature control is required. Since this application doesn't require the light source to match the solar spectrum perfectly, LED light sources may be used. The proposed experimental procedure is as follows:

i) The output current of a fresh device (see Note 6) should be observed for a period of time of at least 30 min at fixed voltage near P_{mpp} under conditions approximating STC. The device should then be allowed to relax in the dark with the terminals at open circuit for the same period of time;
ii) Step i) should then be repeated at least 3 more times, doubling the measurement period each time;
iii) One of the following outcomes should become apparent:
    a. Degradation dominates meta-stability effects at long timescales, in which case stabilisation is not possible and should not be applied. This should be clearly reported whenever results are disseminated;
    b. The shortest period that results in a stabilised current value is identified. This should lead to a second experiment where a new fresh device is cycled between illumination and dark at least 3 times for the same period. If this test confirms that the stabilisation time is sufficient, this should also be confirmed with extended rest periods. If not, the stabilisation time should be increased. The latter experiment should inform the acceptable time delay between the stabilisation step and the measurement. Whenever results are disseminated, the stabilisation process should be reported.

Note 6: A fresh devices is a device that has recently been manufactured and has had limited exposure to light, elevated temperature, humidity or voltage bias.

4. Pre-conditioning

Even when a cell has been stabilised, the sensitivity of the device to exposure history can necessitate a pre-conditioning treatment to bring the cell to a reproducible state prior to *I-V* measurement. Pre-conditioning treatments typically involve applying voltage bias and/or illuminating the cell for a short time, immediately prior to measurement. Pre-conditioning alone may result in a state that is reproducible but not representative, i.e. it is possible to artificially increase the performance of a device above the performance it would exhibit in the field. Pre-conditioning at unrealistic conditions, e.g. voltage bias higher than V_{oc} or irradiance larger than 1000 W/m^2, should only be used if they are proven not to artificially enhance the performance of the device.

Pre-conditioning procedures shorter than 10 mins are primarily relevant for conventional *I-V* sweep methods, and are generally not necessary for dynamic methods, as these techniques inherently account for device settling during the measurement. However, if the pre-conditioning required is longer than 10 minutes it should be used for all measurements.

When employed prior to the collection of conventional *I-V* curves, it may be convenient to set the pre-conditioning voltage to the scan start voltage, such that the first scan measurement point is directly obtained at the completion of pre-conditioning. The pre-conditioning treatment can also be used to achieve cell temperature stabilisation where appropriate.

Place the cell in the test area and illuminate. Hold the cell at a voltage bias appropriate for the intended scan direction, such as the first voltage value, e.g. 0 V for forward scans and the open-circuit value for reverse scans. The temperature considerations in Section 1 shall be observed.

ADV: Hold the cell at the scan start voltage until the measured current settles.

i) If the temperature stabilisation time is less than the settling time at the first measurement point, then the cell should be illuminated until the temperature stabilises and the current settles.

ii) If the temperature stabilisation time is greater than the current settling time at the first voltage value, then:

   a. If cell degradation is a concern, the cell should be illuminated until the current settles (Note 7). The current at subsequent voltages should then be measured without a break in illumination;

   b. If cell degradation is not a concern, the procedure from i) shall be followed.

The resulting *I-V* pairs shall be corrected to the reference temperature according to the procedures described in IEC 60891. This is particularly important for case ii)b.

INT: Hold the cell at the scan start voltage until the measured current settles.

BAS: Hold the cell at the scan start voltage for a previously determined time period shown to allow the current to approximately settle. For pre-conditioning prior to reverse scans, if the cell cannot be held at exactly open-circuit, then a conservative over-estimate of the open-circuit voltage can be used.

The current at subsequent voltages should then be measured without a break in illumination. This should ensure temperature changes for the remainder of the current measurements are minimised. Avoiding a light-dark-light cycle that would be introduced by an illumination break between pre-conditioning and measurement will also avoid the introduction of additional transient processes that may arise due to a light-dark-light cycle.

Whatever pre-conditioning method is chosen (including no pre-conditioning), it will be important that this is recorded and included in any report or dissemination activity of the measurement results.

Note 7: This follows from the assumption that incomplete current settling leads to more severe errors than incorrect device temperature. This was observed experimentally [1], even for the case where the resulting *I-V* data is not corrected to the reference temperature.

5. Efficiency measurement

Below, guidelines are provided for measuring the efficiency of perovskite solar cells using four common methods: conventional *I-V*, dynamic *I-V*, settled current at a fixed voltage (see Note 8) and maximum power point tracking.

Note 8: Settled current at fixed voltage (SCFV) is the term we have introduced for this type of measurement, to avoid confusion over the word *stabilised*. The measurement has previously been referred to as *Stabilised Power Output*.

a. Conventional *I-V* curves:

1. Determine suitable parameters prior to measurement

Using copy test cells, investigate the influence of parameters, such as scan speed and voltage step size, on the resulting *I-V* curves, each immediately following the previously specified pre-conditioning procedure. As reported in Dunbar *et al.* [5], it is suggested to attempt to select parameters that ensure the dwell time at each voltage bias value is sufficiently long to permit settling of the measured current. This can be verified indirectly by observing that *I-V* curves become invariant with sweep direction and small changes in sweep rate. There isn't a universal sweep rate that works best for all devices. Ultimately, the choice is a compromise between current settling (causing hysteresis) and degradation or other practical constraints – including unacceptable temperature increase if control is not available. The slowest practical rate should be used.

2. Perform stabilisation (if possible)

If the device degradation rate is low enough to permit a stabilisation step, stabilise the test device for the period of time determined by the experiment described in Section 3.

3. Perform pre-conditioning

ADV and INT: Perform a pre-conditioning treatment on the test cell such that the current (ADV: and temperature, where appropriate) settle at the first measurement point, observing the considerations provided in Sections 1 and 4.

BAS: Using the results of the earlier investigation, perform a pre-conditioning treatment on the test cell, observing the considerations provided in Sections 1 and 4.

4. Perform *I-V* scans

According to the scan parameters identified in Section 5.a.1, perform the *I-V* scan. Ensure the scan begins immediately following pre-conditioning without a break in illumination.

A second scan in the opposite direction should be performed to verify that the first scan represents steady-state behaviour, i.e. that no hysteresis is observed. The pre-conditioning treatment required for the second scan will depend on the cell properties and the time and conditions experienced by the cell between scans. This should be addressed during the investigation in step 1. An ideal configuration is to perform pre-conditioning treatment 1, scan 1, pre-conditioning treatment 2 (if necessary) and scan 2 in sequence without a break in illumination. Report the measurement parameters for both forward and reverse scans and include a statement on the P_{MPP} uncertainty due to any residual hysteresis.

b. Dynamic *I-V*:

1. Identify the voltage range to be used in the scan

ADV and INT: An effective way of doing this is to set the first measurement point to be at V_{oc}. The subsequent voltage values can then be chosen, for instance with a regular spacing between V_{oc} and 0 V (see Note 9 below). A finer spacing between voltage points will ensure more accurate identification of the maximum power point (MPP), but will incur longer measurement times. Near MPP the spacing should be no more than 50 mV.

BAS: If the cell cannot be held at exactly OC, obtain an estimate of V_{oc} using a copy test cell and start the scan just above the expected V_{oc} for the test cell.

2. Perform stabilisation (if possible)

If the device degradation rate is low enough to permit a stabilisation step, stabilise the test device for the period of time determined by the experiment described in Section 3.

3. Perform pre-conditioning

If the pre-conditioning requires more than 10 minutes, perform it immediately prior to the Dynamic *I-V* as follows, if not it can be omitted.

ADV and INT: Perform a pre-conditioning treatment on the test cell such that the current (**ADV**: and temperature, where appropriate) settle at the first measurement point, observing the considerations provided in Sections 1 and 4.

BAS: Using the results of the above investigation, perform a pre-conditioning treatment on the test cell, observing the considerations provided in Sections 1 and 4.

4. Perform the scan

Follow the instructions in Sections 1 and 4, noting the measurement at the first voltage point is equivalent to pre-conditioning for dynamic methods.

Step through the voltage range, progressing once settling criteria have been met.

If the settling criteria have been correctly chosen and degradation has been shown to be negligible, the resulting scan should represent steady-state behaviour. Therefore, a second scan is not strictly necessary.

Note 9: A more sophisticated and time-efficient method is to use dynamically chosen scan voltage values. Following the first measurement point, the voltage can be stepped toward an estimate of MPP (for instance, using a V_{mpp}/V_{oc} ratio determined from measurements of copy test cells). Using on-board MPP fitting algorithms, the estimate can be continuously refined to ensure sufficient points near MPP are measured to achieve a high-accuracy fit. Once this has been achieved, the voltage can be stepped with coarse spacing to 0 V.

This approach effectively returns a MPPT-derived MPP and additional *I-V* points, such as I_{sc} and V_{oc}.

c. Settled current at fixed voltage (SCFV):

This method is equivalent to performing a single measurement point using the dynamic *I-V* method described in Section 5.b. This method can therefore be performed using the instructions above, modified for a single measurement point accordingly. It can also be considered a pre-conditioning measurement using a hold voltage near an estimate of V_{mpp}.

When SCFV is used to measure the device efficiency, it is critical that the hold voltage should be selected to be as close as possible to the V_{mpp}, which can be estimated from *I-V* scans.

As the accuracy of a SCFV-derived efficiency measurement is highly dependent on the choice of the hold voltage, multiple SCFV measurements can be performed at hold voltages near MPP to refine the estimate of V_{mpp}. For obvious reasons, the MPPT method, described below, is preferable if available.

If MPPT is not available and multiple SCFV measurements are to be made, care should be taken to ensure that there are no breaks in illumination between measurements, and that the bias voltage is not reset to a default value between in between these measurements.

d. Maximum power-point tracking (MPPT)

The MPPT method uses automation to identify the maximum power point for the I-V curve. Algorithms such as *perturb and observe* are commonly applied in software and can be valuable in rapidly identifying the device P_{mpp} if the full *I-V* curve is not required.

MPPT measurements should be performed following a stabilisation step and a pre-conditioning step if required and the degradation rates allow for it. As such only short-term meta-stability effects should have to be avoided. Regardless of the algorithm used, in order to avoid oscillation, i.e. for the algorithm to be able to find a global optimum, and to measure a representative state, the duration of each iteration during the search should at least be in the same order of magnitude as the time required for the current to settle at a fixed voltage near V_{mpp}.

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Glossary

Abbreviation	Definition
ACAP	Australian Centre for Advanced Photovoltaics
AIST	National Institute of Advanced Industrial Science and Technology
ANU	Australian National University
APSRC	Asia-Pacific Solar Research Conference
ARENA	Australian Renewable Energy Agency
CSIRO	Commonwealth Scientific and Industrial Research Organisation
IP	Intellectual Property
I-V	Current-Voltage
LED	Light Emitting Diode
MPPT	Maximum Power Point Tracking
NREL	National Renewable Energy Agency
PhD	Philosophical Doctorate
PVPL	Photovoltaic Performance Laboratory
SCFV	Stabilised Current at Fixed Voltage
UNSW	University of New South Wales
UK	United Kingdom

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