PERSPECTIVE

Metastability in performance measurements of perovskite PV devices: a systematic approach

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Abstract
Performance measurements of photovoltaic devices, including metastable ones, should reflect as closely as possible the behaviour of these devices when deployed in the field, i.e. at constant illumination and fixed conditions. We review the wide-ranging behaviour observed in and previously proposed measurement solutions for perovskite solar cells (PSC) devices and further illustrate the variability during measurement with recent examples from our own experience. We propose a generic measurement protocol for PSC devices to ensure that electrical characterisation under simulated sunlight reflects real life conditions. The approach focusses on determining the steady-state maximum-power output under continuous illumination rather than relying on the $I-V$ characteristics. Given the large variations in device behaviour, this protocol is particularly suitable in cases where a priori information about the devices under test is not available. We conclude that the approach to the electrical characterisation of PSC devices should shift from traditional $I-V$ curves to the maximum-power output under steady-state conditions. The latter is the simplest and most reliable method to evaluate, assess and compare PSC technologies when power and efficiency reporting are required. This protocol also contributes to harmonising comparison between different calibration laboratories thus contributing to increased confidence in the results.

1. Introduction
Emerging photovoltaic (PV) technologies are rapidly evolving and have achieved promising electrical performance (efficiency) in recent years, supported by considerable research effort. Perovskite solar cells (PSC) are currently the best performing emerging PV technology in terms of efficiency. The highest confirmed ‘one sun’ cell, mini-module and module efficiency results reached 21.6% (area 1.0 cm$^2$), 17.25% (area 19.3 cm$^2$) and 16.1% (area 802 cm$^2$) respectively [1]. Very small PSC devices (area 0.09 cm$^2$) surpassed 25% efficiency (notable exception table 2 of [1]). PSC have a realistic potential to compete with standard crystalline silicon-based technologies, owing to a simpler production process, being suitable for flexible substrates (plastics or tissues) [2] or simple integration into building materials [3].

Researchers and companies are now moving beyond the research laboratory phase towards industrial manufacturing: companies developing both single junction PSC and tandem devices (perovskite-perovskite, or perovskite with silicon or with copper indium gallium selenides), are working on scaling up from small cells to large area devices and to improve device stability. While providing the highest efficiency, lead-based PSC have two main barriers to commercialisation: poor stability under illumination and high toxicity of the absorbing material. The low stability is mainly related to the strong sensitivity of the absorber and hole transporting material to environmental factors like oxygen, moisture, temperature and UV light [4]. Improvements in the fabrication techniques and materials have been demonstrated to play an important role

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in the stability of the devices. The development of low-toxicity lead-free materials for the PV market is required, even if electrical performance is somewhat compromised.

In this context, there is a clear need for methods and procedures to reliably measure and characterise the electrical performance of these novel PV devices, which are known to possess a characteristic slow response time to illumination [5, 6]. Electrical power measurements under standard testing conditions (STC), as defined in the IEC 60904 series of standards [7], can only be accurate if sufficient time is allowed for the completion of photocurrent generation and efficient extraction of charges from the devices. This amount of time is usually greater for PSC than for traditional crystalline silicon PV devices. Increasing the sweep time to determine the \( I-V \) characteristic is the standard approach, but this may produce different results, which can influence and compromise the device electrical performance [8]. For PSC characterisation steady-state (rather than pulsed) solar simulators are required.

In the literature, several measurement strategies for different PSC technologies have already been published; these are summarised in section 2. However, given the vastness and variety of PSC materials and device architectures, these strategies are probably not universally applicable to all PSC devices and technologies due to two main reasons: (a) overlapping/superimposition of light soaking and degradation effects; (b) transient effects disturbing the device equilibrium. Therefore, based on results obtained at the European Solar Test Installation (ESTI) with regard to the measurement of PSC devices, which are at the leading edge in efficiency of current technology (section 3), we propose a new generic measurement protocol for PSC devices (section 4) developed to address the issues mentioned above.

2. Measurement procedures developed for PSC

First, we will review the literature concerning electrical performance measurements of PSC devices. Although it covers a relatively short period of time, for our purposes we have divided it into three phases. Starting from the initial discovery of possible effects of measurement procedures (section 2.1) over a broad range of possible solutions (section 2.2), towards a possible consensus approach (section 2.3). In section 4 we propose a generic measurement protocol to advance further towards a general consensus.

2.1. Discovery phase (2014–2015): the ‘anomalous hysteresis’ in \( I-V \) curves

The first reports on the anomalous hysteresis appearing in current–voltage (\( I-V \)) curves of PSC devices when acquired in different sweep directions were published in 2014–2015 [9–14]. A large difference was observed first by Unger [5] then by Snaith [6] when comparing \( I-V \) curves recorded in forward and reverse direction. Forward direction is defined as starting from voltages around short-circuit conditions at \( V = 0 \) V and going to open-circuit conditions at \( V = V_{OC} \). Reverse direction is the opposite, starting from the open-circuit voltage \( V = V_{OC} \) going to \( V = 0 \) V.

Unger et al [5] found that sweep rate and direction during \( I-V \) measurements, as well as light or voltage bias conditions prior to them, can all have a significant impact upon the shape of the measured \( I-V \) curves under illumination. They observed that hysteresis-free \( I-V \) curves were obtained at both extremely fast and slow voltage sweep rates, but only the latter would provide quasi-steady-state conditions for a valid power conversion efficiency measurement. They concluded that for comparison of device efficiencies between laboratories the following should always be reported together with the results: pre-conditioning as well as sweep rates and directions for the \( I-V \) measurements. The effects of these conditions were studied for both mesoporous TiO\(_2\) based perovskite absorber and PSC thin film devices, using typical voltage steps of 50 mV and a delay time of 5–15 s per step. This resulted in \( I-V \) sweeps of approximately 25 points with a total duration between 120 and 300 s, which was declared slow enough for both devices studied.

Snaith et al [6] showed similar effects in \( I-V \) curves measured in forward and reverse sweep directions. Analysing in more detail the sweep rate effect on the hysteresis, they observed that this hysteresis often gets more severe as the sweep rate is reduced, and there can still be significant hysteresis even at extremely slow sweep rates. In their devices, hysteresis did not show at fast sweep rates (0.3 V s\(^{-1}\)), it only started to increase as the sweep rate was reduced to 0.01 V s\(^{-1}\) and reduced again at impractically slow sweep rates (<0.01 V s\(^{-1}\)). They observed that to reach stabilised current output, the applied voltage in some cases had to be held constant for hundreds of seconds. Therefore, one possible way of measuring the steady-state power output was to directly measure the current at a given fixed applied voltage bias. Based on this, they proposed that as long as hysteresis persists, the stabilised power output near the maximum-power point should be reported together with the \( I-V \) curves. Moreover, they suggested that this phenomenon is heavily dependent on device architecture and processing conditions.
2.2. Working phase (2015–2019): the proposed universal methods

After this initial phase, where the hysteresis in $I-V$ curves of PSC was observed by different groups and clearly shown to be a characteristic of PSC, researchers developed specific measurement methods. These were aiming at realising a repeatable and a reliable determination of the steady-state performance. This is a fundamental step towards a more reliable comparison of the performance measurements between laboratories. The work was mainly carried out at world-renowned reference laboratories dedicated to improve the reliability of the measurement protocols and verify the electrical performance of the best available PSC devices developed by the community.

One of the first protocols proposed for the characterisation of PSC devices at STC was published by Christians et al [15]. They confirmed that even devices of the same architecture manufactured in different laboratories with slightly varying techniques display very distinct $I-V$ characteristics, particularly if different sweep rates and cell pre-conditioning were used. They studied a TiO$_2$/perovskite/spiro-OMeTAD solar cell and proposed the following steps:

(a) determine steady-state short-circuit current ($I_{SC}$) and open-circuit voltage ($V_{OC}$),
(b) record forward and reverse $I-V$ curves at different sweep rates,
(c) measure steady-state photocurrent at several voltages near maximum power ($P_{max}$),
(d) calculate $I_{SC}$ by integrating spectral responsivity data over wavelength,
(e) cross check of the results and
(f) perform statistical analysis across multiple sample tests.

They concluded that the determination of the stabilised photocurrent at maximum-power point voltage ($V_{mp}$) is a fundamental step, which can easily be done by holding the solar cell at $V_{mp}$ and monitoring the photocurrent until it stabilises. While exact determination of $V_{mp}$ is often impractical, a close approximation can typically be made from the recorded $I-V$ curves.

Almost simultaneously, another publication by Tress et al focused on the study of the physical phenomena behind sweep rate-dependent hysteresis in $I-V$ curves of PSC [16]. They indicated this to relate to a slow field-induced process affecting the charge transport in the perovskite layer and at the interface. They confirmed in their paper that PSC steady-state $I-V$ curve determination is difficult to achieve with a conventional voltage sweep, because it strongly depends on the voltage sweep rate. Additionally, they observed that the operational point before the sweep (in the dark in open-circuit or short-circuit conditions) alters the obtained results. Moreover, the sweep direction influences the obtained $I-V$ curves. They associated this to the charge carrier collection efficiency that strongly depends on the built-in potential, which is modified by the applied voltage. This modification was observed to occur at timescales of seconds to minutes and was indicated to be linked to ion accumulation at the interfaces of the electrodes, resulting in the screening of the applied field independent of illumination. This process has been confirmed by other work [9, 17–19]. While a universal measurement protocol was not proposed in their paper, the authors indicated that different sweep rates and directions in measuring $I-V$ curves of PSC may result in very different performances. However, the important step in their work was towards an understanding of the origin of the hysteresis observed in $I-V$ curves of PSC.

Hishikawa et al from the Research Centre for PVs at AIST, the National Institute of Advanced Industrial Science and Technology in Japan, studied three different PSCs showing very different behaviour [8]. They observed that the hysteresis in $I-V$ curves changes with the sweep rate in different ways depending on the device type. Their study analysed the temporal response of the $V_{OC}$ and $I_{SC}$ when the bias voltage was repeatedly switched between open-circuit and short-circuit conditions under continuous illumination, and gathered that while different PSC showed a similar behaviour for $V_{OC}$, the same did not apply to $I_{SC}$. This simple experiment confirmed the observation that different types of hysteresis effects are present depending on the device structure. This led them to assume, at the time of writing, that the hysteresis effect in $I-V$ curves of PSC had not been fully understood, and that experimental confirmation for each device structure, or sometimes each sample, was necessary. They suggested that when the hysteresis is persistent even for a long sweep time, the stable $P_{max}$ can be determined by examining the temporal trend of the output current at fixed bias voltage at or near $V_{mp}$, whereas looking at $I-V$ curves overlap in forward and reverse sweep direction is not sufficient. They proposed a protocol with the following steps:

(a) measure $I-V$ curves at a wide range of sweep time (in the order of seconds to minutes) for different sweep directions,
(b) if forward and reverse $I-V$ curves agree within an acceptable range (not defined) at a long-enough sweep time, they can be regarded as stable performance and
(c) when hysteresis is persistent even at long sweep times, determine stable $P_{\text{max}}$ by examining the temporal trend of the output current by fixing the bias voltage near $V_{\text{mp}}$.

It was also commented that repeated measurements at long sweep time may also lead to instability problems and/or device degradation.

A similar protocol specific for PSC was proposed in the same year by Zimmermann et al [20]:

(a) perform standard $I$–$V$ curves in forward and reverse sweep directions (typically at 1 s for entire $I$–$V$ curve plus a settle time at starting point of 5 s),
(b) track $P_{\text{max}}$, $I_{\text{SC}}$ and $V_{\text{OC}}$ for approximately 60 s each and look for steady-state conditions,
(c) perform cyclic $I$–$V$ measurements: maximum-power point $\rightarrow I_{\text{SC}} \rightarrow V_{\text{OC}} \rightarrow I_{\text{SC}}$ (typical total time 500 s) (optional),
(d) perform time resolved $I$–$V$ measurement: forward and reverse (optional) and
(e) perform standard $I$–$V$ measurement as in point (i) and compare with initial measurement (optional).

The proposed protocol was applied to the measurement of six different types of PSC and very different results were found depending on the device structure. They concluded that, for PSC particularly, a transient maximum-power point tracking (MPPT) should be included into any measurement protocol, because this gives comparable stabilised power conversion efficiency at working conditions. It is suggested to add MPPT as the initial measurement with a duration of at least 60 s. As $I$–$V$ measurements cannot provide reliable steady-state conditions for all device architectures, they proposed the stabilisation of the output by holding the device at the maximum power as the only reproducible method.

The asymptotic $P_{\text{max}}$ method used at the National Renewable Energy Laboratory (NREL)'s Cell and Module Performance group to standardise the measurements of PSC was described by Moriarty et al [21]. The method is based on time asymptotic current measurements with a set of constant voltages in the region of $V_{\text{mp}}$. The proposed protocol consists of the following steps:

(a) preliminary perform forward and reverse fast $I$–$V$ sweeps to identify the magnitude of the hysteresis effect and the voltage region to examine,
(b) voltage bias the PSC to a small set of voltages in that region and at each voltage hold it constant until the current settles to an asymptotic level: as the data are collected, fit the last 25% of collected data to a straight line. When the slope of this line reaches some acceptance threshold (typically 0.1% of estimated $I_{\text{SC}}$ per minute) proceed to the next voltage and begin the process again,
(c) hold the cell at 0 V until asymptotic $I_{\text{SC}}$ is reached and at open circuit (or zero current flowing) until asymptotic $V_{\text{OC}}$ is reached,
(d) at each voltage the current vs time is fit to an exponential of the form $I(t) = A e^{b(t-t_0)} + C$ and the asymptotic limit $C$ is the estimated current at this specific voltage.

Moriarty et al employed this method to build the voltage—asymptotic current pairs near $P_{\text{max}}$ and used standard validated polynomial fitting routine to calculate $P_{\text{max}}$. Typically, it would take them 4500 s to measure seven time asymptotic currents and 1500 s to measure an asymptotic $I_{\text{SC}}$. They also commented that spectral responsivity measurements may be affected by bias light level and chopping frequency and that too strong bias light can cause damage to the test device. Given that the devices were usually under full illumination for over 1 h in order to measure all required points for the $I$–$V$ curve (see above), it is surprising that they mention degradation in respect to the measurement of the spectral responsivity rather than the $I$–$V$ curve. In general the long illumination times required to measure the electrical characteristics of PSC devices is a limitation as these devices often degrade under illumination on the same time scale. In our measurement protocol (section 4) we are addressing this concern by repeating the measurement of maximum power output. While this does not alleviate the effect of possible degradation, the data provide information about device stability, so at least the degradation will be detected and can also be quantified. More recently NREL published a slightly revised version of their protocol including a statistical analysis [22]. For PSC they found significant differences ranging to well above ±10% between the results from their asymptotic $P_{\text{max}}$ method and faster transient $I$–$V$ curves. For more than 80% of PSC devices the difference was >1%.

A new dynamic approach to reach steady-state conditions prior to characterisation of PSC was suggested by Dunbar et al in [23] and [24]. They proposed to continue the device pre-conditioning until pre-determined criteria are met. The criteria can be applied to the different parameters separately: $I_{\text{SC}}$ or $V_{\text{OC}}$ by the use of the rate of change in % min$^{-1}$. In [23] this method was applied to the measurements of the temperature coefficients $\alpha$ and $\beta$ of a crystalline silicon reference cell and of a PSC. At each temperature, the $I_{\text{SC}}$ (or $V_{\text{OC}}$) was monitored until the stabilisation criteria were met then the measurement was taken.
before moving to the next temperature. \( I-V \) curves were not performed, but steady state \( I_{SC} \) and \( V_{OC} \) were measured at various temperatures. Consecutive measurements were also performed to check for repeatability of the measurement and device stability. In [24] Dunbar \textit{et al} presented the results of an inter-comparison between ten laboratories in Australia and the USA, focusing on comparing different measurement techniques applied to PSC. The techniques considered in their study are four:

(a) conventional \( I-V \) (automatic continuous or step-wise voltage sweep),
(b) MPPT to identify the \( P_{max} \),
(c) the manual acquisition of the current at fixed voltage (chosen to be as close as possible to \( V_{mp} \)) until stabilization occurs (stabilised current at fixed voltage (SCFV)) and
(d) the dynamic \( I-V \) technique, a step-wise \( I-V \) curve where the device is held at each voltage long enough to permit stabilization of the current.

The authors found that the dynamic \( I-V \) approach is the most reliable. It allows for sufficient current stabilisation at each voltage step to ensure the curve reflects steady-state behaviour. Dynamic \( I-V \) can achieve accurate steady-state measurements even for slow responding devices as long as the device is sufficiently stable. Dunbar \textit{et al} also discuss the effect of possible device degradation. In the presence of degradation, a compromise between capturing the steady-state behaviour and avoiding (irreversible) degradation must be made. In this case the stabilisation and degradation dynamic behaviour need to be understood to determine the optimum duration of exposure to test conditions prior to the final reported measurement. The second-best method found by the authors was the light-soak at open circuit (or short circuit depending on the device architecture) followed by consecutive fast \( I-V \) sweeps. They found that holding the device under illumination at open circuit for 10 min prior to fast reverse and forward sweeps in immediate succession can be a good solution in several cases. However, this may only be a good solution for obtaining consistent results when comparing measurements from different laboratories, but it may still not reflect the performance of the devices under actual operating conditions. Therefore our approach (section 4) concentrates on the performance under conditions at or close to the maximum power point.

A two-step measurement procedure has been proposed by Rakoci\v{c}evi\v{c} \textit{et al} from IMEC [25] for objective PSC characterisation. The procedure is based on an initial transient current density characterisation step followed by MPPT characterisation. The first step determines the optimal parameters (measurement delay and voltage step) for MPPT. The method was applied to three PSC devices and different MPPT algorithms were tested and compared. It was found that the choice of measurement parameters in MPPT can offset the measured performance and \( V_{mp} \) up to 20\%–30\% away from the optimal PSC performance. This study shows how transient current response of PSC can affect MPPT, which is generally regarded as a robust measurement. However, after a correct evaluation of the measurement parameters, MPPT has been proposed by Rakoci\v{c}evi\v{c} \textit{et al} as a fast and accurate procedure for PSC characterisation, allowing for an objective comparison of devices.

Gao \textit{et al} from TÜV Rheinland (Shanghai) have studied the effect of pre-conditioning prior to \( I-V \) measurements on a large area perovskite PV module [26]. They propose the following steps:

(a) general stabilization (10 h at \( P_{max} \) under light),
(b) pre-conditioning just before \( I-V \) measurement (2 h at \( P_{max} \) under light),
(c) dynamic \( I-V \) measurements and
(d) long term reproducibility.

They explain that pre-conditioning (light soaking) is required to stabilise perovskite devices. The dynamic method for \( I-V \) measurements was indicated as the best method due to its suitability to deal with PSC hysteresis. They observed two kinds of hysteresis: one which decreases with voltage and reaches its maximum close to \( I_{SC} \) and a second one which remains relatively constant with voltage. Following their experience, dynamic \( I-V \) measurements reduce both hysteresis phenomena. Spectral responsivity measurements were performed at different chopping frequencies, with and without bias light. The device studied in their work showed identical response within the range (1–100) Hz regardless of the measurement with or without white light bias. As with many other publications, it should be kept in mind that these are measurements on one device only and may not reflect results from other PSC devices.

2.3. Advanced phase (2019–now): stability issues and standardisation

More recently, researchers in this area have moved forward. In parallel to the activity focused on improving the quality of PSC devices (in term of better efficiency and longer stability) and on scaling-up processes to increase the device dimensions (without compromising performance too much), significant effort was
invested in harmonising the measurement protocols, in particular for PSC device stability determination. The stability of PSC is still a critical issue and the protocols used to study and evaluate their stability in the long term must be harmonised.

In the past few years, a large group of researchers was involved on a fruitful worldwide activity, focussing on drafting and publishing the technical report IEC TR 63228 [27]. This document seeks to define the state-of-the-art of the measurement procedures currently used in the emerging PV technology sector (mainly organic solar cells, dye-sensitized solar cells and PSC). The primary focus of the report is the measurement of the $I-V$ characteristics under illumination for the purpose of determining the device output power and power conversion efficiency. This report is based on the best available current knowledge and practices, hence serving as a reference and a starting point for further discussion. Stability issues related to emerging PV devices are discussed in detail. However, it was not possible to find a consensus in the community on how to test reliably the stability of these new devices, although three important definitions are given on steady-state condition, pre-conditioning and device stabilisation prior to $I-V$ measurements. With these terms clarified, the comparison of the electrical performances of innovative PV products should be more reliable, as all parties should use the same terminology and report the relevant parameters. Degradation and metastability are identified as the two main issues affecting the reliability of measurements on emerging PV technologies.

In a perspective article [28] published in this special issue of the Journal of Physics: Energy, C Fell reviews the current status of $I-V$ measurement standards for PV devices focusing on the critical issues of metastable devices, providing a complete overview on how researchers deal with long-term and short-term metastability when evaluating the performance of PSC. In conclusion, the biggest issue for the successful commercialisation of PSC at present is long-term stability of the devices. However, in order to have accurate snapshots of performance that are representative of the device at the time of the measurement, an agreed method to deal with short-term metastability is required.

Another important contribution on this topic comes from Khenkin et al [29], who drew on established protocols for organic PV devices from the International Summit on Organic and Hybrid Photovoltaics Stability (ISOS) [30]. The authors discuss how to adapt these protocols specifically to the behaviour of PSC. Particular attention is given to the protocols developed for accelerated ageing tests, ageing conditions and measurements during these ageing tests of PSC. Common practices for the calculation of the degradation rates and estimation of their lifetime are discussed in the document.

2.4. Summary of previous work and outlook

From the literature review presented, it is clear that there is a variety of solutions proposed and applied in the measurement of electrical performance of PSC devices. However, it also emerges that the devices behave according to their architecture, chemistry and manufacturing process. The reproducibility of the measurements is in our opinion not investigated or given due consideration. Indeed, for a given device the measurement results will depend on the pre-conditioning before the measurement, the actual measurement strategies and the parameters utilised as well as a possible degradation occurring during the execution of the measurements. As some of these effects may potentially occur simultaneously (i.e. improving performance due to light soaking and degradation under illumination) or on similar time scales, their differentiation proves very difficult if not impossible. For manufacturers, it is feasible to spend resources on investigating the effects of their specific type of PSC devices and optimising a measurement protocol to provide reliable performance measurements. However, this is generally impractical for test laboratories charged with measuring the electrical performance of a PSC device: firstly because it would normally require a set of devices (which might not always be available), and secondly because it might require prohibitively large resources (time, personnel, etc). Another significant reason of why this would be inappropriate, is the purpose of comparability between measurements. This is especially relevant when announcing record efficiencies, or when PSC efficiencies are compared with other conventional solar cell efficiencies. Different pre-conditioning or measurement strategies may benefit different devices. Therefore, there is a need for an unbiased method, and this same method should be used by everyone when officially reporting efficiencies.

Therefore test and calibration laboratories require a robust measurement protocol, which they can apply to any PSC device avoiding lengthy investigations into the best measurement strategy. Such a measurement protocol has to be based on the collective experience with the measurement of PSC devices as summarised in this section. While it has not been possible to reach such a consensus for IEC TR 63228 [27], we propose a possible solution which should be universally applicable to PSC devices (section 4). Before that, we will present and discuss some issues related to the measurement of state-of-the-art PSC devices recently experienced at ESTI (section 3).
3. Stability and stabilization: some examples

The most fundamental characterisation techniques for PV devices to standardise the measurement protocols are included in the series of standards IEC 60904 series [7], describing the procedures for the full characterisation of PV devices under natural or simulated sunlight. The IEC 61215 series [31] describing the design qualification and type approval tests for PVs devices includes the procedures for device stabilisation and the special requirements specific for different technologies. Currently, four subparts of IEC 61215-1 [32] have been published specific for crystalline silicon (IEC 61215-1-1 [33]), cadmium telluride (IEC 61215-1-2 [34]), thin-film amorphous silicon (IEC 61215-1-3 [35]) and thin-film Cu(In,Ga)(S,Se)$_2$ (IEC 61215-1-4 [36]) based PV devices. Requirements for other PV technologies are not yet specified, however, they can easily be added as additional subparts when ready.

The two main issues with testing a PV device are how to ensure steady-state conditions of the device under test during the measurements and how to guarantee that the measurements performed in the laboratory (at STC) are representatives of the device as it would perform in the field.

Four possible situations can occur:

(a) **Equilibrium**: the current at every voltage step of the $I$–$V$ curve (or at some of them) needs time to reach equilibrium (stability criterion to be defined). The waiting time can be different at every voltage step but slowing the sweep speed adequately allows for steady-state $I$–$V$ curves. When forward and reverse $I$–$V$ curves overlap, they provide the results. Otherwise, fixed voltage current monitoring close to $V_{mp}$ is required.

(b) **Degradation**: the degradation of the device under illumination is the dominating process occurring during the test. Consequently, the current decreases over time while keeping the voltage constant. This can happen at every voltage step of the $I$–$V$ curve or only at some specific voltages. It is not possible to reach any stable condition even with pre-conditioning or long holding time. Degradation might be reversible or irreversible. There could also be degradation with time without illumination.

(c) **Pre-conditioning**: same as (b) but repetition of $I$–$V$ curves (same sweep direction) with intermediate light soaking (minutes) gives different results. A pre-conditioning step (under illumination or with bias voltage) can possibly stabilise the device and yield reproducible $I$–$V$ curves. This is the typical case of some thin-film devices that need a certain pre-conditioning before the measurement of $I$–$V$ curves.

(d) **Standard steady-state $I$–$V$**: the current at every voltage step of the $I$–$V$ curve stabilises very fast (ms range). Fast $I$–$V$ sweeps (also under pulsed simulated sunlight) are possible. This is confirmed when hysteresis is absent (forward and reverse $I$–$V$ curves overlap and the measurements tend to the steady state condition). If this is not the case, a slower sweep rate is required.

In general, the cases A, B and C apply to PSC devices. Conventional crystalline silicon normally falls under case D whereas more sophisticated silicon or high-efficiency devices fall within case A. Note that for PSC in case A, the observed behaviour might be similar to a capacitive crystalline silicon PV device but the underlying mechanism is different as it is related to charge transport in PSC (section 2.2). The following gives examples for cases A, B and C observed at ESTI when testing PSC devices. To date an example of a PSC device according to case D has not been observed at ESTI.

### 3.1. Case A — equilibrium

$I$–$V$ curves were acquired manually starting from a brief light soaking period close to $V_{mp}$ (5 min), then moving stepwise to $I_{SC}$, then back to $V_{mp}$ (one step), then stepwise to $V_{OC}$ and finally back again to $V_{mp}$ (one step), according to the proposed measurement protocol in section 4.1(b)–(f). An example of such a measurement is shown in figure 1 as the time series data of the acquired voltage and current signals. $I$–$V$ curves were generated averaging the last part of the signals (at each voltage step), when current is considered stable. A repeated $I$–$V$ curve was acquired following this protocol (section 4.1(g)); during 15 min between steps (f) and (g) the device was kept under open-circuit conditions in the dark) and was comparable within the measurement uncertainty of the system (figure 1 bottom). For this particular case, $I$–$V$ curves measured in forward and reverse directions for comparison are not available.

The electrical performance of devices in this category can be reliably measured and reported following the protocol. These are representative of the device performance and behaviour if deployed in the field. Traditional $I$–$V$ curves on the other hand could easily lead to results which have large variations against those determined under steady-state conditions [22].

### 3.2. Case B — degradation

$I$–$V$ curves were acquired following the same protocol described in case A but when the voltage reached a certain value (values slightly above $V_{mp}$ in this specific case), the current did not stabilise (due to the
instability of the device) and continuously decreased over time (and consequently the power decreased) (figure 2). The same effect was observed for different PSC devices and at different voltages between $V_{\text{mp}}$ and $V_{\text{OC}}$, but not at lower voltages between 0 V and $V_{\text{mp}}$, where the current was found to stabilise. Hence, the electrical performance of the device is stable for certain applied voltages, but degrades for others. For this reason, the $I$–$V$ curve can only be constructed for those voltages where the device behaviour is stable (figure 2 bottom right), while for other voltages the measurement results are unreliable and cannot be used to construct the $I$–$V$ curve.

The degradation of devices in this category can easily be overlooked when fast $I$–$V$ curves are acquired. This could lead to results being reported that suggest that the devices are viable, while the protocol applied here clearly indicates that the devices are not suitable and results of electrical performance should not be reported for them.

3.3. Case C — pre-conditioning

$I$–$V$ curves were measured with a standard protocol, applying a constant step-wise voltage ramp to the device and acquiring the current signal. $I$–$V$ measurement parameters such as step time, number of steps and total sweep time were chosen prior to the measurement. After different parameters had been tested and optimised (50 points, step-time 500 ms, integration time at each step 100 ms, total time for $I$–$V$ curve 25 s), $I$–$V$ curves were acquired automatically with these parameters fixed (figure 3). $I$–$V$ curves measured with forward and reverse sweep direction were in acceptable agreement. However, holding the device under continuous illumination for minutes at $V_{\text{OC}}$ and measuring $I$–$V$ curves periodically, different results were observed (figure 3). The $V_{\text{OC}}$ initially increased and then remained almost constant, while $I_{\text{SC}}$ strongly decreased in a matter of minutes. Part of these losses could be recovered afterwards keeping the device in the dark and measuring it periodically (not shown), but the main problem was to establish which $I$–$V$ curve to select as the most representative of the device. This particular device increased in $V_{\text{OC}}$ with $P_{\text{max}}$ remaining almost stable for the first light soaking step (2 min) but afterwards it degraded significantly. The behaviour of $V_{\text{OC}}$ is typical for pre-conditioning, with an initial increase tending to stabilize on a higher level than the initial value. This improvement due to the pre-conditioning is, however, masked by the larger degradation resulting in a decrease of $I_{\text{SC}}$. Others have found that the overall device performance can improve under pre-conditioning and remain stable for sufficiently long times to perform multiple measurements (figure 12 in [23]). Such device behaviour has not yet been observed at ESTI.

When pre-conditioning of devices in this category is not fully performed the risk is that the results of electrical performance are inferior or superior to those reflecting the real potential of the devices. For the example presented, the overlaying degradation is stronger than the pre-conditioning effect, so that it is impossible to report a representative result.

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**Figure 1.** Example of CASE A—equilibrium: measurement of device UZ802 consisting of time series data (top left), $I$–$V$ curve constructed from these data (top right) and comparison of repeated $I$–$V$ curves (bottom).
4. Proposal for universal measurement protocol

4.1. Measurement protocol

Following the experience at ESTI (section 3) and the approaches put forward in the literature (summarised in section 2), we propose the following:

(a) One initial $I-V$ sweep in each direction (forward and reverse, typically 10 s to 20 s each) holding the device under illumination for the shortest time possible. This serves as a rough estimate of the electrical response of the device and to extract an approximate $V_{mp}$ value. $I-V$ sweeps should not be repeated nor be made at slow sweep speeds, as the device might degrade under illumination, in particular at the conditions of $I_{SC}$ or $V_{OC}$ just before or after the actual $I-V$ sweep (where data is not recorded). While these conditions would not normally be considered important (and therefore not be recorded), they could be detrimental for PSC;

(b) Hold device (typically for several minutes) under steady-state illumination at voltage close to the approximate $V_{mp}$ value determined in step (a): monitor the current and wait until a pre-defined stability criterion is met. After stabilization perform minor variations (order of ±2% typically) of the voltage to find real $V_{mp}$ (fine tuning by maximising power output) (figure 4). Wait for the predefined stability criterion after each variation. This constitutes the first measurement of $P_{max}$;

(c) Change voltage step-wise towards $V=0$ V and wait for the current to stabilise at each step. Acquire a minimum of three measurements (depending on the sampling time) at each voltage step after stabilisation of the current. Continue until $V=-(0.02 \times V_{OC})$ is reached;

(d) Move back to $V=V_{mp}$ (in one step) and check (see below) if the current reaches the value obtained in (b) after pre-conditioning. We observed that for certain devices this requires to wait at this voltage for a few minutes. This constitutes the second measurement of $P_{max}$;

(e) Change voltage step-wise toward $V=V_{OC}$ and wait for the current to stabilise at each step (figure 4). Acquire at least three measurements (depending on the sampling time) at each voltage step after stabilisation of the current. Continue until $V=1.01 \times V_{OC}$ is reached;

(f) Move back to $V=V_{mp}$ (in one step) and check (see below) if the current reaches the value obtained in (b) and (d) after pre-conditioning. We observed that for certain devices this requires to wait at this voltage for a few minutes. In some cases, holding the device intermittently for a period (10 s–120 s) at $V=0$ may
accelerate this process. Once stabilisation of the current has occurred, hold the device at $V = V_{mp}$ for at least 1 min. This constitutes the third measurement of $P_{max}$.

(g) Repeat the sequence (b)–(f) and acquire a second $I$–$V$ curve for comparison;

(h) Repeat (a) for comparison.
Comment for (c) and (e): Regulate the voltage step in order to have approximately 30 points in total, with more concentrated points around $V_{mp}$ and around the crossing of the axes ($V = 0$ V and $V = V_{OC}$). If at certain voltage values the current constantly decreases and does not stabilise, do not wait longer than 1 min before moving to the next voltage step and indicate this in the measurement report. Avoid forward bias in order to not damage the device. Consequently, such measurements are not completely performed at steady-state conditions. However, if this concerns parts of the $I$–$V$ curve far from $P_{max}$ conditions, this is a concern regarding the $I$–$V$ curve but not for the steady-state performance of the device.

Comment for (d) and (f): If the current does not match the previously measured value, but stabilises, proceed with the measurement (i.e. following step). If it does not stabilise, this should be noted in the final measurement report.

The comparison of the $P_{max}$ values obtained in (b), (d) and (f) is of importance. Compare the values and check for consistency (figure 5 top right). This gives important information about the stability of the device and its ability to sustain the measurements performed. If this analysis confirms that the device remained stable, proceed to analyse the complete set of measured data to construct the $I$–$V$ curve. Analyse the acquired data calculating the average voltage and average current of the acquired points at each voltage step after stabilisation or the last three acquired measurements if stabilisation of the current did not occur. Plot $I$–$V$ and power-voltage ($P$–$V$) curves (figure 5 bottom) and use polynomial functions to fit the $P$–$V$ data (figure 5 top right) and to extract the $P_{max}$ value as well as the corresponding $V_{mp}$ and maximum-power point current ($I_{mp}$). Repeat the same analysis for the second set of measured data and compare the results.

In addition to $P_{max}$ obtained from the fit to the $P$–$V$ curve, the highest $P_{max}$ value from (b), (d) or (f) (figure 5 top right) should be reported. The latter is usually slightly higher than the value determined from the polynomial fit of the $P$–$V$ curve (figure 5). On the $P$–$V$ curve data points might appear to be due to noise and in this case it would be more correct to use the values determined from the fit. In the present case, however, the variation of data points is not due to noise but due to device instability and measurement.
repeatability. Each measured point is based on the average of a time series and therefore a realistic representation of the device performance, as it was obtained by holding the device at fixed voltage conditions. Hence we propose to report the maximum measured $P_{\text{max}}$ value as the real $P_{\text{max}}$ of the device under test and to use this for the calculation of the power conversion efficiency.

Another aspect not mentioned so far is device temperature control. Under steady-state illumination, PV devices will heat up to device temperatures significantly above 25 °C. Therefore, active cooling is required to keep the device temperature at or near the target temperature of 25 °C. For reference cells this is readily achieved by a suitable Peltier cooler due to their limited size. For PSC devices on the other hand this is much more challenging in particular if they are full size PV modules. Our measurements were made on mini-modules up to sizes of 21 cm by 21 cm, which were mounted on a temperature controlled sample stage using water cooling. For larger devices the temperature control will be challenging and significant deviations from the target temperature of 25 °C may occur during prolonged illumination. This will influence the measurement results and should be accounted for in the measurement uncertainty budget.

4.2. Possible scenarios
Looking at the possible situations described in section 3 (cases A, B, C and D) and at the proposed measurement protocol presented in section 4.1, based on our experience, three different main types of scenarios may be observed when measuring PSC devices. These scenarios will depend mostly on the type of the device being measured. In the following we illustrate all three types with the results obtained in applying our protocol.

4.2.1. Type 1 — stable and reproducible
A reliable $I-V$ curve is obtained and this is in good agreement with the $P_{\text{max}}$ value calculated from holding the device at $V_{\text{mp}}$ (figure 5). The two measured $I-V$ curves are also in accordance within the uncertainty of the system (figure 1). Reliable and reproducible results have been obtained and can be reported.

4.2.2. Type 2 — metastable
A reliable first $I-V$ curve is obtained and this is in good agreement with the $P_{\text{max}}$ value calculated from holding the device at $V_{\text{mp}}$. However, the second $I-V$ curve (4.1 g) shows a different $P_{\text{max}}$ value (higher or lower) if compared with the first one. This suggests that the device has a strong metastability and needs pre-conditioning before characterisation. We suggest proceeding with light soaking and taking additional measurements. Currently no fixed criterion for the duration of the light soaking can be given and the operator needs to make an ad-hoc decision. In general the time is expected to reach from a few minutes up to an hour. If a stable steady-state condition can be reached, reproducible and stable $I-V$ curves as of TYPE 1 will finally be measured. In some cases, the device performance may not stabilise, possibly because device degradation is occurring during measurements. If at least one full $I-V$ curve is measured and the $P_{\text{max}}$ from the curve agrees with the $P_{\text{max}}$ reached holding the device at $V_{\text{mp}}$, then this result can be reported. This means that $P_{\text{max}}$ and $I-V$ results can be reported according to section 4.1(b)–(f), without the need for step (g). However, the results of the second measurement (step (g)) should also be reported for completeness together with the measurement conditions (time of illumination and irradiance). If a full $I-V$ curve is not available, check if there are data points where the device demonstrated constant power output and extract the maximum measured value of power. This is the only reasonable value that can be reported. In this case, it is mandatory to specify that the device was not stable and the reported $P_{\text{max}}$ value was measured only for a certain time.

The example in figure 6 illustrates this. The device was measured according to the protocol section 4.1(b)–(f). While the results of the $I-V$ curve and steps (b) and (d) agree, the $P_{\text{max}}$ value from step (f) clearly showed device degradation which could not be recovered. Therefore, step (g) of the protocol was omitted. Step (h) (results not shown) clearly showed that the device had degraded. So in this particular example the results from the $I-V$ curve and the maximum $P_{\text{max}}$ value can be reported but only together with duly indicating the findings about the instability of the device.

4.2.3. Type 3 — unstable
$I-V$ curves cannot be measured following the protocol described in 4.1, due to the instability of the device. If the current continues to decrease over time when the device is held manually around $V_{\text{mp}}$ and no stable conditions can be found (figure 2), the device cannot be measured and $P_{\text{max}}$ results should not be reported, as power output would not be meaningful for such devices. Although results on such devices have been reported previously in literature we would propose these are not reliable results.
Figure 6. Results on device UZ803 similar to figure 5. P–V curve for data (bottom), zoom near the maximum with polynomial fit (top right) and time series (top left) of highest data point. In the former two plots the data points are colour-coded indicating during which step in the procedure they were acquired. While the data point acquired in step (d) is consistent with those from step (b), the power was lower in step (f) and could not be recovered.

5. Discussion and conclusions

As summarised in section 2, there is a large variety of approaches to measure the electrical performance of PSC devices.

One approach to deal with stabilisation at each voltage step is dynamic I–V, where the device is held at each voltage long enough to permit stabilisation of the current, based on some pre-set criterion. It might be difficult to ascertain these criteria, but even when possible, the measurement could be influenced by the sweep direction. Therefore, forward and reverse sweeps should be made. In general, this approach will give less information about the device performance, particularly after intermittent conditions such as $I_{SC}$ and $V_{OC}$. Furthermore, the device might have changed (e.g. degraded) by the time the maximum power is reached.

MPPT aims at identifying the $P_{max}$ by adjusting the applied voltage to maximise power output at all times. While this as such is very attractive and closely related to the conditions of PV devices deployed in the field, for PSC it is difficult to optimise the MPPT algorithm, despite being essential to avoid large deviations in electrical performance. Therefore, this approach is only feasible for a device of known behaviour and prior knowledge will be essential for PSC devices to be deployed in the field. In these cases, the respective parameters for MPPT can and have to be adapted to the device to give satisfactory measurement results and performance respectively. For unknown devices, however, this is not feasible, as it would require a set of nominally identical devices to first develop such a MPPT protocol.

The SCFV investigates the power output at or around $V_{mp}$, and uses the stabilised value yielding the steady-state efficiency of the PSC device. Using a single voltage value bears the risk of underestimating the maximum power if the voltage is not accurately chosen to be the $V_{mp}$ (which is not known a priori). In this case the measured $P_{max}$ (hence efficiency) will be a lower bound of the real value which may in reality be higher (but cannot be lower). Therefore, to improve on the measurement at a single voltage, several points around $P_{max}$ conditions (i.e. from voltages below to above $V_{mp}$) should preferably be measured. This would essentially determine the section of the I–V curve around $P_{max}$. The NREL method (section 2.2) is essentially
the latter but rather than waiting for stabilisation, it fits an exponential function to the measured data to determine the asymptotic limit. This shortens the time required to acquire data in cases where the stabilisation times at each voltage are very long.

Based on the above considerations, our approach as presented here (section 4.1) overcomes some of the limitations mentioned. It gives foremost attention to determining maximum power output under steady-state conditions, and determines other \( I-V \) curve parameters (\( I_{SC} \) and \( V_{OC} \)) only in a second step. Furthermore, the repeatability of the \( P_{max} \) value is investigated. The latter is interesting from the point of view that the same \( P_{max} \) should be reached independent of whether the previous condition has been \( V_{OC} \) or \( I_{SC} \). This data also reveals whether such conditions (\( I_{SC} \) or \( V_{OC} \)) are detrimental to PSC device performance reversibly (time to stabilise to \( P_{max} \) after other condition) or irreversibly (\( P_{max} \) not reached any more). Furthermore, it could indicate that a \( P_{max} \) value measured has been influenced by the previous conditions and therefore it may not be reliable. The latter could result in deviations to the low or high side of the true value. Repeating measurements following various previous conditions strongly reduces the risk of erroneous results. In field installation, PV devices operate close to but normally not exactly at \( V_{mp} \). This is due to cell mismatch in PV modules and module mismatch in module strings. Furthermore, this can change depending on degradation of individual cells or modules as well as with (partial) shading. Therefore, in the field it is essential that PV devices demonstrate a stable \( P_{max} \) value regardless of operating point history. The protocol presented here provides some initial information on this aspect, which cannot be obtained from traditional \( I-V \) curve sweeps.

Our approach also reduces the executed \( I-V \) measurement by traditional sweeps to a bare minimum, in order to get a rough estimate of device performance. In our view this is essential as the execution of a large number of \( I-V \) sweeps can already alter the device performance and \( I-V \) sweeps for PSC devices are generally uninformative and potentially misleading. While the \( I-V \) curves might look perfectly normal and even identical at different sweep speeds and for opposite sweep directions, there is always a danger that they do not accurately represent the actual device performance under steady-state conditions.

In general, good \( I-V \) curves are thought to be an indication of good measurement, giving reliable \( P_{max} \). However, in PSC and other metastable devices, this might not be the case and in fact optimising the \( I-V \) curve might be detrimental to obtaining the most appropriate \( P_{max} \). So, we need to focus on getting a reliable and representative \( P_{max} \), and then some indication of the other \( I-V \) parameters. This is a real paradigm shift of approach to PV device characterisation. Before starting to investigate PSC devices, we, as most of the community, were convinced that \( I-V \) curves taken by traditional (or advanced) voltage sweeps would give a correct representation of PV device performance, as long as the sweep parameters were adjusted adequately. Now, in our opinion, for PSC we should do away with this conviction and focus on the power output under steady-state conditions. The determination of full \( I-V \) curves and other \( I-V \) curve parameters is a secondary goal. What really counts in the end are power output and electricity generation.

The approach proposed here has been implemented so that the operator has full control and can make decisions about the stability and progressing to the next measurement point. It might appear to be more desirable to automatize this process, as this would inject some degree of objectivity and potentially repeatability. However, there are reasons for concern, as it would also make the approach less flexible. In view of the large variation of device behaviour, it is difficult to envisage an appropriate protocol available for an unknown device, as demonstrated for example by the MPPT tracking, which can give extremely different results depending on the chosen algorithm or parameters. As already mentioned, this could be achievable when working with the same device type on a regular basis, but not for occasional measurements, as performed in test and calibration laboratories. At the current state-of-the-art, in our opinion, it is better to have a more flexible protocol, based on operator experience and interaction. This will obviously require rigorous logging and reporting of the steps taken and the criteria these were based on (even if these criteria are only qualitative).

In our view this is currently the best option, given the limited stability of PSC devices in general. Therefore, at the moment the protocol will be mainly useful for professional PV measurement and testing laboratories. However, we envisage that future PSC devices will be more stable as a result of PSC technology development. The experience gained by the (professional) laboratories applying the protocol will lead to a consensus on an optimized testing protocol. As more experience is gained applying our protocol, preferably by several laboratories, it will be possible to specify objective and quantitative criteria for the decisions to be made, rather than relying on operator experience and skill. Thus, the protocol will become amenable to less experienced operators, easier to follow and robust in reporting. More laboratories will be able to implement and apply the protocol, even when electrical performance measurement is a side activity in support of PSC technology development rather than the main focus of the laboratory. At that stage the measurement process can be partially automated, although we do not foresee full automation, at least not for power and conversion efficiency measurement of state-of-the-art PSC devices. A logical progression will then be
developing either a technical specification or an international standard within the IEC. Therefore, we see our protocol as presented in this work as a starting point for an improved protocol and consensus forming concerning the measurement of electrical performance of metastable and potentially unstable devices, essentially applicable to any PV device.

It would be desirable to compare the results of various measurement methods applied to PSC devices. This would either require an inter-laboratory comparison (round-robin) or for a single laboratory to implement all or at least several methods. Both approaches are currently limited (mainly) by PSC device stability which does neither allow the lengthy circulation between laboratories nor the measurement of the same device with multiple methods. The aim clearly is to reach suitable device stability for such an exercise to be feasible, as device stability is also essential for PSC product feasibility and deployment in the field. In our view, however, this stage of PSC technology development has not yet been reached and therefore it is not possible to realize the proposed comparison of measurement methods. One possibility would be to postpone work on PSC measurement protocols until the PSC device stability is sufficient to execute the comparison. However, this would leave the PSC community in limbo, as PSC manufacturers require measurement protocols to test and evaluate their devices in order to support the technology development process. In this context, we strongly believe that there is value in laboratories developing measurement protocols for PSC devices and publishing them even at the current stage. This will contribute to advance the field, by firstly helping the measurement community to improve measurement protocols and eventually come to consensus and secondly supporting manufacturing in providing possibilities to assess the electrical performance as unbiased as possible. Development of PSC PV devices as well as the measurement of their electrical performance are both currently subject of active research. It is the authors’ view that a comparison of measurement protocols for PSC devices is highly desirable, but currently unfeasible. In any case such an exercise is well beyond the scope of our current paper.

In conclusion, we propose a measurement protocol for PSC devices that is generally applicable to unknown PSC devices in test and calibration laboratories. The protocol principally aims at determining the maximum power output of the test device (hence its efficiency). This is desirable for power and efficiency reporting which is mainly used in comparison between different test laboratories and the assessment of the potential of PSC technology. Our protocol also provides I–V curves and their parameters such as $I_{SC}$ and $V_{OC}$, with the possibility to derive further parameters such as shunt and series resistance. These are relevant in the development process of PSC devices, even if their uncertainty is high. On account of the order of measurements and repetition of the most important measurement at $P_{max}$ conditions, the protocol is robust against erroneous results. Furthermore, it provides information about the electrical behaviour of the device after the application of conditions such as $V_{OC}$ and $I_{SC}$. Moreover, it is straightforward to implement and its largest asset is the flexibility, although this requires a skilled and experienced operator.

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