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TECHNICAL REPORT

Measurement protocols for photovoltaic devices based on organic, dye-sensitized or perovskite materials

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Measurement protocols for photovoltaic devices based on organic, dye-sensitized or perovskite materials

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

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MEASUREMENT PROTOCOLS FOR PHOTOVOLTAIC DEVICES BASED ON ORGANIC, DYE-SENSITIZED OR PEROVSKITE MATERIALS

FOREWORD

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IEC TR 63228, which is a Technical Report, has been prepared by IEC technical committee 82: Solar photovoltaic energy systems.

The text of this Technical Report is based on the following documents:

Enquiry draft	Report on voting
82/1502/DTR	82/1555A/RVDTR

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

INTRODUCTION

For years, considerable research effort worldwide has been invested in the development of new thin-film photovoltaic (PV) technologies that may offer lower cost production, new applications or both. In particular, organic photovoltaics (OPV), dye-sensitised solar cells (DSC) and perovskite solar cells (PSC) have generated great interest and the market potential of these products is being explored.

To date, the performance of all new PV technologies has typically been determined using the test methods described in the IEC 60904 series and IEC 60891. However, these three technologies in particular present some additional measurement challenges that are at present not dealt with in these documents.

This document provides an overview of current best practices for measuring the performance of PV devices subject to these challenges. It seeks to highlight where the existing standards fail to accommodate the requirements of these technologies, to identify what additional measures may be needed for accurate determination of the device efficiency, and how these measures might be standardised in the future.

It is recognised that this is a rapidly developing field and many items presented are subject to ongoing active research. Therefore, currently no concrete suggestions can be made to amend existing IEC standards with respect to these technologies. However, as the field matures, it is expected that procedures evolve and lead to agreement between experts, so that they can be introduced into international standards. Whether this will consist of amending existing standards or in the issue of a separate standard collecting all procedures relevant to these technologies will be decided in the future.

MEASUREMENT PROTOCOLS FOR PHOTOVOLTAIC DEVICES BASED ON ORGANIC, DYE-SENSITIZED OR PEROVSKITE MATERIALS

1 Scope

This Technical Report summarises present perspectives on the performance evaluation of emerging PV technologies, specifically OPV, DSC and PSC devices. These devices present some challenges for accurate measurement under the existing IEC 60904 series of standards, which were developed in the context of silicon wafer solar cells. These challenges can be different for different devices, but in general they arise due to one or more of the following: instability in performance over time; unusual spectral responsivity; small device size; difficulty in measuring temperature; a transient response to external stimulus; optical interference effects; and a non-linear current response to irradiance. These challenges can lead to the cell output in laboratory testing being significantly different to the output that would be observed in a real application.

The primary focus of the report is measurement of the current-voltage (I-V) relationship under illumination for the purpose of determining the device output power, or power conversion efficiency. Where appropriate, the report makes reference to the IEC 60904 series which describes the standard approach to measuring the performance of all PV devices. The report also references existing published standards that seek to accommodate OPV, DSC or PSC devices.

The report does not seek to find consensus on measurement protocols at this stage. A lot of work has been done by the community toward that aim, but more work is needed. The report therefore seeks to document current knowledge and practices, hence serving as a reference and a tool for conducting further discussion. It is hoped that by identifying the issues that remain unresolved, the report will focus efforts toward resolving those issues, such that a guiding Technical Specification can be prepared in the near future. A robust Technical Specification will bring clarity and confidence to the markets for these PV products as they develop.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC TS 61836, *Solar photovoltaic energy systems – Terms, definitions and symbols*

3 Terms, definitions and conventions

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC TS 61836 apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.2 Conventions

Clauses 5 to 12 of this report each deal with a separate issue relating to the measurement of solar cell performance. Each of those sections is structured as follows:

- General
- Review of currently available standards
- Examples of how the issue is currently handled by researchers around the world
- Summary and possible next steps

At times throughout the report, it is instructive to indicate that a particular issue may be specific to only one or two of the PV technologies being discussed. To assist with this, a key has been included at the end of some paragraphs. The key indicates applicability to a particular technology with a filled square, and uses an open square for the technology to which the issue does not apply. For example, (■OPV ■DSC □PSC) indicates that the above issue applies to OPV and DSC technologies, but not to PSC technologies.

4 Draft terminology for discussion

4.1 General

Any study of the various standards for PV measurement, or the scientific literature on the topic, will show that while some terms are well-defined and applied with consistency, others are not. In particular, certain terms relating to the stability of PV devices and their measurements, have not to date been considered important enough to standardize.

For emerging PV devices however, the topic of stabilization is of profound importance, particularly where accurate and representative measurements are desired. For this reason, an attempt is made here to identify the most commonly used definitions for three key terms. It is hoped that by providing draft definitions for these terms here, the industrial and research communities may arrive at a common language to describe these concepts.

4.2 Draft terms

4.2.1 Steady-state

The term steady-state is used in this document to describe the response of a PV device where that response has achieved a defined level of short-term stability under the prevailing conditions of irradiance, temperature and voltage bias. The term may be applied to any point on an appropriately measured I-V curve, and by extension, to any parameter extracted from such a curve. A steady-state I-V curve is one in which the voltage sweep rate is slow enough to allow each current measurement to stabilize to within a defined stability criterion. The efficiency of a solar cell determined from such a measurement is independent of the I-V sweep parameters (to within the margin of the stability criterion) and, ideally, represents the efficiency the cell would exhibit under a maximum power point tracker at the time of the measurement. Note there is no requirement for the cell performance to be stable in the long term.

4.2.2 Pre-conditioning

The term pre-conditioning is used to refer to the practice of holding a photovoltaic device under a certain set of conditions, again irradiance, temperature and voltage bias, for some period immediately prior to making a current-voltage (I-V) measurement. The practice of pre-conditioning has historically been applied as an attempt to create short-term stability in the device, so that a subsequent I-V measurement reflects or approximates the steady-state device performance in a relatively rapid sweep, so limiting device degradation during the measurement. In some cases pre-conditioning may also be used to artificially inflate the measured device efficiency, although this latter practice is discouraged.

4.2.3 Stabilization

In IEC TS 61836, conditioning refers to a process for stabilizing a device prior to an environmental test. It is always performed prior to that test; however, it is unclear whether it shall be performed immediately before the test (as per pre-conditioning above), or whether instead it is designed to stabilize the device in the long term.

To make the above distinction clear, in this document the term stabilize is used to describe treatments that result in the performance of a PV device being stable over much longer time periods. A measurement of the device performance parameters may or may not be independent of the I-V sweep parameters, however steady-state measurements on a stabilized device produce the same result regardless of any reasonable device exposure and/or time between measurements. This definition is consistent with the historical use of this term in the published PV efficiency tables.

5 Pre-conditioning

5.1 General

The practice of pre-conditioning an unstable PV device prior to *I-V* measurement is contentious, owing to its ability to influence the measurement, sometimes producing a result that would not represent the device's performance in a real-world environment. Nevertheless, many endorse its use as a way of achieving reproducible results. Certainly, pre-exposure of a solar device with light seems reasonable, given the environment it will ultimately be used in. This clause seeks to briefly summarize the practices that invoke pre-conditioning and the standards that refer to it. At present, there is no single pre-conditioning procedure recognized as effective for all devices, even within a given technology type.

5.2 Review of currently available standards

5.2.1 IEC 60904-1

IEC 60904-1 (*Photovoltaic devices – Part 1: Measurement of photovoltaic current-voltage characteristics*) [1] provides no guidance for devices that are unstable on the timescale of the *I-V* curve measurement. The only reference to device instability in that document is as follows: "In measuring PV devices which are non-stable, care shall be taken in selecting a representative spectral responsivity".

At the time of preparing this report, a new edition of IEC 60904-1 is in draft. The draft currently includes text that extends the above statement to include reference to "pre-conditioning"; however, the use of that term is more akin to what we have defined above as *stabilization*. This is understandable for OPV and DSC devices, where long term stabilization can usually be achieved with pre-treatment. However, to accommodate PSC devices, it may be of value to distinguish between pre-conditioning and stabilization using the definitions above.

The draft of IEC 60904-1 suggests that guidance on pre-conditioning can be taken from the Clause on Stabilization (Test MQT 19) in the current IEC 61215 series (described specifically in IEC 61215-2:2016 [2]). The MQT 19 method contains good detail, particularly in regard to stabilization by light soaking. Regarding other types of stabilization, the document permits any method provided the method is validated, and a validation procedure is described in the document.

In summary, the MQT 19 procedure states that all PV modules should be electrically stabilized prior to measurement. It defines electrical stabilization as a stabilization of the observed output power value (P) according to

$$(P_{max} - P_{min}) / P_{average} < x \qquad (1)$$

where P_{max}, P_{min} and $P_{average}$ are the extreme values of P taken from a sequence of three measurements interleaved with periods of irradiation to a defined minimum dose. The values of both x and the minimum dose are defined in the technology specific sub-parts of IEC 61215-1 [3] (IEC 61215-1-1 for crystalline silicon, IEC 61215-1-2 for cadmium telluride, IEC 61215-1-3 for amorphous silicon and IEC 61215-1-4 for copper indium gallium (di)selenide). Presently, there is no current plan to include sub-parts for OPV, DSC or PSC into the IEC 61215 series, although this is likely at some point in the future if these technologies reach market maturity.

5.2.2 SEMI-PV57

The SEMI-PV57 [4] is a standard from Semiconductor Equipment and Materials International (SEMI) about test method for current-voltage performance measurement of organic photovoltaic and dye-sensitized solar cell. In SEMI-PV57 is stated that in order to anneal and stabilize the electrical characteristics of a device under test using simulated solar irradiation for 10 minutes to 30 minutes, some requirements are recommended as follows (SEMI-PV57, 9.6.1):

– use a reference device to adjust the irradiance in the range 600 W/m^2 to 1 000 W/m^2, then record the irradiance (SEMI-PV57, 9.6.2);

– mount the device within the light field and monitor its maximum power using a source-measure unit (SMU) or variable resistive load;

– stabilization is achieved when the check criteria defined in Formula (2), based on measurements from two consecutive periods of at least 43 kWh/m^2, each integrated over periods when the temperature is in the range 40 °C to 60 °C, are in agreement to better than 2 %.

$$\text{check criteria} \equiv (P_{max} - P_{min}) / P_{average} \times 100\ \% \qquad (2)$$

This method is very similar to the MQT 19 method described in IEC 61215-2 and summarised in 5.2.1 above and uses the dose of 43 kWh/m^2 used for the thin-film a-Si devices as in IEC 61215-1-3.

This standard is similar to IEC 60904-1 but does not address preconditioning or stabilization criteria.

(■ OPV ■ DSC □ PSC)

5.3 Some examples of pre-conditioning procedures applied to OPV/DSC/PSC

5.3.1 General

A number of different approaches to device pre-conditioning are described in the literature. Different groups appear to be using procedures suited to their own particular material system. The situation is further complicated by degradation effects, which impact different devices in different ways. The most common approaches are described briefly in 5.3.2 to 5.3.4, and the issue also comes into the subsequent clause on I-V measurement.

5.3.2 Avoidance of light soaking

Some groups do not recommend pre-conditioning with light, based on the fact that light can cause degradation, or in some cases even artificial enhancement in the device. The latter may occur if the device incorporates doped oxides as barrier layers, as many oxides are photoactive under the UV component of the light source. Ultraviolet (UV) is often not present in a real application, owing to absorption by encapsulating layers in the final commercial product.

Even in the absence of UV effects or light-induced degradation, PSC devices are well-known to be sensitive to the exposure history, with effects that vary with the voltage bias during any recent light exposure. A recent report based on a multi-lab intercomparison experiment [5], identified a persistent relationship between the measured cell efficiency and the type of light soak performed. Light soaking at the short-circuit condition was observed to produce low hysteresis, but also the lowest efficiency result. Avoidance of light soaking produced a similar result. Light soaking at V_{mp} produced a higher efficiency with some hysteresis. Light soaking at the open circuit condition produced the largest hysteresis and hence no efficiency could reliably be extracted.

The argument to avoid light soaking in PSC devices is understandable, given the complexities of the device response described above.

(□ OPV □ DSC ■ PSC)

5.3.3 Pre-conditioning by light soaking

The impact of light soaking is not restricted to PSC devices. In addition to irreversible degradation, effects on OPV and DSC devices can include short-term variations owing to reversible degradation and/or annealing, as well as recovery from dark ageing. For these reasons, light soaking is a common form of pre-conditioning treatment for these devices.

A light soaking pre-treatment has been shown to have a stabilizing effect on the performance of OPV and DSC devices, especially for devices that were kept in the dark beforehand ([6] and [7]). For devices stored in the dark for long periods, a suitable treatment is to hold the device for around 40 minutes at open circuit under broadband illumination, with irradiance around 1 000 W/m^2 and temperature held around 25 °C. This pre-conditioning treatment primarily stabilises the fill-factor of the resulting I-V curve. After this treatment, shorter light soaking treatments of around 10 minutes are usually sufficient to bring the device back to its light-stable performance, provided only a few days have passed since the last full light soak.

In accelerated ageing studies of OPV mini-modules, the need for longer light-soaking treatments (up to about 1 h) with increased ageing was noticed, particularly for devices kept under humidity stress [7].

The enormous range of device behaviours at the R&D stage means that standardising a light soaking procedure for pre-conditioning will not be an easy task. This may be made simpler once device technologies mature to a stage at which they can be stabilized using a procedure such as MQT 19 in IEC 61215-1. Stabilization will not necessarily remove the need for special steps to achieve a steady-state measurement, such as pre-conditioning, or one of the other techniques discussed in Clause 6.

(■ OPV ■ DSC □ PSC)

5.3.4 Recognition of a diurnal instability

Some groups have identified the fact that some devices, particularly PSC, can exhibit a reversible instability over the 24 hour day-night cycle [8], [9] and [10]. They contend that this means it is not appropriate to seek a single stabilized device performance, but instead a fair assessment should consider that the real application also includes nighttime. How this should be measured in the laboratory remains an issue for discussion; however, it may mean that pre-conditioning before I-V measurement is not useful, or perhaps should be performed in two parts, one for the morning performance and the other for the afternoon performance.

(□ OPV □ DSC ■ PSC)

5.4 Summary and suggestions

Based on the draft terminology in Clause 4, the aim of a pre-conditioning procedure is to reduce the exposure time required for an I-V curve to represent the behaviour of the device in a real application. Shorter exposures reduce the impact of exposure effects during the measurement; hence this issue may become less important as devices become more stable.

Stabilization of devices, as proposed, is a different concept, albeit equally important. Standardising this term for OPV/DSC/PSC to match the existing usage in IEC 61215 series will remove ambiguity for the test laboratories in making measurements for the record efficiency tables, by clarifying the requirement for a device to avoid being marked as 'not stabilised' in those tables.

Having an agreed method for confirming long term stability will also simplify exchanges between test laboratories, meaning stronger validation of devices and ultimately better measurement practices.

Adoption of the IEC 61215-1 approach to stabilization for OPV/DSC/PSC devices will mean that stability parameters (the values of x and the minimum exposure dose in Clause 5.2.1) will need to be developed for these devices. These parameters can be codified in additional technology-specific sub-parts of IEC 61215-1-x (e.g. -1-5, -1-6, -1-7).

If the definitions in Clause 4 become widely agreed upon, it will be of value for these to be codified in IEC TS 61836.

Alternatively, the opportunity may be afforded to opponents of the IEC 61215-1 stabilization concept to argue that any such definition should accommodate a diurnal behaviour in these devices.

At this stage, the large number of device/material combinations for OPV/DSC/PSC means that the necessity and nature of pre-conditioning will need to remain at the discretion of the individual researcher. It may be helpful to have a structured decision process for evaluating the need for pre-conditioning on any device, and for selecting the appropriate method. Whatever pre-conditioning method is chosen (including no pre-conditioning), it will be important that this is recorded and included in any report of the measurement.

Whichever approach is identified as best, it will be of value to work with the developers of the next edition of IEC 60904-1 to ensure consistency in terminology. For example, it will likely be important that the difference between pre-conditioning and stabilization be captured in that document. Likewise, the concept of a steady-state measurement may be addressed, with specific instructions for achieving a steady-state measurement being potentially available in a separate document, such as a Technical Specification for OPV/DSC/PSC. A possible wording to include in IEC 60904-1 could be:

> "Care shall be taken in measuring PV devices that are metastable. If it is possible to stabilise the device, stabilisation should be performed before any characterisation (*I-V* or spectral responsivity measurement). Any stabilisation procedure performed shall be reported together with the test results. The IEC 61215 series of standards provides guidance on technology-dependent appropriate stabilisation."

6 *I-V* measurement

6.1 General

The standard procedure for measuring the current response of a PV device to an applied voltage under illumination is described in IEC 60904-1. The procedure is robust if the current response to changes in the applied voltage is rapid compared to the time between changes in voltage. The procedure does accommodate devices with a slightly slower response, with the following text:

> "Depending on the cell technology, *I-V* measurement may be influenced by the voltage sweep rate and the sweep direction. Cells with high capacitance are more problematic. These effects should be carefully analyzed in a test programme. Negative effects can be excluded when measurements in the positive voltage direction starting at the short-circuit current and in the negative direction starting at the open-circuit voltage overlap optimally."

The above statement is effective in dealing with devices where *I-V* hysteresis is the result of a simple time constant in the current response to a change in irradiance or applied voltage bias. The existing standards listed in Clause 6.2 are primarily designed to assist in the selection of appropriate sweep speeds (delay times for each voltage step) so as to avoid measurement errors arising from this kind of device response.

However, certain PV technologies are not compatible with the above procedure. In particular, recent reports, e.g. [11] have shown that for many PSC devices, agreement between the forward and reverse *I-V* curves does not guarantee that the result will be repeatable, even in the absence of irreversible degradation. This situation occurs when the device, which may be stable on a 100 ms timescale, exhibits a change in its performance under illumination or applied voltage on a timescale of seconds to minutes, or even hours. This is problematic for the *I-V* curve measurement, for two reasons:

1) Slow *I-V* sweeps, designed to avoid errors due to a transient response, are not completed before the device exhibits changes under the influence of the light or applied voltage, and,
2) Rapid *I-V* sweeps, designed to avoid long-term drift in the device, are often affected by the transient response time, or even if not, are unlikely to be representative of the performance of the device in a real application with continuous illumination.

According to the report in [11], when the forward and reverse *I-V* curves agree under a wide range of sweep conditions, the measurement result can be defined as the "true" *I-V* curve. In many cases however, it is not possible to find agreement between *I-V* curves taken using different sweep conditions, hence the true result simply cannot be determined. Subclause 6.3 discusses some approaches being applied by the PV research community to address this problem.

(□ OPV □ DSC ■ PSC)

6.2 Review of currently available standards

6.2.1 IEC 60904-1

This has been described in 5.2.1.

6.2.2 SEMI-PV57

This SEMI-PV57 standard includes three relevant clauses:

> "*I-V* Sweep by Setting Delay Time – The delay time should be longer than 20 ms for measuring OPV, longer than 40 ms for measuring DSSC with organic solvent electrolyte, and be longer than 1 000 ms for measuring DSSC with ionic liquid electrolyte [SEMI-PV57 section 9.7.2]."

"I-V Sweep Including Real-time Removing Capacity Effect – This method needs to read simultaneously multi-point forming step after taking the optimization stabilizing area as a point on the I-V curve [SEMI-PV57 section 9.7.3]."

"I-V measurements of both scan directions are necessary to estimate the related measurement error, as the temporal response is expected to be dependent on the device structure of the device under test and the I-V curves measured at the different sweep directions. The final performance data shall have deviations 0,2 % or less [SEMI-PV57 section 9.7.4]."

(■ OPV ■ DSC □ PSC)

6.2.3 OITDA-PV01-2009

The OITDA-PV01-2009 standard from the Japanese Optoelectronics Industry and Technology Development Association (OITDA) is about an evaluation method of the performances for dye-sensitized solar cell devices (original in Japanese) [12].

A translation reveals the following:

"When I-V measurements are performed by stepwise changes of bias voltage, sampling time is selected based on the Japanese Industrial Standards JIS C 8934 1 5.2, but, in the case of DSSC, determination of the time constant is not so easy. In this case, the delay time should be set long enough, e.g. 50-100 ms, to allow the I-V curve determined by the forward scan (from short-circuit to open-circuit) to be coincident with that by reverse scan. The appropriate sweep time should be examined for each device because it depends on the range of the voltage scan, measured points, materials and structure of the device. Sweep time should be set at 13-25 s for a typical DSSC [OITDA-PV01-2009 Clause 7.2.1]."

(■ OPV ■ DSC □ PSC)

6.2.4 JIS (Japanese Industrial Standards)

JIS C 8934 5.2(2)(b) (Measuring method of output power for amorphous solar cells, in Japanese) [13] says:

"When I-V measurements are performed by stepwise changes of bias voltage, the delay time for data sampling should be set more than 4 times longer than the time constant of the PV device."

6.3 Some examples of I-V procedures applied to OPV/DSC/PSC

6.3.1 General

This clause describes some perspectives on issues important to I-V measurement on PV devices that exhibit transient effects. It should be recognised that the PV community, having lived with this issue for many years, has collectively developed some common strategies for maximising the robustness of the measurement. The following points are widely accepted as part of a best-practice approach. They can be attributed to many authors, and are paraphrased here [14]:

- Mask the cell appropriately to avoid stray light, and measure the mask area accurately
- Adjust the source irradiance carefully using a calibrated reference cell
- Determine the steady-state I_{sc} and V_{oc} and monitor the stability of these
- Measure the steady-state current at voltages near P_{max}
- Record forward and reverse I-V scans at various scan rates and check for consistency with the steady-state value
- Check that the measured I_{sc} is consistent with the absolute spectral responsivity of the device, integrated over the AM1.5G spectrum.

The above steps provide a sound, high-level guide to making a robust *I-V* measurement; however, they lack detail. For example, they provide no guidance as to what constitutes 'steady state' for the various parameters, or what constitutes 'consistency' between *I-V* curves, and with the steady state P_{max} value. Further, they provide no guidance as to what to do when these criteria cannot be satisfied.

6.3.2 Criteria for a steady state measurement

Clearly, accurate *I-V* curves depend on the measured current at each voltage step having time to achieve a level of short-term stability. The management of this step time (or sweep speed) is the subject of many of the standard methods described in 6.2. More advanced methods, not yet standardised, involve actively monitoring the settling of the current measurement at each voltage step. This approach, known variously in the literature as dynamic *I-V* or stabilised *I-V*[1], is explored in more detail in 6.3.5.

6.3.3 Criteria for agreement between forward and reverse *I-V* curves

Also clearly, if *I-V* curves in the forward and reverse sweep directions do not overlap, then neither can be called correct and a reliable efficiency measurement cannot be obtained. This raises the question as to what metric might be used to quantify *I-V* curve overlap. For example, is it sufficient that the P_{max} values extracted from each curve agree, or shall the curves overlap over the full voltage range? Further, what metric should be used to describe the magnitude of overlap?

Informal discussions between groups suggest a possible metric for the agreement between P_{max}^+ and P_{max}^-, the P_{max} values from the forward and reverse *I-V* curves respectively, as follows

$$|(P_{max}^+ - P_{max}^-) / (P_{max}^+ + P_{max}^-)| < x \quad (3)$$

where in that case, x might take a value of around 1 %. Alternatively, one group [15]) propose a more comprehensive requirement, with $\Delta P_{max} < 0,5$ % (corresponding to < 0,25 % in the criterion above) plus ΔI_{sc} and $\Delta V_{oc} \le 0,1$ %.

6.3.4 Flow charts for *I-V* measurement of PV devices showing transient effects

A useful flowchart for pre-conditioning and *I-V* measurement is shown in Figure 1, based on the work and results presented in [11], [15], [16], [17] and [18]. This chart guides the user to perform a measurement with the goal that the forward and reverse *I-V* curves overlap to within some specified criterion. If overlap cannot be achieved then other methods are suggested (see box C in the figure) these other methods are described in 6.3.5. The time response analysis in box B is described in [15] and [17].

Condition 1 in Figure 1 represents one or more criteria for overlap of the forward and reverse *I-V* curves. Brief examples of such criteria are described in 6.3.3.

The approach described in Figure 1 has been applied effectively for OPV and DSC devices and will likely be applicable to PSC devices, although some of these will require the special methods listed in box C. The special requirements for some PSC devices arise from a longer-term instability to light and/or applied voltage. For these devices, I_{sc}, V_{oc} and/or P_{max} values may not be stable on the timescale of the *I-V* measurement. Agreement between forward and reverse scans may not be achievable, or may not be repeatable over a range of different sweep conditions. For such cases, it is important to distinguish between a slow drift that will eventually reach a steady state and an irreversible degradation that will not reach a steady state.

1 Note the use of the term *stabilised* in that case would be inconsistent with the usage being discussed in this document, see Clause 4.

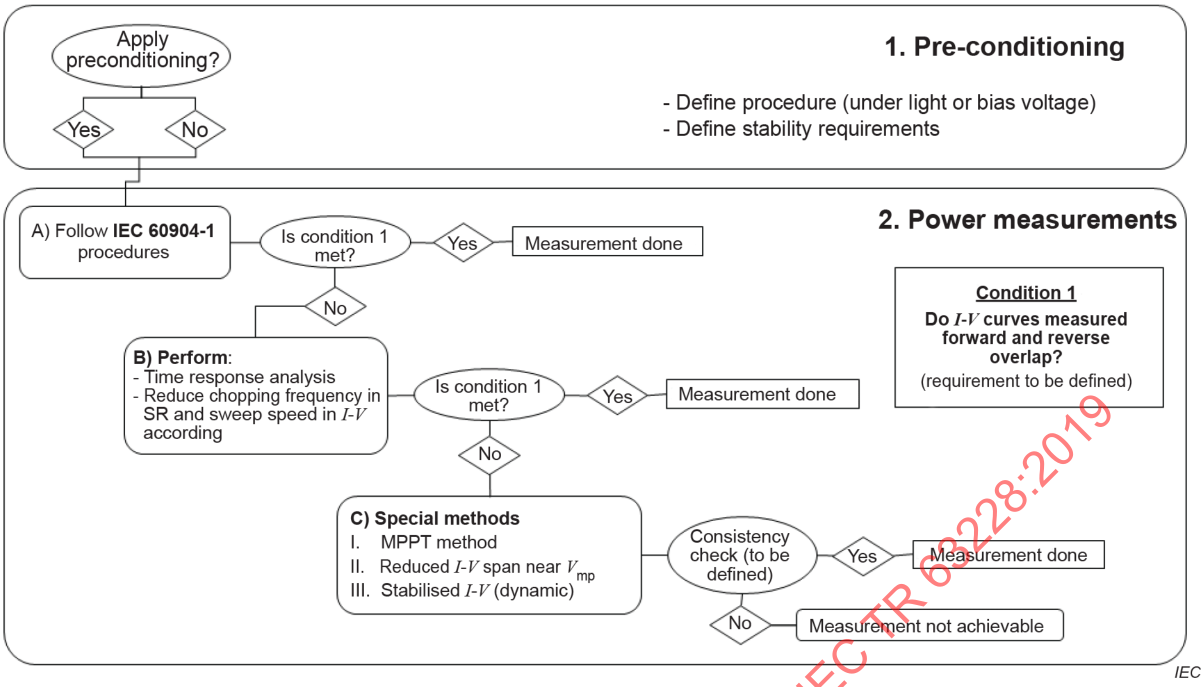

Figure 1 – Example flowchart for the electrical characterization of OPV/DSC/PSC

One group has reported a flowchart [14] for determining I-V sweep parameters in the context of two key decision parameters, the stabilisation[2] time, t_{stab}, and the degradation time, t_{deg}.

The chart is shown in Figure 2. In this approach, a sacrificial device that is nominally identical to the test device is used to first determine the two important time constants. If the time constant for degradation is smaller than the time constant for stabilisation (settling), then the measurement should be abandoned. Conversely, if stabilisation (settling) is faster than degradation, then a suitable range of sweep rates can be identified. The degradation rate can then be considered when assessing the uncertainty of the measurement, along with the level of agreement between results at different sweep rates.

2 Again, this use of the term *stabilisation* to describe short-term stability clashes with its use elsewhere to describe long-term stability, hence perhaps *settling time* would be a better term in this instance.

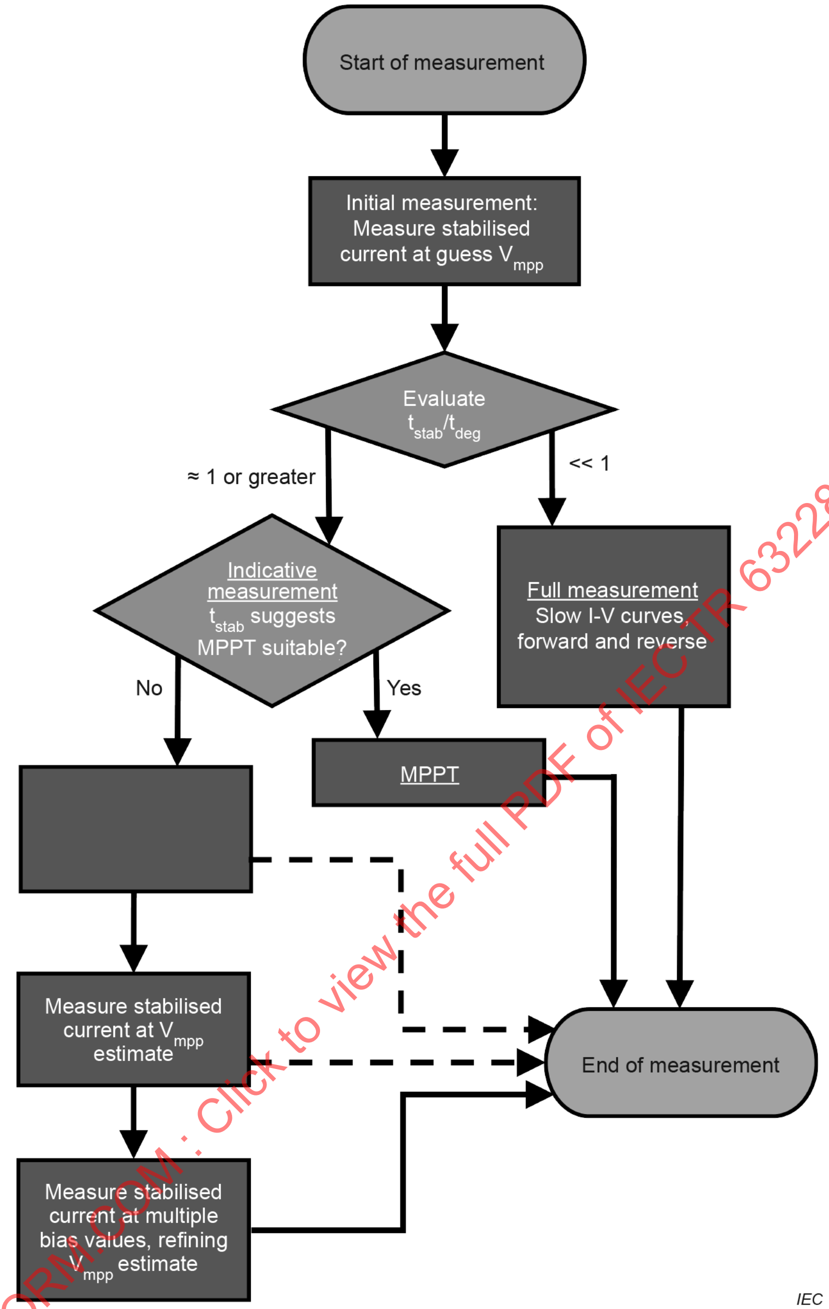

Figure 2 – Alternative flowchart for devices exhibiting long-term drift

6.3.5 Special methods

6.3.5.1 General

When standard *I-V* curves with fixed sweep speeds are unable to demonstrate overlap between the forward and reverse curves, the steady-state performance of the device cannot be determined. In that case, following advanced methods in 6.3.5.2 to 6.3.5.5 may be of value.

6.3.5.2 Stabilised* *I-V* (Dynamic *I-V*)

Given that in Clause 4, the word "stabilized" is defined as referring to long term device stability, rather than short-term stability, or "settling", it may be of value to stop using the word to describe this type of *I-V* measurement.

In this popular extension of the typical *I-V* curve measurement, the wait time at each step in the applied voltage is not fixed, but is allowed to vary in order to achieve a pre-determined degree of stability in the measured current [19], [20] and [21]. The current is monitored from immediately after the voltage step occurs, but only recorded after certain conditions are met, e.g. when the rate of change of current falls to a specified value. This value may be specified in a relative sense or an absolute sense, e.g. to match the noise level in the measurement electronics, or to meet an agreed criterion.

The primary advantage of the dynamic *I-V* method is that the length of the sweep is selected based on the device response. This means that the sweep speed can easily be made long enough, without being too long, where there may be a risk of device degradation. If the sweep speed needs to be varied to achieve overlap in the forward and reverse *I-V* curves, useful information is obtained from the current stability setpoint.

In a recent report [5], this method was shown to produce a repeatable efficiency measurement for a PSC device, with practically no hysteresis.

6.3.5.3 Reduced *I-V* span (measurement only near V_{mp})

When full *I-V* curves cannot be made to overlap, important information, including the device efficiency, can still be obtained by performing the *I-V* sweep over a truncated range of voltages around the estimated maximum power voltage. The voltage range need not be large, as long as the maximum power point is included in the range. The smaller voltage range in this method means that the sweep can be shorter in time, the device is not exposed to voltages outside its typical operating range, or to large voltage steps. The influence of unusual voltage bias, sometimes known as "poling", is therefore removed from the measurement.

This test is in fact an important cross check, identified in 6.3.1, as a means of confirming the value of P_{max} obtained from the full *I-V* curves. A common example of the method is to measure the current at only a single voltage near V_{mp}. Naturally, the Dynamic *I-V* approach (point i) is still of value when the *I-V* span is reduced, even to a single voltage point.

6.3.5.4 Maximum power point tracking (MPPT)

The MPPT method described in [22] and [23] is similar to the Reduced *I-V* span method, except that instead of a pre-determined voltage scan, the applied voltage points are determined based on the measured current. The aim of the method is to measure the current at precisely V_{mp}, thus providing a direct measurement of P_{max}. Thanks to the prevalence of MPP trackers for outdoor operation of PV systems, a number of tracking algorithms are available. These algorithms attempt to locate the maximum power point as efficiently as possible. Some algorithms have been specifically modified to handle unstable devices (e.g. [24]) which are at risk of producing an oscillating result with this method.

6.3.5.5 Cyclic *I-V*

This method produces full *I-V* curves using a special sweep sequence. The *I-V* sweep is commenced at or near V_{mp}, proceeding first to the short-circuit end, then to the open-circuit end and back to V_{mp}. Automation of the sweep means the transitions at each end are fast and smooth, minimising the impact of voltages away from the operating point [23].

6.4 Summary and suggestions

In its current form, the standard for measuring *I-V* curves of PV devices (IEC 60904-1:2006) does not sufficiently handle devices with a slow transient response to changes in the irradiance or the applied voltage. This situation has led to ambiguity for developers of many emerging PV, especially PSC devices, since *I-V* curves are the primary method for establishing device performance. The PV R&D community will benefit from an accurate and consistent approach to *I-V* curve measurement in these devices, so that only genuine progress is shared, rewarded and pursued.

This clause summarises the various approaches to *I-V* measurement in common use today. Following further discussion on these matters it is envisaged that the information could form the basis for an IEC Technical Specification. In particular, the following concepts would represent a valuable extension to the existing standard:

1) The PV community should seek to reach consensus as to the meanings of the terms steady-state, pre-conditioning and stabilization;
2) The use of a variable dwell time at each voltage step to specifically allow the current measurement to settle (dynamic *I-V*) should be the recommended practice;
3) It should be acknowledged that a lack of hysteresis at a single sweep rate does not guarantee the measurement is consistent with the device performance under steady-state conditions;
4) Recommended practice should also include use of a reduced voltage sweep range, typically around the maximum power voltage, as a cross-check against the full *I-V* curves – this includes measurements at a single voltage point and also potentially maximum-power point tracking techniques;
5) It would also be valuable for any Technical Specification to confirm the majority view, that reportable device efficiency measurements shall represent the steady-state performance of the device.

7 Reference cell

7.1 General

By far the most important external influence on the output of a PV device is the incident irradiance, hence PV measurements are typically reported at defined irradiance values and a good reference cell is critical to the accuracy of the measurement. The reference cell establishes the effective irradiance (see IEC 60904-7 [25] or ASTM E973 [26]) of the light source for the device under test, correcting for the fact that the light source spectrum is never precisely the required reference spectrum.

The use of a reference cell is appropriate to measurements both indoor and outdoor, using either continuous or pulsed light sources. For indoor measurements, the light source is typically adjusted to produce a known short-circuit current in the reference cell, the calibration value. At this setpoint, the effect of the light source on the reference cell is identical to a light source with the true reference spectrum at the specified irradiance, often 1 000 W/m^2.

Having completed the above step, many groups proceed with the measurement with no further adjustment to the irradiance. That approach is valid, provided the spectral responsivities of the device to be measured and the reference cell are identical. For reasons of stability, most PV reference devices are based on silicon cells, hence the assumption is usually reasonable (although not sufficient for a testing laboratory) if the device to be measured is also a silicon device. For many emerging PV devices however, the difference in spectral responsivity between the test cell and the reference cell should be considered by either a further adjustment of the light source, or a spectral mismatch correction to the measured result. Either can be achieved by determination of the spectral mismatch factor, using the method described in IEC 60904-7. For light sources that can be readily adjusted without affecting the spectrum, this adjustment is the preferable option, since correcting the *I-V* points after the measurement often requires several device parameters and can increase the overall measurement uncertainty.

A challenge for these devices is that determining the spectral mismatch factor can be time-consuming, particularly in a research environment where many cell measurements need to be made each day. This is often not an issue in the early stages of cell development; however, at some point the error due to spectral mismatch between the silicon reference cell and an OPV, DSC or perovskite test cell becomes important, e.g. when reporting a breakthrough cell efficiency in scientific literature. An apparent solution is to create a reference cell using the same technology as the test cell; however, this is usually impractical owing either to the requirement that the device current response is linear with irradiance, or owing to a lack of long-term device stability.

7.2 Review of currently available standards

7.2.1 IEC 60904-2

IEC 60904-2 [27] describes the requirements for photovoltaic reference devices for all applications other than those requiring concentrated sunlight. The document defines different classes of reference cell (primary, secondary, working) and provides guidance as to the device design, including packaging requirements, temperature measurement and electrical connectivity. Example calibration methods are also provided.

The current edition also includes the following statement on the use of built-in optical filters to adapt the spectral responsivity of the reference cell material:

> "The spectral responsivity of the reference device, for example, is determined by the transmission of any protective cover in front of the device and the spectral responsivity of the device itself. Therefore, the overall spectral responsivity can be adapted by using suitable filters as or in addition to the protective cover."

7.2.2 SEMI-PV57

This standard includes the following statements:

> "Calibration for the secondary photovoltaic reference cell should consist of short-circuit current (I_{sc}) under natural or simulated sunlight, using a primary reference cell to measure the incident irradiance (SEMI-PV57, 7.2.1)."

> "Reference cell is important during calibration for solar simulator, which is required long-term stability for frequent calibrations. Until now, a test sample matching such requirements has rarely been found. Therefore, a crystalline silicon (c-Si) solar cell with long-term stability is generally used as an alternative (see Table) (SEMI-PV57, 7.2.2)."

Table 1 is included in the standard as a guide to which type of filter may be suitable for providing an approximate match between the spectral responsivities of the reference cell and the test cell. It should be remembered that this result also depends on the light source spectrum; however, these results should be approximately valid for any light source that reasonably approximates the AM1.5G spectrum, such as the very common Xe arc lamps fitted with AM1.5G filters.

Table 1 – Filtered c-Si reference cell

Windows with Filter Type	*Applied Type*
Si + BK7 or Quartz	Monocrystalline Si (c-Si)
Si + BK7 or Quartz	Polycrystalline Si (mc-Si)
Si + BK7 or Quartz with KG2	Amorphous Si (a-Si)
Si + BK7 or Quartz with KG3	DSSC with N749
Si + BK7 or Quartz with KG5	DSSC with N719, and OPV with polymer

(■ OPV ■ DSC □ PSC)

7.2.3 OITDA-PV01-2009

A translation of the section entitled *Pseudo-primary reference solar cell* (OITDA-PV01-2009, 3.2.1) follows:

"When a stable primary reference solar cell of a DSC is unavailable, a pseudo-primary reference cell having spectral responsivity similar to that of a DSC may be used following JIS C 8910 Clause 5[3]."

JIS C 8910 Clause 5[3] (*Primary reference solar cells*) [28]:

"When a stable solar cell whose spectral responsivity and linearity of output current against input light irradiation are not available, a pseudo amorphous silicon solar cell having spectral responsivity similar to that of the test cell, for example optical filter equipped c-Si PV, may be used."

A translation of the section entitled *Pseudo-secondary reference solar cell* (OITDA-PV01-2009, 4.2.2) follows:

"When a stable secondary reference solar cell of a DSC is unavailable, a pseudo-secondary reference cell having spectral responsivity similar to that of a DSC may be used following JIS C 8934 2.(1)."

(■ OPV ■ DSC □ PSC)

7.2.4 JIS C 8904-2

The JIS 8904-2 (part 2) standard from the Japanese Standard Association (JSA) is about the requirements for reference solar devices [29]. A translation of the section entitled *Construction of reference devices* (JIS C 8904-2, 3.2) follows:

"Pseudo reference cells are stable PV cells, e.g. crystalline silicon, equipped with optical filters to modify the spectral responsivity so as to match the relative spectral responsivity of the test cell. Such cells may be used as reference cells. Structures to prevent multiple reflections are desirable, and the integrated filter shall not be of the interference-type. Pseudo reference cells with various filters are available to suit the spectral responsivities of various emerging PV device types."

7.2.5 ASTM E1040

The ASTM E1040 [30] is a standard specification from ASTM International for physical characteristics of non-concentrator terrestrial photovoltaic reference cells. This specification describes the physical requirements for primary and secondary terrestrial non-concentrator photovoltaic reference cells. The secondary reference cell package is the World Photovoltaic Scale (WPVS) package designed by the Japanese, German, and US calibration labs. The WPVS package design specifies a "durable, smooth front window" to protect the photovoltaic cell. A coloured glass or other optical filter may also be used to modify the spectral responsivity of the cell, allowing it to better match the spectral responsivity of a non-silicon test cell.

(■ OPV ■ DSC ■ PSC)

7.3 Common practices for reference cells for OPV/DSC/PSC

A frequent approach to dealing with spectral mismatch for these PV devices is to use filtered reference cells, as discussed in several of the standards cited in the previous section. The use of a crystalline silicon cell provides the stability and irradiance linearity, and the filter provides the required spectral match. Such devices can lead to reduced uncertainty for rigorous PV measurements (where a mismatch correction is still performed) and may avoid the need for mismatch correction altogether in an R&D environment, where measurement accuracy is less critical.

3 JIS C 8934 has been withdrawn.

At the time of writing, one supplier of PV reference cells publishes the spectral responsivity curves for ten different filtered reference cells available for purchase from that laboratory [31]. For each of these reference cells, Table 2 lists the magnitude of the necessary spectral mismatch correction for each of twelve devices measured at an accredited PV testing laboratory [32] (based on an AM1.5G-filtered Xe arc lamp solar simulator). A further device (perovskite HBG) is included to indicate an extreme mismatch case; this is based on a synthetic SR curve for a high band gap perovskite cell (methyl ammonium lead bromide).

The table of spectral mismatch deviations indicates the typical range of values that this correction can take (from 0 % to 5 %), as well as the potential benefit of choosing an appropriately filtered reference cell.

Table 2 – Typical AM1.5G spectral mismatch errors for various device/reference combinations for an AM1.5G-filtered Xe arc lamp

Cell type	Filter type (mismatch error in percent [%])									
	BG38	BG40	OG590	KG3	KG5	HOQ mono	HOQ poly	HOQ IR-ext	RG695	LARC HQC
a-Si	1,85	2,10	1,35	0,88	1,03	0,22	0,29	1,27	1,47	1,17
OPV 1	1,48	1,73	1,73	0,51	0,66	0,59	0,08	1,64	1,85	1,55
OPV 2	0,55	0,81	2,69	0,42	0,27	1,54	1,02	2,60	2,81	2,50
DSSC 1	0,01	0,25	3,27	0,99	0,84	2,12	1,60	3,18	3,39	3,08
DSSC 2	0,30	0,04	3,57	1,28	1,13	2,41	1,89	3,48	3,69	3,38
DSSC 3	1,24	1,49	1,97	0,27	0,42	0,84	0,32	1,89	2,10	1,79
DSSC 4	1,77	2,02	1,43	0,81	0,96	0,30	0,21	1,35	1,55	1,25
Perovskite 1	1,35	1,60	1,87	0,38	0,53	0,73	0,22	1,78	1,99	1,69
Perovskite 2	0,41	0,67	2,83	0,56	0,41	1,69	1,17	2,75	2,95	2,65
Perovskite 3	2,12	2,37	1,06	1,16	1,31	0,06	0,57	0,98	1,18	0,88
Perovskite 4	0,73	0,98	2,51	0,25	0,10	1,36	0,85	2,42	2,63	2,32
Perovskite 5	0,64	0,89	2,60	0,34	0,19	1,46	0,94	2,52	2,72	2,42
Perovskite (HBG)	1,87	1,61	5,19	2,87	2,72	4,02	3,49	5,10	5,32	5,00

7.4 Summary and suggestions

It is important when working with emerging PV technology types to be aware of the potential for spectral mismatch errors in I-V measurement. These errors are equivalent to an incorrect setting of the irradiance and hence lead to a proportional error in I_{sc}, and a similar relative error in P_{max} and the device efficiency.

During the R&D stage, it may not be necessary to consider spectral mismatch error, since the magnitude of the error is often small. Where more accurate measurements are required, however, the issue can be avoided either by performing the spectral mismatch correction, or by using an appropriately filtered reference cell. For AM1.5G-filtered Xe arc solar simulators an appropriate filtered reference cell can reduce the spectral mismatch error from several percent to tenths of one percent.

The matter of which filter is appropriate for which device type is non-trivial, owing to (i) the range of different device spectral responsivities (SR can vary significantly within devices of the same type), and (ii) the fact that not all solar simulators have the same spectral output.

8 Spectral responsivity measurement

8.1 General

Spectral Responsivity (SR) describes the wavelength-dependent current response of a PV device to monochromatic light, usually under short-circuit conditions. SR is used as an analytical tool during the research and development stage of the device, and also for determining the spectral mismatch correction to the irradiance when high-accuracy measurements of the device performance are required (Clause 7).

The SR measurement is made by irradiating the device with a narrow-bandwidth light source at a series of different wavelengths covering its responsivity range and by measuring the short-circuit current and the irradiance at each of these wavelengths. Since the narrow-bandwidth irradiance is typically very low (and variable), a broadband bias light is used simultaneously to place the device nearer to its typical operating irradiance. In that case the quasi-monochromatic light is pulsed or chopped and the responsivity measured using a lock-in amplifier. The total irradiance is then relatively constant and the measurement is referred to as differential spectral responsivity (DSR) [33].

It is important to recognise that since the DSR measures the incremental effect of a small monochromatic perturbation on a large background irradiance, it only represents the true SR if the device under test is perfectly linear up to the bias irradiance, i.e. only if the relationship between current and irradiance remains constant between zero irradiance and the bias irradiance. If the device deviates from linearity (usually by being slightly sub-linear or super-linear), then the SR at the bias irradiance is best represented by the DSR at a different bias irradiance. It has been shown [34] that for modest deviations from linearity the best DSR bias irradiance to reproduce the SR at 1-sun is approximately 0,37 of the 1-sun irradiance. Other authors have confirmed that bias values in the range 30 % to 40 % of the 1-sun value are suitable, including for some PSC devices [35].

For some applications, the SR does not need to be an absolute measurement, but instead may be acquired in a relative sense, i.e. normalized to unity at the highest point on the curve. Determining spectral mismatch as a correction to determine the device I-V parameters is one such application. Importantly, if the device non-linearity is independent of wavelength, then for the mismatch correction the DSR is a suitable substitute for the SR, regardless of the light bias level. A method for determining the wavelength dependence of the device linearity is given in IEC 60904-8 [36].

Issues sometimes affecting SR measurements for emerging PV devices include:

- Transient response; where the device current response to a change in irradiance is time-dependent, hence the chopping frequency shall be reduced to allow the current to stabilise;
- Non-linearity; where the ratio of current to irradiance is not constant. This is important for applications requiring the absolute SR, but less so where only the relative SR is required, e.g. spectral mismatch determination;
- Non-uniformity; where the typically small size of the narrow-bandwidth light spot fails to capture a representative sample of the cell area;
- Stability; where the device may need to be pre-conditioned (Clause 5); and
- Degradation; where the exposure requirements of the SR measurement lead to irreversible damage to the cell – more common for very early-stage cell development.

8.2 Review of currently available standards

8.2.1 IEC 60904-8

IEC 60904-8 (*Photovoltaic devices – Part 8: Measurement of spectral response of a photovoltaic (PV) device*) for SR measurement of single-junction PV devices was updated in 2014. The standard describes two methods, (i) a constant light source with a chopper, and (ii) a pulsed light source, usually with a set of band pass filters. A third method covers PV modules.

It is outside the scope of this report to describe the 60904-8 methods in detail, however the following extracts are reproduced from the document for discussion in relation to OPV/DSC/PSC devices, the majority of which are measured using the first method, based on a grating monochromator, mechanical chopper wheel and a source of broadband bias light.

- Regarding the presence of a transient response

  The chopping frequency should be chosen such that the cycle time is longer than the time constant of the device under test. A method for determining the time constant of the device under test is described in 8.3.1.

- Regarding device non-linearity

  The standard describes a full method for determining the SR under standard test conditions, based on a set of at least five DSR measurements at different bias light irradiances between 5 % and 110 % of the short-circuit current at standard test conditions. In case the full procedure cannot be applied, the standard then permits certain simplifications, firstly to determine a bias light irradiance for which the DSR is a suitable approximation to the SR. If that is also not possible, then a 30 % to 40 % bias light level may be used, and failing that, any bias light level > 10 %, along with a check that the result does not vary if the bias light is increased and decreased by 50 % respectively.

- Regarding device non-uniformity

  In order to determine the output current of the device, the bias light as well as the monochromatic light should irradiate the entire area of the device uniformly. It is important to illuminate effectively the entire area of the device, as light not directly falling onto the active area may also contribute to the measured signal. If the spectral responsivity is used for the calculation of the spectral mismatch correction according to IEC 60904-7 the illuminated area during the measurement of the spectral responsivity should be identical to that during the measurement of the current-voltage characteristics. This is normally the entire device area. If not it should be suitably delimitated by an aperture.

  In case the area of the device is larger than the respective beam sizes, the latter should be scanned appropriately across the entire device area to provide a uniform illumination. If both beams are scanned, the scanning should be synchronous with the bias light always illuminating a spot larger than the monochromatic light.

  These requirements may seem arduous, but for absolute SR they are very important. As for I-V measurement, the use of an aperture mask for small devices is highly recommended. For relative SR, the requirement for uniform illumination over the entire device is less important; however the reference to scanning in the second paragraph is still important for capturing any non-uniformity in the device. A common interpretation of the scanning requirement is that this does not necessarily need to involve complete coverage of the area, but can instead consist of repeat measurements across the device such that any non-uniformity is captured.

- Regarding device stability (reversible)

  Preconditioning – Before beginning the measurements, the device under test shall be stabilized (if necessary) by an appropriate light soaking test procedure, as specified in IEC 61215 series. Different photovoltaic technologies may require different preconditioning procedures.

- Regarding device degradation

  It may not be appropriate/possible to make an accurate measurement of SR for devices subject to irreversible degradation under light.

8.2.2 ASTM E1021

The ASTM standard E1021 (Standard Test Method for Spectral Responsivity Measurements of Photovoltaic Devices) [37] was first published in 1993 and last updated in 2012 and is similar to IEC 60904-8. ASTM E2236 (Standard Test Methods for Measurement of Electrical Performance and Spectral Response of Nonconcentrator Multijunction Photovoltaic Cells and

Modules) [38] was developed for multijunction cells. These standards do not exclude thin-films or metastable devices, but they directly address measurement issues such as slow response time and metastability. The standard does require that you select a chopping frequency that is compatible with the frequency response of the reference photodetector, test device, and modulated current measurement instrumentation. The frequency should not be an integer multiple of the ac line frequency. For slow-responding devices, a shutter is convienent for frequencies below 5 Hz.

8.3 Practices for spectral responsivity on OPV/DSC/PSC devices

8.3.1 Determining the chopping frequency for devices with a transient response

The circumstances of a DSR measurement often require a higher chopping frequency than can be tolerated by the response time of this type of device. In these cases, it is important to know the highest chopping frequency that may be used while still allowing the device time to stabilize at each cycle from dark to light. The following method can be used to select this frequency for a given irradiance and for all irradiances if the device time constant is irradiance independent.

The setup for time response analysis consists of a chopped continuous broadband illumination (typically a Xenon light source) directed through a lens to the measurement plane. Here the device under test and a calibrated reference device with a much faster response (usually a c-Si reference cell) are placed next to each other, illuminated with the same broadband chopped light and measured simultaneously. The alternating signals generated by the two devices are typically acquired as a voltage drop across shunt resistors, or as the output of a transimpedance amplifier, using a storage oscilloscope or a multimeter, i.e. without the use of lock-in amplifiers.

The chopping frequency shall be varied to span the entire frequency range of interest (typically from 0,3 Hz to 80 Hz) and the device signals are acquired for at least three periods at each frequency. The peak-to-peak amplitude variation of each device over the whole measured frequency range shall be analysed. The response from the reference device is typically invariant over this frequency range, while the slower device under test exhibits a peak-to-peak amplitude that begins to decrease above a certain chopping frequency ([16], [39], [40], [41] and [42]). This information can be used to select the highest frequency before the response time of the device leads to errors in the measurement.

To exclude a possible wavelength dependency of the cut-off frequency, a series of DSR measurements can be performed at three chopping frequencies around the selected one, e.g. its half and its double, and the DSR spectra compared.

(■ OPV ■ DSC ■ PSC)

8.4 Summary and suggestions

The methods described in the IEC 60904-8 standard are capable of dealing with most if not all OPV/DSC/PSC devices, provided certain precautions are taken. In particular, device non-linearity and device response time are factors that may require special attention. Device non-uniformity and stability are also important.

9 Sample preparation

9.1 General

For emerging PV devices at the research stage, careful packaging will usually improve the accuracy of an I-V measurement and will almost always improve the agreement between measurements made on different test systems. This is important to ensure only true improvements are recorded as progress. Elements of effective packaging include rear-side support, wiring and the ability to fit an appropriate aperture mask for measurements.

9.2 Elements of effective packaging

9.2.1 Rear-side support

For reproducible measurements, the rear side of the PV device should be flat, parallel to the light-receiving surface of the device and have no protrusions that cause the device to be tilted when being measured. In some cases, the support may also be used to provide strain-relief for any wires that are attached to the device. Provided the device is not intended to be transparent, the rear-side support can be opaque, meaning a wide range of materials can be used.

To allow for good temperature control of the device if necessary, the rear support should be as thermally conductive as possible and should, if practical, allow for the inclusion of a temperature sensor on the assembly. Care should be taken to maintain high thermal conductivity across the interface between the device and the rear support. This can be achieved using a thermally conductive compound or pad to bridge microscopic air gaps, however it shall be remembered that these products have thermal conductivity much lower than metals, hence they should be kept as thin as possible.

A good rear-side support can also be designed to allow for consistent positioning of the device in the light field of a solar simulator.

9.2.2 Wiring

The attachment of wires to a device is usually necessary when a measurement is to be made on more than one test system and may be necessary in any case. For devices with significant current, or where the wires are required to be very thin, a 4-wire method is preferred, since this avoids ohmic losses that may become significant for a 2-wire configuration.

9.2.3 Aperture masking

The smaller the test device, the more critical it is to use an aperture mask when performing an I-V measurement, to avoid stray light entering the active area from outside the area that will be considered when determining the device current density or efficiency. The mask should be completely opaque to all wavelengths within the spectral responsivity range of the device. It should have a low-reflectivity surface, to avoid secondary reflections from the solar simulator lens. It should be as thin as practical, to avoid shading of any non-collimated component of the incident light.

The dimensions of the mask should be as close as practical to the dimensions of the active area of the test device, without exceeding them. The small part of the active test device outside the aperture window will contribute to measurement error, since it will behave like a diode in the dark, opposing the device photocurrent for non-zero voltages, hence reducing V_{oc}.

The mask should be fitted to the device in such a way as to avoid any light exposure other than through the clear aperture, remembering that light is capable of channelling laterally through glass to reach an active device, even when incident far from that device.

9.3 A note on sample size

Groups working in OPV/DSC/PSC have for over a decade made use of very small samples to achieve the best possible cell performance, since this minimises ohmic losses during extraction of the charges. While this approach can be useful in the very early stages of development, small samples are particularly prone to several different sources of measurement error. Some scientific journals will not publish measurement results based on samples below 1 cm^2, hence the sample size 1,1 cm^2 is commonly used.

9.4 Summary and suggestions

When publishing performance parameters for research-scale OPV/DSC/PSC, groups are encouraged to package their devices to allow the results to be confirmed on a different measurement system. Elements of proper packaging include a rear-side support, wires attached and the ability to include aperture masking.

At this stage, the standardisation of device packaging for these small-scale cells is unlikely to be helpful; however, the sharing of best practice guidelines should be of value.

10 Temperature control

10.1 General

Although not as important as irradiance, the temperature of the active components in any PV cell has an influence on both the current and the voltage output, hence appropriate monitoring and control of temperature can improve the accuracy of performance measurements. Temperature coefficients for current, voltage and power in OPV/DSC/PSC are not the same as for silicon devices, but fall within a similar range, i.e. ±1 %/°C.

Since standard test conditions require a device temperature of 25 °C, which is close to room temperature, the use of steady-state solar simulators can lead to device temperatures significantly above the desired value. An over-temperature of 10 °C could result in an error in the measured efficiency of greater than 5 % in relative terms.

The monitoring and control of temperature in OPV/DSC/PSC is more challenging than for silicon wafer devices for several reasons. Firstly, like all thin-film PV devices, these cells require a substrate or superstrate. Typical substrate/superstrate materials are non-absorbing and have poor thermal conductivity. When combined with the typically high absorptivity of the very thin active layers in the device, the result is a large temperature difference between the inside and the outside of the device, with typically only the outside being accessible to a temperature sensor.

Secondly, with many OPV/DSC/PSC devices being very small, the space to attach a temperature sensor is extremely limited. In many cases the sensor position is forced laterally away from the active device area, making the temperature error even greater.

10.2 Review of currently available standards

The IEC 60904-1 standard states:

> "The temperature of the reference device and the specimen shall be measured using instrumentation with an accuracy of ±1 °C with repeatability of ±0,5 °C."

The lack of any further guidance on temperature measurement and control stems from the fact that silicon wafer PV cells absorb light over their entire thickness, and can be directly mounted on a temperature-controlled stage, meaning their temperature is very easy to control.

10.3 Current practices in temperature measurement/control for OPV/DSC/PSC

10.3.1 Keeping the exposure time short using a shutter

A simple way to limit the increase in sample temperature when exposed to a continuous light source is to shutter the light source such that the sample is not exposed to the light prior to commencement of the I-V sweep. This is effective provided (i) the sweep is relatively short, often not the case with emerging PV devices, and (ii) there is only one test cell on the substrate to be measured. In all other cases, measurement and control of the temperature is recommended.

10.3.2 Use of a temperature sensor and a temperature-controlled stage

For most PV devices, when accurate performance measurements are required, a temperature sensor and cooled stage are extremely valuable. The temperature sensor should be placed to avoid interfering with the measurement, but with the minimum practical thermal impedance between the sensor and the active part of the cell. Care should be taken that the thermal impedance between the sensor and the active part of the cell is much lower than the thermal impedance between the sensor and the stage (cooled stage or high thermal mass platform).

Alternatively, if geometry permits, the device temperature can be monitored using a remote infra-red sensor. A drawback of this method is that most affordable infra-red temperature sensors are not sensitive to wavelengths at which glass is transparent, meaning that if a glass substrate/superstrate lies between the active cell and the remote sensor, the sensor will observe only the surface temperature of the glass.

(■ OPV ■ DSC ■ PSC)

10.4 Summary and suggestions

Temperature measurement and control for small-scale OPV/DSC/PSC is much more challenging than it is for silicon devices, and there is no guidance provided in the existing standards. Unfortunately, the wide range of test device configurations and measurement setups at present means that specific guidelines are unlikely to assist. The advice in this clause may be of some value to readers.

11 Non-standard testing light condition

11.1 General

Although the primary purpose of all PV technologies is the collection of solar energy, some of these technologies may also find a market for low-power applications within living spaces. This brings into consideration the harvesting of indoor light sources, which typically differ from sunlight in both their spectral composition and their much lower energy content.

If the indoor application for photovoltaics were to become commonplace, there may be value in standardising the measurement and performance requirements in a different way to the existing IEC 60904 series, or at least extending this series to accommodate the new application. Although the word *solar* is used frequently within that series, in fact only relatively minor changes would be required to extend the application to non-solar light sources.

An extension to the IEC 60904 series for indoor light sources would present an interesting quandary for the developers of that IEC standard. At present, the 60904 series is wholly maintained by IEC Technical Committee 82, the scope of which covers all matters relating to *photovoltaic conversion of solar energy*. It will be at the discretion of the IEC and TC 82 to decide whether any such extension is minor enough to avoid an infringement of the scope. Such an argument may perhaps be made on the basis that a solar cell remains a solar cell, even when used for a non-solar application.

11.2 Review of currently available standards

11.2.1 General

At the heart of the IEC 60904 series of standards is 60904-1, which describes the *measurement of photovoltaic current-voltage characteristics*. The series therefore does not per se exclude PV devices for non-solar applications. The series does however presume throughout that the light source will be solar in nature. The inclusion of non-solar applications would suggest that terms such as "solar simulator" may be changed to "light source simulator", and "simulated sunlight" may become "simulated light source", or something similar.

Beyond the above cosmetic alterations, the following changes to the IEC 60904 series would be required to accommodate non-solar applications:

- IEC 60904-5 [43], 60904-7 [25], 60904-8 [36] and 60904-10 [44]: no further changes
- IEC 60904-2 [27] (reference devices): may need to be modified to include special reference devices for indoor light sources, or special requirements, e.g. angular response, depending on any new light source simulator requirements identified in 60904-9 [45].
- IEC 60904-3 [46] (reference spectrum): one or more additional reference spectra would likely need to be added, presumably via a 60904-3-1 document dedicated to reference spectra for indoor light sources.
- IEC 60904-4 [47] (calibration traceability): two of the four example calibration methods would not be valid for non-solar light sources; the document would need to explain this.
- IEC 60904-9 [45] (solar simulator requirements): may need an extension, presumably 60904-9-2, to set out the requirements for non-solar light sources for testing.

NOTE There is already a draft IEC 60904-9-1 for collimated solar simulators for concentrating PV applications.

11.2.2 JEITA

JEITA (Japan Electronics and Information Technology Industries Association) has published JEITA ET-9101 [48] for indoor measurement of photovoltaics based on fluorescence lamps, white LED lamps, D50 lamps and user defined light sources. The standard is based on the condition that a new reference light source is to be determined in the future. Therefore, as long as IEC 60904-1 is used to measure PV performance, there still remains the issue of light source traceability.

(■ OPV ■ DSC ■ PSC)

11.2.3 SEMI

SEMI (Semiconductor Equipment and Materials International) has been involved in discussions about measurement of emerging PV and indoor lighting since 2012. SEMI published SEMI PV57 [4] for I-V measurement; SEMI PV69 [49] for spectral responsivity measurement under the AM 1.5G reference spectrum for OPV and DSC devices; and SEMI PV80 [50] for classification of indoor lighting simulators for performance rating of emerging PV in indoor applications. The standards use a reference spectrum based on the CIE light source colour standards, see 11.2.4.

(■ OPV ■ DSC ■ PSC)

11.2.4 CIE spectra

The International Commission on Illumination (CIE) is responsible for publishing binding standards for the many different types of light source (illuminants) available. A standard illuminant represents a theoretical reference spectrum of radiant power versus wavelength, in much the same way as the AM1.5G reference spectrum currently serves PV measurements. The CIE reference spectra therefore may provide suitable starting points for nominating reference spectra for indoor PV, noting that the CIE spectra are currently (i) relative spectra only and (ii) only specified up to 830 nm.

An alternative suggestion would be to use black body spectra as the reference, since they are easy for anyone to generate.

11.3 Practical issues when using illumination sources to characterise PV cells

Round-robin studies (e.g. [51]) have identified that determining the absolute irradiance of indoor light sources is challenging. Reference devices for PV measurements were often found to have an inappropriate angular response and by default are calibrated to the wrong reference spectrum.

Some groups have suggested making use of the wide range of instruments available for measuring the photometric (rather than radiometric) output of indoor light sources, e.g. illuminance meters. In this case, a calculation is made to convert the reading to a radiometric one, with reference to the CIE Photopic Luminosity Function.

Some groups have also identified that at typical indoor irradiance levels, problems with *I-V* hysteresis may be exacerbated in DSC and some PSC devices [52]. Where this is the case, the special *I-V* methods described in 6.3.5 may become important.

11.4 Summary and suggestions

With OPV/DSC/PSC technologies potentially having indoor applications, it may be of value to consider the international standardisation of these products. While the IEC 60904 series could be extended to deal with the indoor application, it remains to be seen whether the current technical committee views this extension as within its scope.

While the necessary changes to IEC 60904 would not be extreme, new light source simulators would need to be developed. At this time, there may need to be a stronger industry driver before such developments are undertaken.

12 Tandem solar cells

12.1 General

As an extension of single junction photovoltaic devices, tandem or multi-junction solar cells are currently explored as a route to increase the power conversion efficiency beyond the levels attainable for single junction technologies. Tandem solar cells are not new. Examples include thin-film silicon tandems suitable for converting direct and diffuse sunlight in electrical power and III/V multi-junctions often applied in concentrator solar cells with record efficiencies of 46 %.

Many of the emerging solar cell technologies lend themselves in an excellent way to tandem devices. They have for example a wide and often tuneable range of absorption spectra which is often difficult to achieve with currently applied inorganic semiconductors like c-Si, CdTe and CIGS.

In general, the materials applied in OPV/DSC/PSC can be easily processed on top of each other from solution or vacuum, without requiring epitaxial growth. The ease of processing and the variety of process options allows tandem devices to be fabricated not only using similar deposition processes and similar materials, such as OPV/OPV tandems and perovskite/perovskite tandems, but also opens up the possibility to combine PV technologies which are fabricated using different processes and/or materials, such as perovskite/c-Si or DSC/CIGS. These latter tandems are often referred to as hybrid tandems.

12.2 Review of currently available standards

The method to accurately characterize tandem devices is currently covered by the IEC 60904-1-1 and 60904-8-1 standards. It is beyond the scope of this document to describe these complex procedures, here; however, the following observations can be made:

- The application of those procedures to OPV/DSC/PSC can be challenging, given that some measurement challenges around even single junction versions of these technologies are yet to be resolved, e.g. instability, transients and non-linearity;
- In addition, a few specific aspects of tandems based on these PV technologies should be considered, such as (a) the presence of an optical interference pattern, (b) tandem devices with identical sub-cells, and (c) the definition of the aperture area for the performance evaluation.