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PERSPECTIVE

Standardising current–voltage measurements for metastable solar cells

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Abstract

The present situation with respect to current–voltage measurement standards for metastable photovoltaics, including perovskites, is discussed. New draft updates to the IEC 60904-1 standard do not fully capture the needs of metastable devices. A new document within the 60904 series capturing the academically favoured SPO and MPPT methods would go a long way toward solving the present ambiguity, however the lack of an effective stabilisation procedure remains the greatest hurdle for perovskite PV.

1. Introduction

More than 100 years after their discovery [1, 2] and after decades of stigma about their high cost, photovoltaics (PV) have advanced to become the most cost-effective solar energy devices, and in many cases the lowest cost form of electricity supply [3]. Although many of the value gains have come from economies of scale in manufacturing and improvements in reliability, no single factor has been more important than gains in the power conversion efficiency. This is because improvements in device efficiency boost the economics of every single part of the value chain, from mining the resource materials through to installation of the solar array. For this reason, efficiency has long been regarded as the figure of merit for a solar PV device.

Importantly, the growth in efficiency (over decades) for the many different PV device technologies has tended to be incremental, as can be easily seen in the well-known world-record efficiency chart [4] published by NREL [5] and in more detail in tables published elsewhere [6]. When improvements in any technology are incremental, validation of these improvements is critical to ensure the appropriate recognition of achievement and allocation of resources to further research. Validation does not need to be an obstacle, provided the measurement procedure is simple, the equipment standardised and the sources of error widely understood. Unfortunately, in the case of many photovoltaic devices, none of these are true.

Despite a procedure having been agreed and documented in the IEC 60904 series of standards [7] the measurement of PV device efficiency remains a complex exercise with many sources of uncertainty that require special expertise to quantify. This has led to the establishment worldwide of dedicated PV measurement laboratories, including at NREL, AIST [8], Fraunhofer-ISE [9], JRC-ESTI [10], ISFH CalTeC [11] and CSIRO [12] plus others including laboratories at industrial services companies such as TÜV-Rheinland. Many of these laboratories have asserted their expertise by achieving and maintaining accreditation under the international agreement administered by ILAC [13]. Signatories to the ILAC *Mutual Recognition Arrangement* are generally national bodies that act to accredit testing laboratories for quality and competency according to the standard IEC/ISO 17025 [14].

IEC 17025 accreditation places auditable requirements on the laboratory relating to governance, personnel, resourcing, equipment, procedures, training, supervision, authorisation, impartiality and more, as well as thorough monitoring of technical and administrative competence. Measurement uncertainties must be developed in line with international standard methods. For complex measurements this task is extremely involved—CSIRO's PV Performance Laboratory typically considers 68 different sources of uncertainty when

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reporting a PV efficiency measurement. The understanding of each of these small sources of potential error and how they should be combined has been developed over many years.

Compliance with the requirements of IEC 17025 comes at significant expense in terms of labour, fees and calibration costs. In many cases, laboratories rely on government support to be able to provide the service at prices that research clients can afford.

A key aspect of an accredited measurement service is its *scope*, which describes the range of activities captured under the accreditation. Narrower scopes are easier (less expensive) to achieve and maintain, but limit the range of device types that can be measured. If a particular device measurement falls outside the scope of accreditation for the measurement laboratory, the laboratory might still conduct the measurement, but the report will not include the stamp of the relevant national accreditation agency. Such *non-accredited* measurements by accredited laboratories have become relatively common in the past decade, following the proliferation of research into emerging PV technologies with widely variable form factors and electrical behaviour, e.g. dye-sensitised, organic and perovskite solar cells. These devices all present measurement challenges that exceed the guidance provided in the IEC 60904 PV measurement standard. As a result, permitted variations in procedure regularly lead to different results for the all-important device efficiency [15]. Laboratories performing such measurements face decisions around how to deal with procedural ambiguity, most commonly relating to the *I–V* sweep rate and pre-conditioning requirements, particularly when clients request specific values for these.

For the above reason, many researchers have argued for new standards (or extensions to existing standards) that support performance measurement for emerging PV technologies. Such new guidelines would mean that researchers (and research funding agencies) around the world would have a common reference method for the typically incremental improvements in performance that continue to be made.

In recent years the International Electrotechnical Commission (IEC) has taken steps toward this goal, with the publication of a consensus-based Technical Report, IEC TR 63228 [16]. Like other IEC *Technical Reports*, the document does not seek to provide specific guidance. Rather, it seeks to define the present state of the art, as a platform for discussion about what might be included in a future *Technical Specification*, and then potentially, after further refinement, in an *International Standard*.

2. The problem of stability

The most logical approach to recording consensus on special measurement practices for new PV devices would be to update the existing IEC 60904 series, which was originally developed for PV devices made from silicon wafers. Although an entirely new standard should not be ruled out, the 60904 series has developed over time into a somewhat logical ecosystem, based around IEC 60904-1 'Measurement of photovoltaic current–voltage characteristics' as the core document, referencing ten component standards with a numbering scheme that allows for intuitive expansion.

Fortuitously, the 60904-1 standard is presently undergoing a significant revision by the IEC. The most recently published version, Edition 2, was released back in 2006. That version provides effectively no guidance for dealing with the two biggest issues for emerging PV, which are degradation and metastability. It can be argued that degradation is not a problem per se, because any solar cell that degrades during testing is not really ready for inter-comparative testing anyway. However the situation is complicated by metastability. Metastability, when used to describe solar cells, means the device performance depends on its exposure history (voltage bias, irradiance and temperature), even in the absence of degradation. Metastable devices may or may not stabilise after a period at fixed exposure conditions, however attempts to explore this scientifically are frequently confounded by device degradation. This can make it difficult, if not impossible, to develop measurement procedures that give repeatable results.

At the time of writing this, the new Edition 3 of IEC 60904-1 is a mature draft, and contains two paragraphs designed to accommodate devices with short- and long-term metastability. These terms and the proposed modifications to the 60904-1 standard are described below.

2.1. Short-term metastability

Short-term metastability is the slow response to external stimulus on the time scale of seconds to minutes. The most commonly observed impact of this is that *I–V* curves exhibit hysteresis, i.e. curves measured in the forward and reverse sweep directions do not overlap, even in the absence of capacitance effects. The underlying causes of metastability-induced hysteresis in different device types are discussed extensively elsewhere, e.g. [17, 18]. The impact of hysteresis is that the maximum power point determined from either curve, or even the average of the two curves, is not (necessarily) representative of the maximum power point the device would exhibit in the field, where the irradiance and voltage bias are relatively stable much of the time.

Extensive research, e.g. [19–21] has shown that for sufficiently stable devices, short-term metastability can be dealt with by allowing time at any given voltage bias setpoint, for the current to settle (sometimes referred to as 'stabilize', although that usage clashes with another meaning, see the following section) to a relatively constant value. This principle can be applied to entire *I–V* curves, e.g. the *dynamic I–V* method [19] or equally to specific *I–V* points, e.g. the *stabilised power output* (SPO) measurement [20] or a *maximum-power-point tracking* (MPPT) method [20, 21]. Such measurements have come to be known as *steady-state* measurements, or sometimes *quasi-steady-state*, since the relatively constant output is often affected by additional instabilities with longer time constants.

In its present (still pre-published) form, Edition 3 of IEC 60904-1 deals with *I–V* hysteresis with the following statement: 'The *I–V* characteristic for the device under test shall be measured such that it reflects, as closely as possible, the performance of the device under steady-state conditions, i.e. where there is no influence due to drifts in irradiance or device temperature or due to the voltage sweep rate.' This requirement is a valuable addition to the method, since it removes the ability to produce an artificially inflated efficiency result by using a high *I–V* sweep rate.

2.2. Long-term metastability

If metastability in solar cells was limited to short-term effects, diagnostic *I–V* measurements could easily be made repeatable and representative of performance in the field, by applying the methods referred to above. Long-term metastability however, makes things significantly more complicated. *I–V* measurements either cannot be made slow enough to allow the forward and reverse curves to overlap, or even if they do, a repeat measurement performed the next day on the same device gives a different result, even in the absence of irreversible degradation [22].

The presence of long-term metastability in some solar cells, particularly perovskite-based devices, invokes the concept of *stabilisation*. Stabilisation of the device (with respect to a particular parameter, usually P_{mp}, I_{sc} and/or V_{oc}) refers to any treatment that can be shown to result in repeat measurements thereafter giving the same result. The concept came to prominence in the 1980s in regard to amorphous silicon PV products, which are subject to a light-induced metastability known as the Staebler–Wronski effect [23]. The effect meant that devices in the field experienced a degradation in power by up to 30% over the first ~six months.

Metastability in amorphous silicon devices required measurement laboratories to distinguish between devices that had and had not been 'stabilised' prior to measurement. Recent editions of the NREL world record efficiency chart contain the note '(stabilized)' in the legend describing the amorphous silicon records, indicating that NREL has placed some requirement for pre-stabilisation on these devices prior to measurement. By contrast, the legend for perovskite cells includes the note '(not stabilized)', suggesting that the recorded values are for devices that have not had a stabilisation procedure applied. Similarly, the world record efficiency tables published by *Progress in Photovoltaics* [6] include the note 'Initial performance' against all records for organic, dye-sensitised and perovskite solar cells and modules, along with cited references describing the stability of these devices in general.

The fact that both publications place these caveats on their results is a clear reminder that the research community has not yet identified a reliable stabilisation method for those devices. This is not because a standards framework does not exist. The IEC 61215 series of standards (normally used for device design qualification and type approval) includes technology- dependent stabilisation methods for PV devices made from crystalline silicon, amorphous silicon, cadmium telluride or copper indium diselenide. This would be the logical place in the standards framework to insert stabilisation procedures for organic, dye-sensitised or perovskite PV—as soon as these are developed. For this reason, the present draft Edition 3 of IEC 60904-1 states the following: 'The IEC 61215 series of standards provides guidance on technology-dependent appropriate stabilisation. In the case of a stabilization procedure being applied, the device under test should be measured before and after the procedure… If it is not possible to stabilise the device, or stabilisation was not attempted, this shall be indicated in the measurement report.'

3. To standardise or not to standardise

The above updates to the IEC 60904-1 standard, scheduled for publication in late 2020, represent a significant step forward for emerging PV devices. If approved by the member countries, measurements will need to be performed under steady-state conditions and reports will need to explicitly state whether or not a stabilisation treatment has been applied, and whether it was successful. So the question is, what next?

In the absence of a stabilisation procedure (or devices that can be stabilised) what is important is a way to secure trust in measurements, even if they only capture a snapshot in time. Trust is engendered by openness—when a procedure is widely accessible and clearly described, it enters a cycle of validation and refinement, growing the level of trust over time. This can occur through the scientific publication process, and has to some extent in this case, with the SPO and MPPT methods both now widely used to snapshot the output of metastable devices. So is it time to capture these methods in a published Technical Specification?

IEC standards (including Technical Specifications) are intended to be driven by industry, for industry. The nameplate rating on a commercial PV module carries a high level of economic significance, hence the energy that has been, and continues to be invested in standardising the *I–V* measurement. But can we also consider the development phase, at least in the case of PV, an industry? Worldwide, thousands of researchers and many millions of dollars are committed to bringing emerging PV into the commercial realm. Accredited testing laboratories are trusted by funding agencies and investors to produce reliable measurements. At present these laboratories are independently filling the gaps in the standards using methods based on their own experience. There is no guarantee that each is interpreting the missing steps in the same way.

Notwithstanding the imminent updates to IEC 60904-1, that document is still about measuring full *I–V* curves. Full *I–V* curves are of great importance diagnostically and for generating voltage and current label ratings for system designers, but for metastable devices they are not the best way to isolate the maximum power output, because by design they create a variable voltage history immediately prior to the most important part of the measurement. There is little doubt that SPO and MPPT are superior methods for obtaining a representative value for the device efficiency. However these methods have been developed independently by research groups and published in multiple places with varying levels of detail, under often non-intuitive titles, somewhere within the huge ecosystem of scientific literature.

By contrast, IEC published methods (international standards or technical specifications) are developed (or refined) collaboratively, selected democratically, explained in detail and published alongside related documents in a single, intuitive location. Methods can be discussed and further improved over time, thus stimulating interactivity between laboratories and building trust.

3.1. Is now the right time?

The most common argument against standardisation of measurement protocols for metastable or short-lived PV devices is that they are not ready for commercialisation, and hence not ready for standards. Metastability and degradation are features of most pre-commercial PV technologies, hence developers of such devices should simply wait until the technology improves, then use the existing standards. However the same argument can equally be made for the opposite point: There will always be metastable and short-lived devices, so why not develop a genuine consensus approach to capturing their performance?

Are the new methods perfect? No. SPO is simple, but does not necessarily identify the maximum power point. MPPT is complex to set up, and still produces a result that may depend on the algorithm applied, and even oscillates with time in some devices. But these issues can be solved, either during the process of building consensus, or over time.

3.2. Will standardising SPO/MPPT alone really help?

Without doubt, the greater issue for perovskite PV at present is long-term stability. Until either the devices are improved, or a suitable stabilisation process is identified, even the best measurements will be subject to the vagaries of the exposure history of the device. But in the spirit of one challenge at a time—an agreed method to deal with short-term metastability would ensure accurate snapshots of performance that are representative of the device at the time of the measurement.

But then, is the device at the time of measurement representative of the device as it would perform (even if briefly) in the field? To be so, it does not need to be stable in the long term. However it would not seem fair if a pre-treatment were applied so as to invoke a temporary elevation in performance, especially if this pre-treatment were to shorten the life of the device in some way. So a discussion on allowed pre-conditioning may become a valuable part of the standardisation process.

3.3. Is there an alternative approach?

Some argue that a single measurement at the Standard Test Conditions [24] is not the best way to represent the performance of a solar PV product anyway. Alternative technologies to crystalline silicon often produce higher specific yields (energy produced over time per unit nameplate rating) due to their different responsivities to irradiance, spectrum and/or temperature. Perovskites may have an additional energy yield advantage, if the observed diurnal metastability [25] works in their favour.

Many have argued for a PV rating scheme based on energy. Significant effort has been invested over many years and a scheme is now codified in the IEC 61853 series of standards. These allow calculation of a *climate-specific energy rating* (CSER), based on four device properties (presently not including a diurnal metastability) and six representative climate data sets.

To date, the CSER scheme has been almost completely ignored by the PV industry, although this may be simply because most of the industry is crystalline silicon, where there is little difference between products in terms of energy yield. The presence of a CdTe PV product on the market has not proven enough incentive

yet—it will be interesting to see what happens if and when perovskite technology begins to compete for market share. There is no reason the IEC 61853 series could not be expanded to incorporate the effect of a diurnal metastability, and new PV devices hence be marketed against silicon PV on the basis of a CSER value.

4. Conclusions

The core measurement standard for photovoltaics, IEC 60904-1, is being updated for the first time in 13 years. The present draft of the update includes requirements relating to short-term metastability—devices will need to be measured under 'steady-state' conditions—and long-term metastability—reports will need to explicitly state whether or not a stabilisation procedure has been applied, and whether or not it was successful. If approved (voted), these additions would go some way to improving the consistency of reported efficiency measurements for metastable PV devices, including perovskites.

Regardless, the 60904-1 standard relates to full *I–V* curves, which although important, are not the best way to obtain a representative value for the device efficiency. The SPO and MPPT methods have achieved acceptance in academic literature and the time is now right for these to be captured in the industry standards framework. This will ensure fair and accurate tracking of advancements in perovskites and all other metastable PV technologies.

The lack of a stabilisation procedure (or devices that can be stabilised) remains the biggest hurdle to be overcome before perovskite PV can genuinely challenge silicon PV in the market.

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