Interlaboratory Comparison of Short-Circuit Current versus Irradiance Linearity Measurements of Photovoltaic Devices

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Abstract

This work presents the results of the first interlaboratory comparison of linearity measurements of short-circuit current versus irradiance that includes a wide variety of photovoltaic (PV) device types, from reference cells to full-size modules. The aim of this inter-comparison was to compare the methods employed and to collect new inputs useful for the revision of the standard IEC 60904-10, which deals with linearity measurements for PV devices. The procedures and facilities employed by the partners include the differential spectral responsivity, the white light response, the solar simulator method and the two-lamp method. The facilities are generically described and compared and their main sources of uncertainty are discussed. Comparison results show good agreement within declared uncertainties between all partners. A few minor exceptions under low-light conditions raise questions of possible uncertainty underestimation for these specific conditions. The overall outcome of the comparison also highlights the importance of considering correlations in the uncertainty budget, which can potentially improve the overall stated uncertainty. A critical review is made of the data analysis adopted in the standard IEC 60904-10 to calculate the linearity degree of the short-circuit current towards irradiance. The analysis review suggests a way to make results based on different methods more comparable and less prone to erroneous linearity assessment.

Keywords: Photovoltaics Characterization, Linearity measurement, Interlaboratory comparison, Uncertainty

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1 Introduction

The measurement of linearity of the photocurrent output with the irradiance incident on a photovoltaic (PV) solar cell is an important aspect, especially for reference devices (IEC 60904-2, 2015). Indeed, for the proportionality principle at the basis of the common use of a reference PV device to measure the irradiance, a non-linear reference would cause undesirable errors of irradiance reading when used at other conditions than those at which it was calibrated and if proper correction for the deviations from the linear function were not made. Therefore, the international standard IEC 60904-2 (IEC 60904-2, 2015) requires a reference device to have a linear response of the short-circuit current I_{SC} versus the incident irradiance G. The I_{SC} response is deemed linear if it shows a deviation from perfect linearity below 2% (ASTM-E1143-05, 2005; IEC 60904-10, 2009).

Linear dependence of the short-circuit current of a reference cell (RC) versus irradiance (hereafter called simply linearity) is also important in power matrix measurements (i.e. performance measurements at different temperatures and irradiances (IEC 61853-1, 2011)) for energy rating purpose or when using a reference module for field performance measurements (IEC 61829, 2015). Furthermore, if a device under test (DUT) is proved to be linear towards irradiance and temperature variations, both performance matrix measurements under varying irradiance and temperature and spectral responsivity (SR) measurements to be used for the energy-rating procedure can be significantly simplified (IEC 61853-1, 2011; IEC 61853-2, 2016), with substantial reduction of measurement time and cost.

To properly assess a DUT as linear, the expanded uncertainty (k=2) of the measurements propagated to the linearity calculation should be considered as well. Whether this uncertainty (UC) has to be included or not within the 2% threshold for linearity is still under discussion in the PV community. Certainly, low measurement UC is desirable for determining linearity of reference devices with the highest level of confidence possible. Indeed, this may lead to reduced energy-rating testing costs and eventually to the possibility to correct for non-linearity of PV devices.

In order to assess the measurement UCs stated by the participant laboratories, this work evaluates the results of an interlaboratory comparison on $I_{SC}(G)$ linearity measurements of samples of different size and technology, from WPVS-type reference cells to full-size modules. To the authors' knowledge, this is the first interlaboratory comparison of this kind. The facilities employed by the partners cover the majority of procedures detailed in the standard IEC 60904-10 (IEC 60904-10, 2009). One of the purposes of this work is to evaluate the different methods and facilities that are employed by the laboratories, with a critical view on comparability and measurement uncertainties that is beneficial for improving them. Additional purpose of the work presented here is the evaluation of possible lacks in the current edition of the IEC 60904-10. The experience gained as part of this inter-comparison will therefore serve directly as input to the on-going revision of the IEC 60904-10 and indirectly for refinement of the standards series IEC 61853 for PV module energy rating with regards to I_{SC}(G) linearity testing.

In the following, the procedures and data analysis from the linearity standard IEC 60904-10 are critically described and areas of improvement in results, comparability and accuracy are highlighted. Thereafter, the measurement methods and facilities employed by the participants are generically outlined with their main UC contributions. Finally, the measurement results are compared and discussed.

The laboratories that took part in the measurement intercomparison were the German Physikalisch-Technische Bundesanstalt (PTB), which acted also as round-robin coordinator, the European Solar Test Installation (ESTI) of the European Commission's Joint Research Centre, the Centre for Renewable Energy Systems Technology (CREST), the Fraunhofer Institute for Solar Energy Systems (FhG-ISE), the Institute for Solar Energy Research Hamelin (ISFH).

2 Calculating linearity

According to the standard IEC 60904-10 (IEC 60904-10, 2009), with the exception of the two-lamp method, the linearity of a PV parameter with respect to a test parameter is in general determined by calculating a least-square linear fit as regression line on all measured points taken over the region of interest. In the case of this paper, the PV parameter is I_{SC} and the test parameter is the irradiance. A percentage deviation of each measured point from the regression line is then calculated. While this approach is adequate to evaluate for example linear dependence of open-circuit voltage on temperature, calculating the linearity of $I_{SC}(G)$ by allowing a Y-axis intercept other than zero can result in erroneous evaluation of the real linearity degree of a PV device, whose short-circuit current is usually better described by a direct proportionality to irradiance than by a generic straight-line fit. This indeed is also what the standard IEC 60904-4 on traceability of PV devices explicitly states (IEC 60904-4, 2009) and it implies the physical fact that $I_{SC}(0\ \mathrm{W/m^2}) = 0$ A. As previously mentioned, the irradiance measured by a RC is usually calculated by the following equation (1). Essentially this is proportionality (i.e. half the signal corresponds to half the irradiance), whereas a general linear fit including a non-zero intercept would need to provide both the slope and the intercept to determine the irradiance from the measured signal. The latter is never considered, and in fact all standards which require linearity of RC output with irradiance mean implicitly proportionality. Hence, generic linear regression leads to a different quantification, which is inappropriate for describing the dependence of $I_{SC}(G)$.

Figure 1 illustrates this problem. A non-linear device (left side of Figure 1, black dashed line with squares) would be considered linear over the range of (700 ; 1100) W/m^2 using linear regression according to the IEC 60904-10 (Figure 1, blue line with dots), while in reality at 700 W/m^2 the error introduced by the linear but non-proportional dependence of I_{SC} to G would be about 15% if this device were used as a RC calibrated at Standard Test Conditions (STC). By using the proportional dependence defined by:

$$G_{meas} = \frac{I_{meas}}{I_{STC}} \cdot 1000\,\frac{W}{m^2} \tag{1}$$

to determine the linearity degree of I_{SC}, this large deviation would be spotted and no error in the assessment of the linearity degree of the device would occur (beyond the measurement uncertainty). Within the proportionality approach, it is useful also to define an additional quantity, which is the normalized responsivity given by:

$$s_{norm}(G) = \frac{s(G)}{s_{STC}} = \frac{I_{sc}(G)}{G} \cdot \frac{G_{ref}}{I_{STC}}\,, \tag{2}$$

where I_{SC} and G are the measured short-circuit current and irradiance, respectively, and G_{ref} is the reference irradiance 1000 W/m^2.

Based on this approach the correct deviation from linearity (ΔL) for the short-circuit current would be given by:

$$\Delta L(G) = 100 \cdot (s_{norm}(G) - 1)\ . \tag{3}$$

As shown in Figure 1, the proportionality approach (see red dashed line with triangles) represents the actual non-linearity of a reference cell calibrated at STC. The curve $\Delta L(G)$ calculated via the proportionality approach (red dashed curve of the right side of Figure 1) gives inverse values to those obtainable by the IEC standard's definition of deviation from linearity (blue and green lines with dots and diamonds respectively), because here a positive ΔL reflects the physical fact that such a DUT has higher I_{SC} compared to a perfectly linear device for the G at which it is calculated.

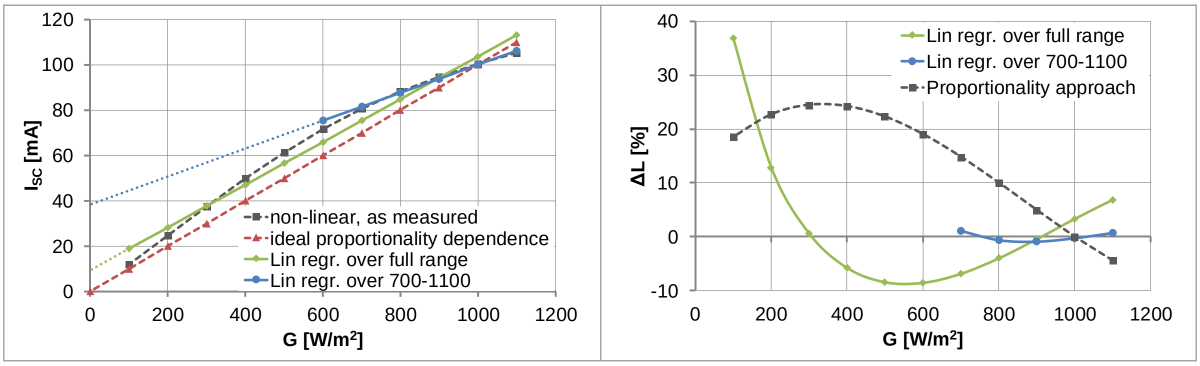

Figure 1: (left) non-linear DUT (black dashed line) compared to ideal proportionality dependence (red dashed line) and the calculated linear fit by the standard IEC 60904-10 definition (blue and green lines for entire or limited range, respectively), the non-zero intercept is highlighted with an extended dotted line; (right) deviation from linearity using general linear regression defined in the standard compared to the one obtained by using a proportionality approach.

Another lack of the IEC standard lies in the linearity calculation specific for the two-lamp measurement approach. According to this, the linearity degree of a DUT is measured between the irradiance level achieved when the two lamps (labelled A and B) are individually illuminating the DUT (A or B) and the level reached when both lamps illuminate it simultaneously (A + B). As detailed in the IEC 60904-10, the percentage deviation from linearity is calculated according to equation (4), where I_A, I_B, I_{AB} and I_{room} are, respectively, the measured short-circuit currents of the DUT generated by the individual lamps, by both lamps together and with none of them illuminating it (background light).

$$D_{lin} = \left[\frac{I_{AB} - I_{room}}{I_A + I_B - 2 \cdot I_{room}} - 1\right] \cdot 100 \tag{4}$$

Even if the 50/50 balance recommended by the standard for I_A and I_B is applied, the deviations from perfect linearity do not represent in their raw form the actual $I_{SC}(G)$ linearity function over the entire irradiance range, but rather the (average) linearity degree just between two measured points that are separated in irradiance by a factor of 2. Currently, there is no indication in the standard on how to combine these separate measurements in order to calculate the deviation from linearity over a larger (i.e. > 2) irradiance range, let alone the entire irradiance range of interest, which should cover at least one order of magnitude (i.e. typically from 100 W/m^2 to 1000 W/m^2).

As discussed in (Emery et al., 2006; Müllejans and Salis, 2018), two-lamp data in their raw form cannot be compared to other methods of the IEC 60904-10. Although some methods from the photometry sector could be applied (Coslovi and Righini, 1980; Hamadani et al., 2016), they may be too complex for reasonable full inclusion in the IEC standard. Therefore, a simpler approach has been proposed in (Müllejans and Salis, 2018), building a connection between the individual irradiance subranges. According to the new approach, essentially the deviation from linearity for each single measurement is then calculated using:

$$D_{lin} = \left[\frac{I_A + I_B - 2 \cdot I_{room}}{I_{AB} - I_{room}} - 1\right] \cdot 100 \quad (5)$$

as this represents a change in the photocurrents generated by the individual lamps as compared to the condition in which both lamps illuminate the DUT, which is the typical case in PV (from the reference irradiance 1000 W/m^2 down to low irradiance levels).

Between the data points measured with the 2-factor method, information is necessarily missing and can be estimated at first by simple linear interpolation, which, however, only approximates the actual full curve. The approximation, though, can be refined by additional intermediate measurements, as already foreseen in the standard. The same normalisation applied to the other methods (see equation (2)) can be adapted to this new approach as well while merging the separate irradiance ranges (see (Müllejans and Salis, 2018)). The final deviation from linearity that is calculated through this new procedure for the two-lamp method can then be written in the same form as given by (3). In this way the results of the two-lamp method can be made comparable to the results obtained by the other measurement methods included in the IEC 60904-10. This new approach was used to analyse the data included here from the two-lamp method (see section 3.4).

The linearity results reported in this paper were calculated and are compared according to the proportionality approach as given in (1) to (3), with specific steps for the data analysis of the two-lamp method data. The I_{STC} value necessary in (2) was determined by each participant and is not explicitly compared in this work.

3 Measurement facilities and uncertainty components

All main procedures described in the standard IEC 60904-10, with the exception of measurements under natural sunlight, are represented by one or more participating partners. The following sections report in a generic way the methods and facilities utilised by the participating partners; more details can be found in the references given, where available. This section also highlights the key UC components of the different measurement methods keeping in mind that the proportionality approach will be used for comparison of results. The reported uncertainty $U_{LIN}(G)$ of each facility depends strongly on the individual measurement setup and procedure, including UC correlation estimates.

3.1 Differential Spectral Responsivity (DSR)

DSR measurements were introduced by J. Metzdorf (Metzdorf, 1987). The procedure determines the DUT's I_{STC} indirectly from the AM1.5G reference spectrum (IEC 60904-3, 2016) together with the absolute spectral responsivity (SR), which is calculated from measurements of differential spectral responsivity as a function of bias light intensity. Thus, the non-linearity measurement of a PV solar cell is an integral part of the DSR measurement. Detailed descriptions of the general procedure are given in (Metzdorf, 1987; Winter et al., 2014).

DSR measurements use a dual beam configuration with a monochromatic beam and a constant white bias-light source (as included in the IEC 60904-8 (IEC 60904-8, 2014)). The bias light is used to set the overall light intensity on the DUT and consists commonly of dichroic halogen light sources (Ebner et al., 2000; Winter et al., 2014, 2000) or LEDs (Hamadani et al., 2013). The monochromatic light beam is used to probe the DUT SR. In order to separate the photocurrent generated by the monochromatic light from the photocurrent generated by the bias light, the lock-in technique is applied by modulating the monochromatic light with a chopper. The monochromatic beam can be generated essentially in two ways. The first is to narrow a broad light distribution of xenon or other broadband sources by using monochromators (Hamadani et al., 2013; Winter et al., 2000) or bandpass filters (Ebner et al., 2000). The second is to use already narrow-band light sources like LEDs (Young et al., 2008; Zaid et al., 2010) or lasers (Schuster et al., 2012). There are also cases in which tuneable lasers are used in combination with a monochromator (Winter et al., 2014). A calibrated reference is used for determining the absolute spectral irradiance. A monitor detector is used to correct for intensity variation of the monochromatic beam.

From a linearity measurement perspective, the advantage of the complete DSR method (i.e. with measurement of SR at all bias-light levels and use of AM1.5G) is that it does not have any significant UC related to spectral mismatch because $I_{SC}(G_{bias})$ is obtained mathematically using the reference spectrum AM1.5G (Winter et al., 2014). Furthermore, the measurement UC in $I_{SC}(G_{bias})$ caused by the calibrated SR of the reference detector and by imperfect positioning of the reference/target plane are in general the same for all $I_{SC}(G_{bias})$ measurements. Thus, those correlated uncertainties are greatly reduced in the $U_{LIN}(G)$ budget. The remaining UC contributions are comparatively small and include the non-linearity of the reference detector and of the amplifiers, imperfect monitoring of the monochromatic light beam, temperature variations of the reference and DUT and their deviation from the reference temperature 25 °C as well as the impact of a changing bias light spectrum at different bias light intensities. Spatial uniformity stability and wavelength repeatability of the monochromatic beam also need to be considered.

The facilities included in this inter-comparison use halogen bias light and generate the monochromatic beam either by filtering a xenon and halogen light sources with a monochromator or by a combination of a tuneable laser system with a monochromator. Both setups over-illuminate the DUT (i.e. the illuminated area is larger than the DUT active surface), which simplify the absolute calibration of the differential spectral responsivity. Due to the complexity of the systems, both setups can measure samples only up to wafer size, i.e. about 15.6 cm by 15.6 cm.

3.2 White Light Response (WLR)

The WLR method is not explicitly mentioned in the linearity standard, even though it is included in the IEC 60904-8. It was developed by J. Hohl-Ebinger (Hohl-Ebinger et al., 2007) and inspired by (Dalal and Moore, 1977). It resembles the DSR method as for linearity measurement, with the exception that it measures differential white-light responsivity with a white light source rather than the spectral responsivity with monochromatic light. Hence, $I_{SC}(G_{bias})$ is directly measured instead of calculated using the AM1.5G spectrum. This significantly reduces linearity measurements time but requires correction of the spectral mismatch present between the white light and the reference spectrum as well as between the SR of RC and DUT. The differential white-light responsivity $I_{sc}^{WLR}(\,G_{bias})$ is integrated to acquire the absolute $I_{SC}(G)$ curve to determine the linearity of the DUT.

Using a white light instead of a monochromatic beam means that a UC contribution due to the spectral mismatch factor (MMF) (IEC 60904-7, 2008) is likely introduced. The systematic error introduced by the presence of a MMF does not per se significantly affect $U_{LIN}(G)$ if the MMF is the same for all $I_{SC}(G)$ measurements in $I_{norm}(G)$, because it will be cancelled in the mathematical ratio. However, as shown in (Hohl-Ebinger et al., 2007), the MMF can also change significantly with bias-light irradiance on nonlinear devices if they exhibit a strong bias-light dependence of the relative spectral responsivity. Such a relative change in MMF will, instead, affect the final $U_{LIN}(G)$ budget. Other main UC contributions are similar to the DSR measurements.

The partner facility participating in the inter-comparison uses an unfiltered xenon lamp as white light source. However, the source can in general be improved upon by applying suitable AM1.5G filters to the xenon lamp, by adding/using LEDs or by using a shaped supercontinuum laser source (Mundus et al., 2015). The facility employed here measured devices up to wafer size.

3.3 Solar simulator

The solar simulator method measures directly $I_{SC}(G)$. The irradiance on the test plane of the solar simulator can be adjusted by interposing attenuation masks, filters or meshes in front of the lamp(s) (Kenny et al., 2013), by changing the solar simulator's lamp power or by excluding some light sources in a multi-source setup with fully independent light sources (Salis et al., 2017). The irradiance has to be measured by a reference cell of known linearity. Because the change in spatial and spectral irradiance on the test plane can be significant depending on the specific procedure chosen to vary the total irradiance, one should apply a MMF correction (IEC 60904-7, 2008) and, if possible, a correction for spatial uniformity (Bliss et al., 2017) in order to reduce the overall measurement UC. The main advantage of using a large-area solar simulator for linearity measurements is that it can be used for measuring PV devices up to full-size modules.

Because the solar simulator method relies on the irradiance measurement by a RC, the accuracy of $I_{norm}(G)$, and so of ΔL, depends also on the linearity of the RC short-circuit current over the entire irradiance range. Therefore, the reference cell linearity is an uncertainty component. Significant UC can also be introduced by the procedures employed to vary the irradiance on the test plane. Changes in the spectral irradiance can directly affect the spectral MMF and variations in the spatial uniformity on test plane can affect the $I_{SC}(G)$ due to possible different irradiance received by the RC and the DUT. However, usually only the relative change in spectral irradiance and spatial uniformity between I_{SC}(G) measurements has significant impact on $U_{LIN}(G)$, because any systematic error is generally introduced for all $I_{SC}(G)$ in (2) and has thus little to no impact on $U_{LIN}(G)$. The UC due to the data acquisition systems as well as that due to temperature difference between RC and DUT and variations from the reference 25 °C can also be major contributing factors.

The participants to this measurement inter-comparison used either pulsed or steady-state xenon solar simulators. Attenuation masks, lamp intensity adjustments or lamps shuttering were used to change the irradiance on the test plane. MMF correction was applied by all partners on all measurements. Correction for irradiance spatial non-uniformity was included by one participant and for RCs only.

3.4 Two-lamp method (TLM)

The TLM was introduced in PV by K. Emery (Emery et al., 2006) as pass/fail test only. It is based on the superposition principle well known in photometry and its principle has already been roughly described in section 2. The basic set-up consists essentially of two light sources A and B, which can be intended in a wide sense from a single lamp with two main intensity levels (e.g. by applying a filter to it, so to halve the total irradiance) up to two separate groups of lamps (as in (Müllejans and Salis, 2018; Salis et al., 2017)). The necessary irradiance levels can be achieved by interposing filters, mask attenuators or meshes between the light sources and the test plane, by changing the power to the light source(s), by varying the distance between light source and device under test or by excluding some of the lamps in a multi-source solar simulator with individually-controllable lamps. A combination of these procedures can be used too, and this can be applied to various steps in the irradiance change as well. However, this should be done always with the forethought that the same principle must be used for a complete data set {I_A; I_B; I_{AB}; I_{room}}. For example, if a mesh is used with distinct lamps A and B to decrease the total irradiance (A + B) to a certain level, it has to be used for all three levels I_A, I_B and I_{AB} but also for their I_{room}, as in principle it could change also the background light detected by the DUT.

The advantage of this method is that it does not require a RC, but only one calibrated point of the function $I_{SC}(G)$ (which is usually I_{STC}) according to the approach presented in (Müllejans and Salis, 2018). In case of single PV cells (as applied to this work) it is also independent on spectral and spatial variations of the irradiance, although it still requires class A temporal stability of the light source according to the IEC 60904-9 classification (IEC 60904-9, 2007) during the acquisition of one data set (I_A, I_B and I_{AB}).

Variations in DUT temperature and in irradiance temporal stability are the main UC contributions to $U_{LIN}(G)$ because the three to four measurements of the short-circuit currents are taken sequentially in time. Monitor devices integrated into each light source could be used to correct for temporal instability of the irradiance, even though averaging the DUT's reading over a long-time acquisition (typically 60 s) may be enough to significantly decrease this UC component. The use of a temperature-controlled system to keep the DUT stable in temperature can decrease the other UC component. The process of converting the raw data to the correct $I_{norm}(G)$ could be the most significant source of uncertainty, depending on the method employed (Müllejans and Salis, 2018).

The partner facility in this inter-comparison used a multi-source Xe-lamp steady-state large-area solar simulator with independent lamps to illuminate the DUT with suitable subsets of the total of 11 lamps, when necessary in combination with a mesh to reach the lowest irradiance levels (about 25 W/m^2 for sources A or B, meaning 50 W/m^2 for their combination A+B).

4 Inter-comparison results

The inter-comparison included 25 PV devices of different size from WPVS-type reference cells to full-size modules. A description of the devices measured in this intercomparison can be found in Table 1 of (Salis et al., 2019). Furthermore, the spectral responsivity of the DUTs detailed here are available as supplementary data. The results of the different partners are anonymised with identifiers including the name of the method used to maintain some link between results and methods employed.

4.1 Reference cells

The active area of the tested RCs has dimension of 2 cm x 2 cm. A selection of the ***worst comparing*** ΔL results for RCs is shown in Figure 2. They are four devices: S03- c-Si with KG5 filter cover, S04- non-linear c-Si with clear cover glass, S06- c-Si with 590 nm long pass filter cover glass and S01- c-Si without cover glass (see supplementary materials for SR data). All measurements show that there is an overall good agreement within stated UCs between all the laboratories, with only few exceptions. At 100 W/m^2, the spread in ΔL between partners is within ±0.2% at best and ±0.5% at worst.

As evident from Table 1 and in Figure 2, the stated UCs of DSR 1 and TLM are significantly lower than for the other partners. These results, considered together with their UC, overlap in all cases. Even though, this overlap is very small at low irradiance in measurements of S01 and S04. In those cases, the small overlap between DSR 1 and TLM UC bands might indicate that the uncertainty may be too stringent for one or both facilities at those conditions. However, it is noted that the results from the TLM for S01 and S04 are overall statistically closer to the reported non-linearity of the other two partners.

The results reported by SolSim for S03 and S06 generally deviate the most from other partners. Even though these deviations are within the stated expanded UCs, one could attribute them to a possible error in the MMF correction due to some causes not fully considered in the calculation.

The device S04 shows the strongest deviation from linearity for all laboratories and it was previously investigated in (Winter et al., 2008), where it shows a wavelength-independent nonlinear effect caused by the surrounding area of the active cell part. Since all participating facilities are over-illuminating the DUT area, all laboratories can spot the effect in a similar way. If an under-illuminating system had been used with the measurement spot in the centre of the sample, the device would have been measured as linear (Winter et al., 2008).

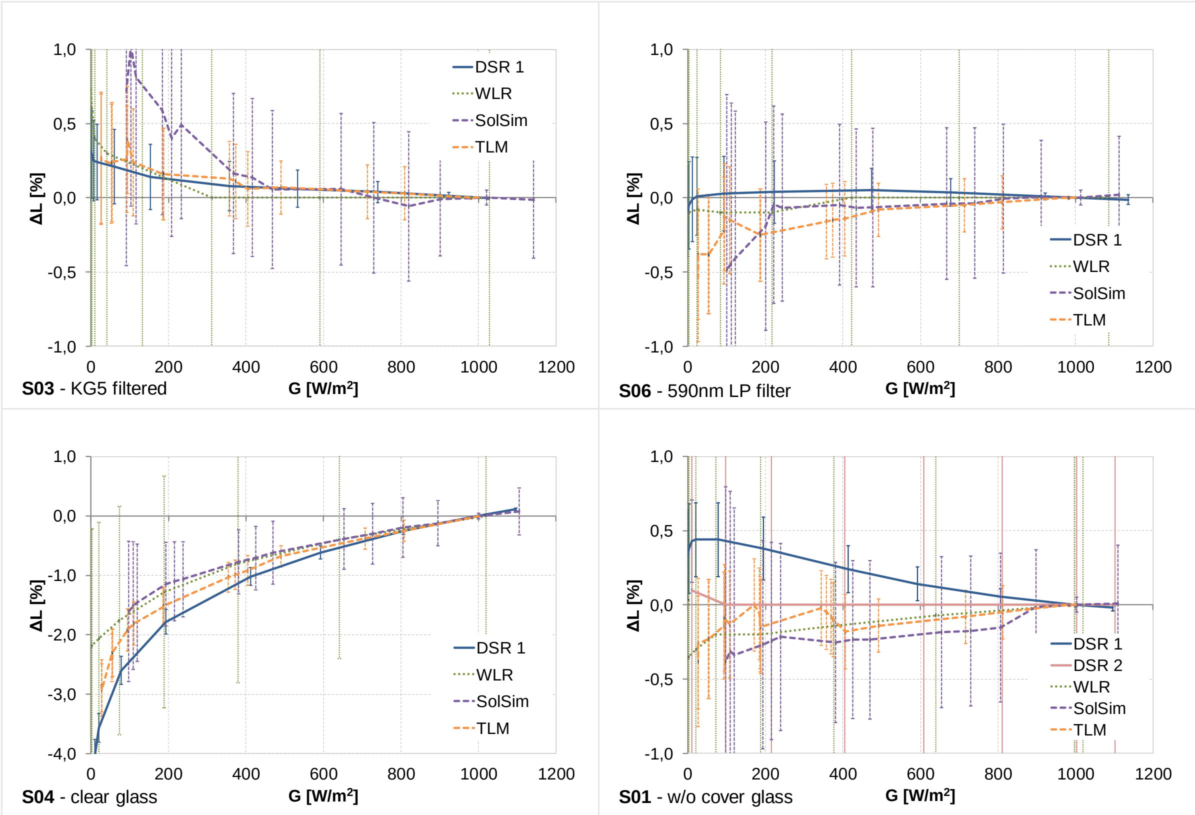

Figure 2: A selection of ***worst comparing*** ΔL results for WPVS-type RCs; error bars indicate the stated UC. A few results do not overlap even within UC (see text), but overall there is a good agreement between partners. Note the different vertical scale for S04.

Table 1: Example of UC in ΔL as stated by the partners at various irradiances for device S01; the UC of the nearest datapoint to the irradiance was used.

Nominal Irradiance [W/m²]	Device S01 - Combined Uncertainty k=2 [%]				
	DSR 1	DSR 2	WLR	SolSim	TLM
200	0.21	2.38	2.00	0.70	0.31
400	0.16	2.42	1.93	0.54	0.25
600	0.11	2.36	1.96	0.51	0.18
800	0.05	2.36	2.05	0.50	0.18
1000	0.00	2.38	2.01	0.05	0.00

4.2 Bare wafer cells

Three different types of mono c-Si and one of poly c-Si large-area bare cells have been tested, which are identified in this paper as Type I, Type II, Type III and Poly c-Si. Spectral responsivity methods and solar simulator method were used to measure these devices.

Figure 3 shows a selection of the bare cells' results. As evident from the plots, all of them agree with each other within their stated uncertainty (worst-case ±0.75% overall). However, large scattering in the results of SolSim 2 is clearly evident for all devices. This might be related to a possible change in irradiance spatial non-uniformity, which was not corrected for but instead included in the measurement UC and which allows agreement with the other results. Improvements of the measurement procedure and of its UC calculation have already been initiated on the basis of this round-robin inter-comparison. Note that the WLR system reported results only up to about 300 W/m^2 or 500 W/m^2, depending on the case. This was due to limitations in current measurements.

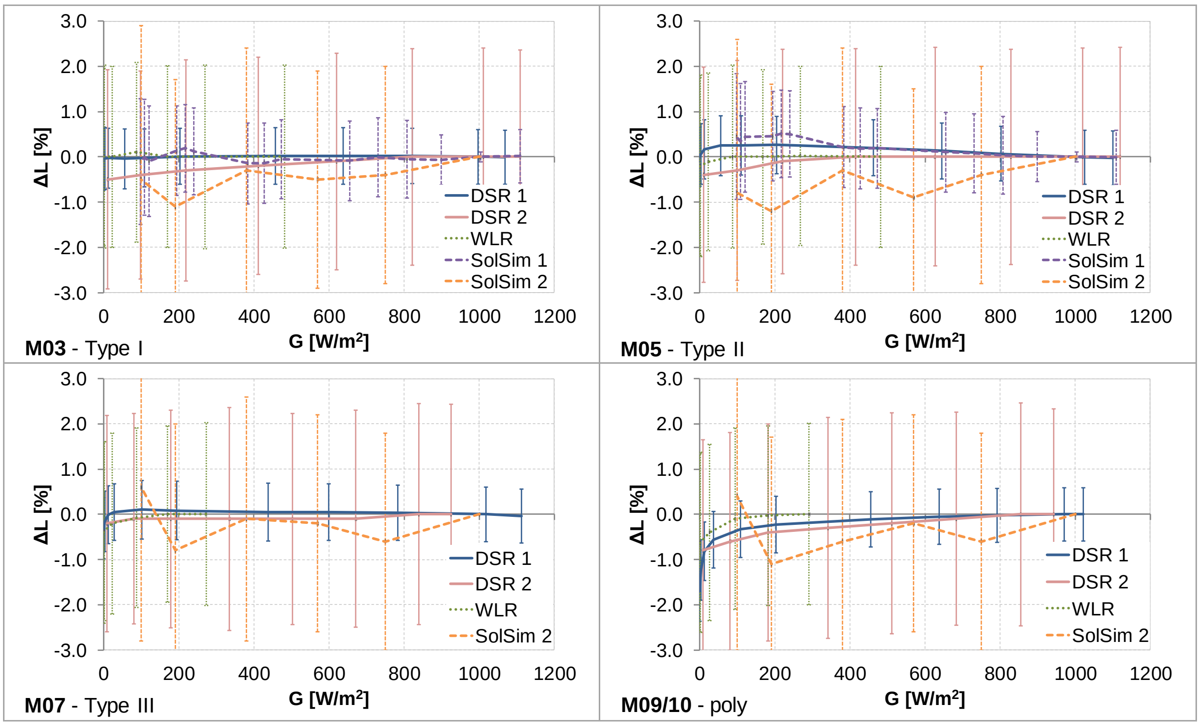

Figure 3: Selection of Δ*L* results of c-Si bare wafer cells; all shown measurements agree with each other within stated expanded uncertainties (k=2).

4.3 Encapsulated wafer cells

The same type of cells used for the previous group was encapsulated in mini-modules, where only individual cells were contacted and measured. Figure 4 shows a selection of the submitted results. Only three partners were able to measure these devices due to their increased size. Similar to the case of bare cells, all shown measurements agree with each other within their stated uncertainties (±0.75% overall). The DSR 1 facility reported an I_{SC} dependence on irradiance closer to perfect linearity than the other two partners. Even though within uncertainty, SolSim 1 reported systematically higher values than DSR 1, while SolSim 2 seem to show more random behaviour.

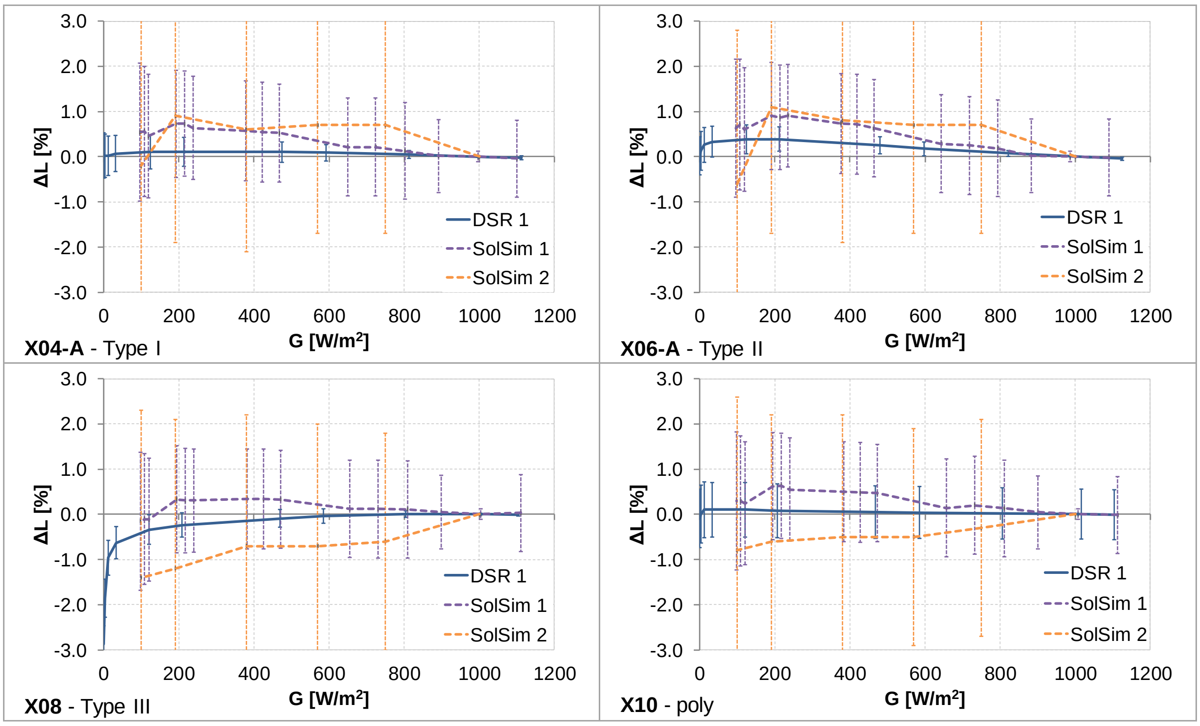

Figure 4: Selection of ΔL results of encapsulated wafer cells; all shown measurements agree with each other within stated expanded uncertainties (k=2).

4.4 Mini modules

The mini modules tested are CIGS devices with 17 and 67 cells in series and an active area of about 10 x 10 cm^2 and about 30 x 30 cm^2, respectively. The largest device was measured using the solar simulator method only. As shown in Figure 5, a general good agreement is found with typical deviation between the results within ±0.5%, which is well within the stated uncertainties. The SolSim 1 solar simulator reported consistently larger deviations from linearity.

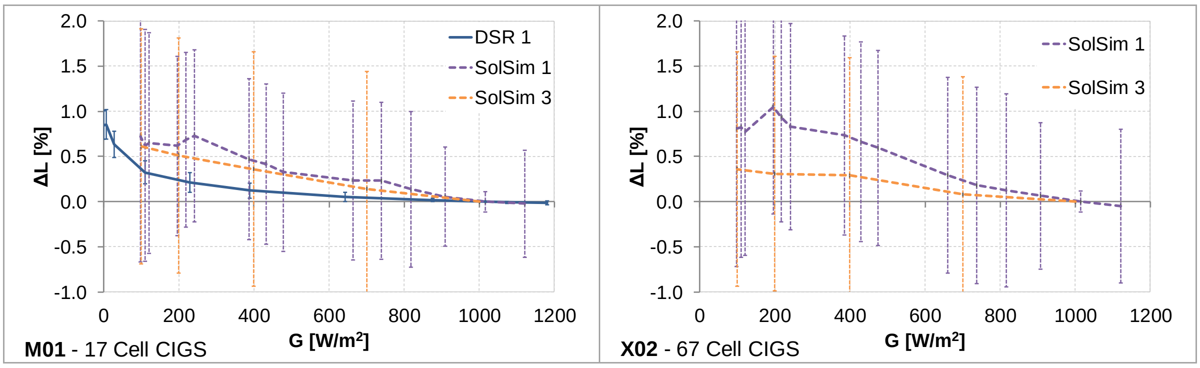

Figure 5: ΔL results of the two CIGS mini modules.

4.5 Modules

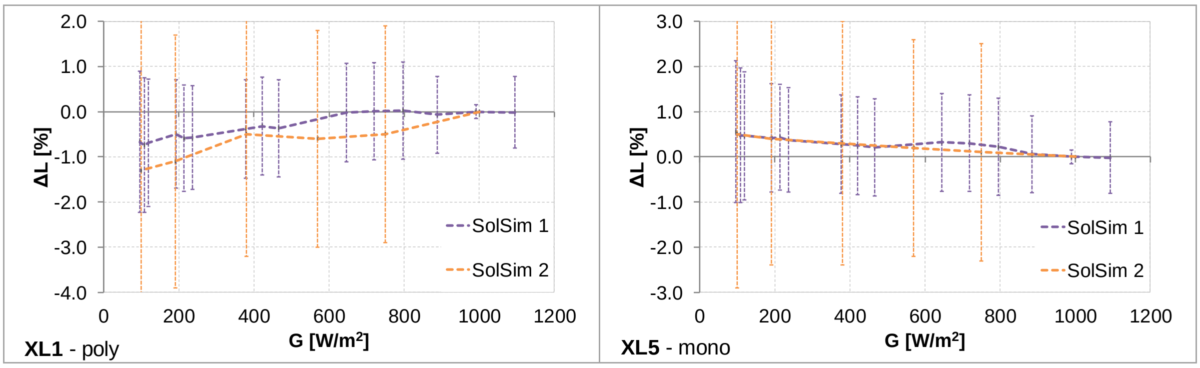

Figure 6: ΔL results of full-size PV modules; only the best- and worst-case comparisons are shown.

Full-size PV modules were only measured using the solar simulator method. The five commercially available modules cover the same four c-Si wafer types tested as bare and encapsulated cells and incorporate either 60 or 96 cells within an area of about 1.6 x 1.0 m^2. The ΔL results shown in Figure 6 represent the worst- and best-case comparison of the five modules tested. Observed deviations between the two reported sets of results are all within stated uncertainties and no particular offset between them is observed.

5 Discussion

Overall, the results show that in all cases the measurements of the partner laboratories agree with each other within their stated uncertainties. As no clear measurement outliers were spotted, this intercomparison exercise gives a first input based on which all measurements can be considered reliable within stated UCs. However, the measurements and results reported here are –for the majority of the partners– only a first step towards full implementation of the linearity measurements for short-circuit current's dependence on irradiance, because most laboratories had to develop their own procedure and UC calculation specifically for this project. This is especially relevant in the case of full-size PV module measurements, for which there can be significant additional UC contributions due to the device size, and here only two laboratories reported results. All partners will now therefore critically assess their own uncertainty analysis based on the outcome of this inter-comparison as well as on further independent evaluations.

In order to state that the non-linearity of the short-circuit current of a PV device as function of irradiance is within the limit of ±2% required by the standard IEC 60904-10, its expanded measurement uncertainty (k = 2) should be much below this. Some of the reported uncertainties are above 2% and most possibly represent just the uncertainty in I_{SC}. The uncertainty of the linearity result should consider the correlations between the single measurements, but also those introduced by the analysis. For example, if the same RC is used for all measurements, the uncertainty of I_{STC} is correlated between all $I_{SC}(G)$ measurements and thus it has reduced effect on the UC of ΔL itself. However, the contribution of the (non-)linearity of the RC (and therefore of the UC of its reading at conditions other than STC) should be considered. Additionally, because $I_{norm}(1000\ W/m^2) = 1$ by definition (see equation (2)), this point has very low uncertainty, caused only by the uncertainty in the irradiance reading due to imperfect determination of the I_{SC} of the RC used to measure it. Thus, depending on the measurement procedure and set-up, $U_{LIN}(G)$ can be lower than the combined uncertainty for $I_{SC}(G)$.

Some RC results (devices S01 and S04) suggest that uncertainties are likely too stringent at low irradiance for the DSR 1 and/or the TLM procedures. However, even though the overlap of UC bands is very small, statistically both still agree with each other.

Overall it was found that most PV devices tested were linear (within stated uncertainties), which is good news for their use as reference devices. For a comparison of methods and actual procedures a DUT with a significant (i.e. larger than uncertainties) non-linearity would be more appropriate. At least for the RCs there was one DUT of such kind (S04).

6 Conclusion

This work presented the results of the first reported interlaboratory comparison of linearity measurements for short-circuit current as function of irradiance. All linearity results submitted by the partner laboratories agree with each other within the stated expanded uncertainty ($k = 2$). Because a large variety of devices of different size and spectral responsivity (with regards to procedures including point by point MMF corrections) has been used, it shows that the applied procedures can measure a large range of PV devices sufficiently reliably, although the UCs calculation has likely to be refined for all. For the TLM, linearity curves over the full irradiance range were constructed from the measured data, so that for the first time linearity results obtained by this method were directly comparable to those obtained by the other methods.

A critical assessment of the measurement uncertainties led to several outcomes. First, in a few cases partners seem to have a too stringent uncertainty at low irradiance as some results show very little overlap within the stated UCs. Secondly and more importantly, the uncertainty of ΔL can in principle be overestimated when uncertainty correlations are not considered and can thus result in false positives. Depending on the measurement procedure and facility, accounting for correlations might significantly reduce the final linearity uncertainty $U_{LIN}(G)$. The latter needs to be below 2% to meaningfully assess a device as linear within the present standard's specifications.

Inputs for improvement of the linearity standard IEC 60904-10 have been discussed here on the basis of the intercomparison methodology and results. A clear need to separate the data analysis for the short-circuit current's dependence on irradiance from all other linear dependences dealt with by the standard has been shown. The suggestions are aimed to improve comparability between measurement procedures and to greatly reduce the possibility of false positives (i.e. declaring devices as linear when in fact they are not).

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