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Traceability of solar irradiance, reference materials and validation of PV products and measurement methods

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Abstract

Photovoltaics (PV) are expected to make a major contribution to achieving European and global climate change mitigation goals over the coming 35 years. It is the renewable energy technology with the largest scope for cost reduction and efficiency gains, as well as exploiting the largest resource. The rapid technical evolution needs to be matched by standards to ensure the highest level possible of product quality, reliability and sustainability, as well as transparent market conditions. This requires reliable, reproducible and widely applicable measurement protocols for the assessment of electrical performance of PV devices of traditional as well as emerging PV technologies. The Joint Research Centre (JRC) plays a prominent role in developing, validating and implementing such measurement protocols, exploiting more than 35 years of expertise developed in the European Solar Test Installation (ESTI), the European Commission's reference laboratory to validate electrical performance and lifetime of PV devices. The JRC works together with policy makers, industry and the research community to monitor the progress of PV technology and helps develop the solutions for the future. This directly supports the European Union's objective of attaining an increasing share of renewable energies in the market (20% in 2020 and at least 32% in 2030).

ESTI is an ISO/IEC 17025 accredited calibration laboratory. As such, it is involved in benchmarking, intercomparisons (bilateral and round robin (RR)) and proficiency tests to maintain and improve its measurement capabilities for solar irradiance and electrical performance of PV devices. The results of these international activities is directly used, mainly through the International Electrotechnical Commission's Technical Committee 82 (IEC TC 82), as input for revision of existing standards or for development of new standards for assessment of the electrical performance of PV devices. This work concerns both measurement methods and PV technologies. Furthermore, ESTI actively promotes transfer of knowledge about the measurement procedures to the European and International research community, provides the PV traceability chain by generating PV reference materials for its partners and clients and offers verification of PV devices (mainly based on new technologies).

In this report the activities of 2018 are summarised. Starting from the traceability chain of solar irradiance measurements according to international standards, the activities of ESTI in establishing the PV traceability chain at its own laboratory is outlined. Then the activities in international intercomparison measurements for the major instruments used in the traceability chain are described, starting from cavity radiometers and spectroradiometers to PV devices (both cells and modules). These serve to establish the traceability, stability and conformity of ESTI calibration measurements. This in-house metrology activity is then used to provide the PV traceability chain to clients and partners by generating reference materials, i.e. by calibrating PV cells and modules for them under the ISO/IEC 17025 accreditation as calibration laboratory. Another crucial activity is to verify those PV devices which claim to have achieved extraordinary performance, be it world record efficiencies or other performance beyond the usual. Last not least, the activities on measurement methods are described, which span from the actual development of new methods and their validation to their implementation into the ESTI quality system and ISO/IEC 17025 accreditation scope.

Thereby, this annual report:

— verifies the status of ESTI's unique independent traceability chain for solar irradiance measurements;

— summarises benchmarking activities with peer external international organisations;

— summarises results of PV device calibrations performed for EU industry and research organisations;

— provides an update on the adequacy of measurement methods used to assess the electrical performance of PV products and prototypes.

1 Introduction

The European Union's (EU) policy for the Energy Union aims at making the European citizens' energy supply more secure, affordable and sustainable. This may also have an indirect positive outcome on the global approach to a more secure and sustainable energy supply for everybody. A part of this policy framework for energy and climate for 2030 is in place, including a commitment to achieve a 32% share of renewables by 2030 [1]. Furthermore, the EU's recent reaffirmation of its commitment to achieving a competitive and climate neutral economy by 2050 [2] recognises the importance of renewable energy to achieving that aim.

Among renewables, photovoltaics (PV) are expected to make a significant contribution to achieving these goals, being the renewable energy technology with the largest scope for cost reduction and efficiency gains. The sector has been growing rapidly, the worldwide installed capacity increased from around 40 GW in 2010 to more than 400 GW in 2017 with an estimate of over 500 GW in 2018 [3]. This growth is characterised by rapid technological development, not just scaling up existing systems. In this context, reliable measurement methods for electrical performance of PV devices and corresponding international standards are essential to ensure market transparency, help to cut costs and strengthen investors' confidence. When correctly and timely designed, they can also play a critical role in accelerating the uptake of innovative solutions [4].

The Joint Research Centre (JRC) supports all this by performing, among other activities, pre-normative research on technical areas of its competence and by taking a proactive role in International and European standardisation bodies. In particular, the JRC expertise in PV is based on the work carried out at the European Solar Test Installation (ESTI), which is an independent European reference laboratory to validate electrical performance and lifetime of PV devices based on traditional as well as emerging PV technologies. Among its activities aimed at building and spreading a robust knowledge in PV and in PV metrology, ESTI also performs pre-normative research to develop and improve traceable, reliable and accurate measurement techniques, which are then often considered for inclusion in the International Electrotechnical Commission's (IEC) standards for PV. In support of the EU political objective of increasing the share of renewable energy in the market, 'ESTI also works together with policy makers, industry and the research community to monitor the progress of this technology sector and to help develop the solutions for the future.

The PV market is at present defined by a price per watt approach (that is, Euros per watt-peak of rated electrical power of the PV modules). With the annual world PV production exceeding 100 GW in 2018 and a market value only for the PV module components reaching over €25 billions, the methods and standards for the calibration of the power of PV modules and systems are vital. Given the increasing importance of the PV contribution to the energy supply and to the financial investments, the PV market relies on high accuracy of the power measurement.

The power of a PV module is directly influenced by the spectral content of the sunlight that illuminates it, because a PV module essentially directly converts incident sunlight into direct-current (DC) electricity. As such, the measurement of electrical performance of PV cells and modules entails the measurement of the solar irradiance, which can be described from two interconnected points of view. The first considers the irradiance as a whole, and measures the overall (total) irradiance; the second looks at the spectral irradiance that constitute it, i.e. the distribution of the total irradiance over the wavelengths. International standards require foremost the PV calibration at standard test conditions (STC) (as defined by [5]), which include a total irradiance of 1000 W/m^2 with a spectral irradiance distribution of the reference spectrum defined in the standard IEC 60904-3 [6].

Therefore, this report considers, as an initial point, the two critical aspects related to the irradiance measurement, which in turn influence the power calibration and energy yield determination for PV devices.

The first concerns the measurement of the level of direct normal (beam) solar irradiance (DNI) using radiation broadband detectors (such as cavity radiometers). Such a measurement is not only indispensable for determining the incident irradiance in PV device calibrations, but is also critical for (i) the development and deployment of solar energy conversion systems, (ii) improving our understanding of the Earth's energy budget for climate change studies and (iii) science and technology applications involving the solar flux.

The second aspect concerns the measurement of the spectral content of the incoming natural or simulated sunlight used in the electrical performance assessment of PV devices. Today's broad portfolio of available PV technologies, with their different responsivity to the spectral content of the incident light (named spectral responsivity (SR)), makes this information a key item for reliable characterisation, calibration and energy yield estimation of PV devices.

ESTI has a well-established and world-wide acknowledged capability for both types of measurement, based on over 20 years' experience with a set of precision instruments. As part of its role to disseminate and manage knowledge on PV, ESTI has coordinated and provided the scientific guidance to a European inter-laboratory group since 2011 in order to develop and expand the knowledge base of these fundamental solar measurements. Periodic intercomparisons are in general also part of performance-based quality-control checks for laboratories working according to ISO/IEC 17025 [7] and, in the specific case of solar radiation measurements, highly recommended by the World Meteorological Organization (WMO). During these comparison campaigns ESTI, together with other participating institutes, organises a series of seminars and discussions to further disseminate the best practices and knowledge to a wider scientific/technical audience. Occasions such as this allow not only international harmonisation of measurement procedures and instruments, but they also provide training and education opportunity for the peer laboratory community which is difficult to achieve in conventional seminars.

Strictly connected to this topic, chapter 0 describes the activities performed in autumn 2018 at the US National Pyrheliometer Comparison (NPC 2018) [8] (as part of the total irradiance measurements) and the preliminary results of the 2018 International Spectroradiometer Intercomparison (ISRC 2018), held at the INTA site in Madrid, Spain (as part of the spectral irradiance measurements).

In PV performance measurements, instead, the total irradiance is usually measured by one or more PV reference cell(s). Essentially, the calibration of irradiance measurement is transferred to the device under test (DUT) (e.g. a PV module). As the measurements are made under natural or simulated sunlight that will always differ more or less significantly from the reference spectrum, a spectral mismatch error is introduced in the DUT performance measurement, as the reference device and the device under test will in general have different SRs. This spectral error can be corrected mathematically *a posteriori*, but this requires the knowledge of the SR of both reference device and DUT and of the spectral content of the natural or simulated sunlight used for the measurement. The latter can be measured by spectroradiometers. However, over the years it became evident that accurate measurements of the spectral irradiance are far from being trivial and require state-of-the-art equipment and experience. Therefore, the JRC is organising and running annually the International Spectroradiometer Comparison (ISRC) in order to gather and spread knowledge and good practices on this.

While the traceability transfer between two PV devices is relatively straightforward due to their common operating principle, the very first PV device in the PV traceability chain needs to be calibrated against a measurement standard[1] (or *étalon*) [9], which measures irradiance traceable to international measurement standards. In the case of natural

[1] i.e. the physical realisation (or nowadays more and more the calculated value of a physical or mathematical constant) of a given measurable quantity, with stated quantity value and associated measurement uncertainty, which is then used as a reference for further measurements. The physical prototype that defines (until the 20th May 2019) the unit mass [kg] of the International System of units is kept at the *Bureau international des poids et mesures* (BIPM) near Paris.

sunlight the latter is represented by the conventional World Radiometric Reference (WRR), which is measured with cavity radiometers (or more simply named cavities). However, the latter have entirely different characteristics from PV devices (most notably a very broadband spectral responsivity that covers the electromagnetic spectrum much beyond its visible part and a slower response to the incident electromagnetic radiation). Therefore, the calibration of PV devices against cavities requires special measurement procedures and skills. Such procedures and skills are part of the core knowledge at ESTI, which owns cavity radiometers among its calibrated precision instruments. The cavities in use at ESTI are measurement standards that are defined "secondary standards", because they are calibrated against the WRR, which represents the "primary standard" for solar irradiance measurement (in PV the sun is considered a primary standard itself). The calibration of ESTI cavities occurs every five years against the primary standard during the International Pyrheliometer Comparison (IPC) held at the World Radiation Centre (WRC) in Davos, Switzerland, and in years in between with other secondary standards (through the National Pyrheliometer Comparison, NPC) for stability check.

The metrological transfer from the WRR to the first PV reference cell in the traceability chain is called a primary calibration, as it calibrates a PV device against something which is not a PV device. From then on, the transfer is between PV devices which are more alike, and as such it can be considered more straightforward and to some extent affordable by a wider range of measurement laboratories.

Different primary calibration methods are historically in use in the PV community and the question arose whether they all agree and which one is the best, if any. In the course of international round-robins, an agreement was found and it was decided that all valid measurements should be considered for producing the average reference value, thereby generating the World Photovoltaic Scale (WPVS). ESTI has decided in 1995 to implement from then onwards this WPVS in its own PV calibration chain, as that is the best reference, providing the highest level of reliability of solar irradiance measurements for PV. Other laboratories, instead, decided to use it only for their proficiency testing (as required under ISO/IEC 17025 [7]), i.e. only to check that their results are still in agreement with the WPVS (within measurement uncertainty (UC)). ESTI has used the WPVS ever since. It has also continuously developed the concept further, thereby generating in 2008 the ESTI reference cell set (made of five primary reference cells) to which it has assigned the weighted average of all valid primary calibration measurements. In that way, it not only provided the highest confidence but also the lowest uncertainty in PV calibration, target unachievable by any individual measurement. A noteworthy side effect of this is that secondary calibrations (i.e. PV against PV) can be performed at ESTI with the same resulting UC as the best primary calibration methods, thereby saving on effort and cost without compromising accuracy. These traceability chain and facilities are unique and establish ESTI as the laboratory owning the PV devices with the lowest UC for solar irradiance measurement.

The WPVS at ESTI is updated whenever new valid measurements become available, but the annual stability is always checked and verified. The set of five reference cells is well maintained under rigorously controlled storage conditions and PV devices under these conditions have very long-term stability (>30 years). Furthermore, the ESTI laboratory regularly compares its measurements with its peers around the world, either in bilateral or round robin campaigns.

This whole background and fundamental work is then the basis to offer PV device calibration under the ISO/IEC 17025 accreditation scheme of the laboratory. ESTI was the first laboratory to be accredited initially for PV device testing (COFRAC 1-0717 in 1996) and later for PV device calibration (COFRAC 2-1671 in 2004), which was subsequently transferred still as accreditation for PV device calibration (Accredia LAT 225 since 2011) [10]. The ESTI laboratory remains one with the largest range of methods. Clients and partners send PV devices (cells and modules) to ESTI for traceable calibration (incl. delivery of calibration certificates). In this way, ESTI generates PV reference material, which can then be used by the original owner of the device to calibrate further

PV devices of its own (chapter 0). This creates the uninterrupted metrological connection of the traceability chain between the testing laboratories or PV manufacturers and the international standard through ESTI. With the growing PV market, it would be very difficult for ESTI to provide a calibration service for hundreds of manufactured PV modules, therefore ESTI specialises in providing the traceability chain to the PV community, which is costly and cannot be maintained by each laboratory.

The expertise in ESTI is furthermore used to (officially) assess the electrical performance of PV devices that claim to achieve world record or other extraordinary performance (chapter 5). In fact, ESTI is a member of the small peer group editing the world-record PV efficiency tables [11, 12]. As ESTI is independent of any commercial as well as national interests, it is acknowledged as neutral in assessing such PV devices. Again, it is the long-term expertise built over decades of constantly refined practice that has led ESTI to being entrusted with this role.

ESTI is involved in the dissemination of its knowledge to improve measurement and calibration of PV devices worldwide (chapter 0).

In order to be ready for future challenges, measurement methods are continuously improved and updated at ESTI (chapter 7). Furthermore ESTI verifies alternative methods to ensure world-wide compatibility of results. This pre-normative research is eventually used as input for international standardisation. Similarly, sometimes ESTI deals with methods which will be applicable to all PV devices, sometimes there are procedures more specific to new or emerging PV technologies. The latter is an important point, as the development of new technologies can be assessed and guided only through reliable measurement. Once more, this requires recognised independent assessment, which can only be provided and developed based on long-term experience and expertise. The activities on measurement methods described span from the actual development of new methods and their validation to their implementation into the ESTI quality system and ISO/IEC 17025 accreditation scope. The latter is usually achieved by a two-step procedure under the accreditation scheme with which ESTI is required to comply, which allows the temporary inclusion of the validated methods under the flexible scope that ESTI has gained under its IEC/ISO 17025 accreditation and the successive inclusion of the method in the published list of accredited methods once the accreditation body has approved it.

Overall, the activities of ESTI in all these aspects of PV make ESTI a unique European reference laboratory for the assessment of electrical performance of PV devices. Traditionally, PV measurements are not located in National Metrology Institutes (NMIs), but rather in specialised laboratories dealing with renewable energies. ESTI is among the only handful laboratories around the world providing PV measurements at the highest level. ESTI compares regularly to these peers ensuring equivalence of results from all laboratories around the globe (for examples see chapter 3.3).

This technical report for the first time collects and summarises all ESTI activities in connection with the measurement of electrical performance of PV devices. It is intended that this will become an annual report to be published towards the end of each year, updating on the report of the previous year. As this is the first report of its kind, it necessarily gives the overall background. Therefore, many activities and results reported here are pertinent to 2018, but some from 2017 and earlier are included as well to complete the overall picture and give the necessary information to put the 2018 activities and results into context. Also some activities stretched over several years and were completed in 2018.

2 Traceability of solar irradiance measurement for photovoltaics

The measurement of the solar irradiance is the most crucial measurement in the assessment of electrical performance of PV devices because it contributes the largest part to the measurement UC. Therefore, its traceability to the international measurement standard is relevant. This section describes ESTI activities in this field from international standardisation, i.e. the primary measurement of total and spectral irradiance, down to the unique reference for PV irradiance measurement, which is the ESTI reference cell set incorporating the WPVS.

2.1 International standard IEC 60904-4

The International Standard IEC 60904-4 [13] describes the traceability chain of the solar irradiance measurements for PV. This standard was developed with JRC-ESTI acting as project leader. Currently, it is under revision again under leadership of the JRC-ESTI. The work has progressed to the stage of final draft International Standard (FDIS) and the publication is envisaged for early 2019.

The IEC 60904-4 describes the requirements for traceability as well as the possible routes to achieve it. Furthermore, typical implementations of currently available methods are described in detail in its annex.

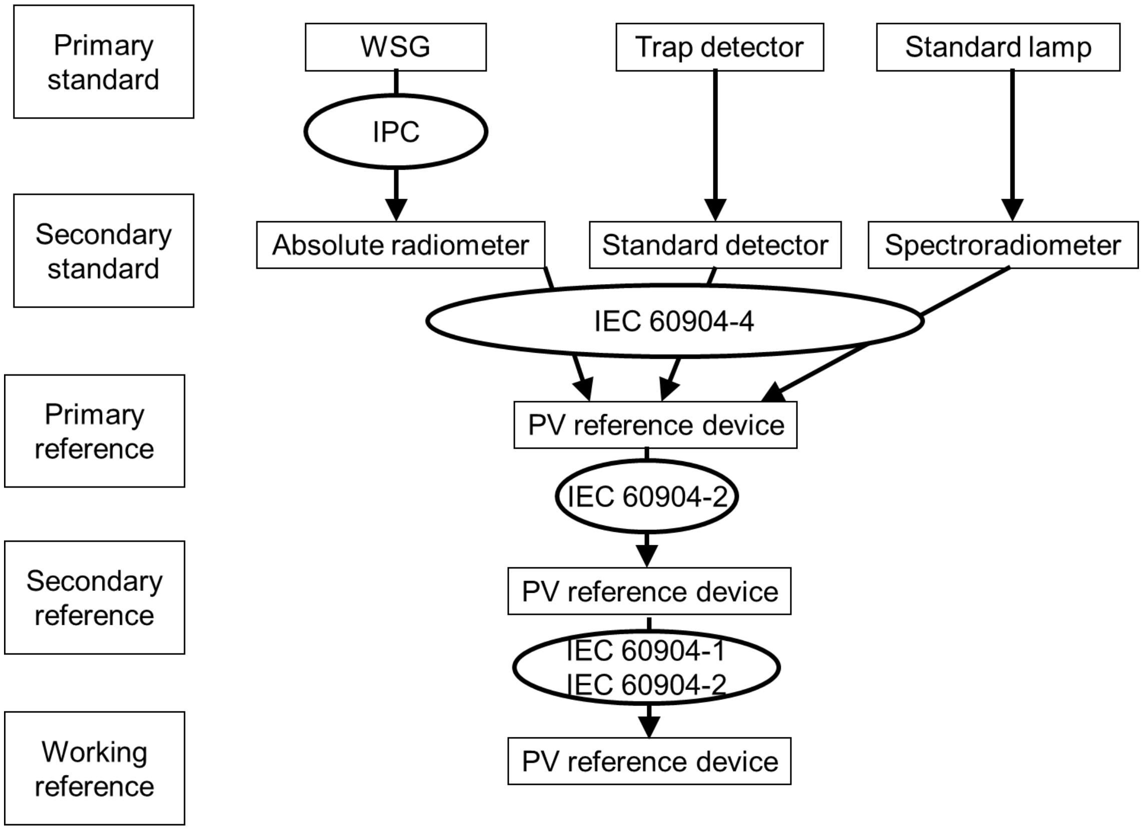

Figure 1. Schematic diagram of the traceability chain for PV reference devices.

Essentially, the irradiance measurement can be traced either to the WRR, which is a conventional detector-based measurement standard for direct natural sunlight, or to the International System (SI) irradiance scale, through standard detectors, spectroradiometers, standard lamps and black-body sources (see Figure 1). The former has total irradiance and spectral irradiance similar to the PV reference spectrum [6] and requires outdoor measurements under suitable conditions. The other methods are laboratory based and typically have much lower irradiance intensities and very different spectral irradiance compared to the reference spectrum, thus requiring extra efforts during the metrological transfer to PV devices concerning linearity and spectral mismatch. The implementation of the traceability chain at ESTI is shown in Figure 2.

Once the transfer to a PV reference device (typically a solar cell) has been achieved traceably by these methods (i.e. primary calibration), the further transfer (i.e. secondary calibration) to other PV devices can be performed and is governed by separate IEC Standards.

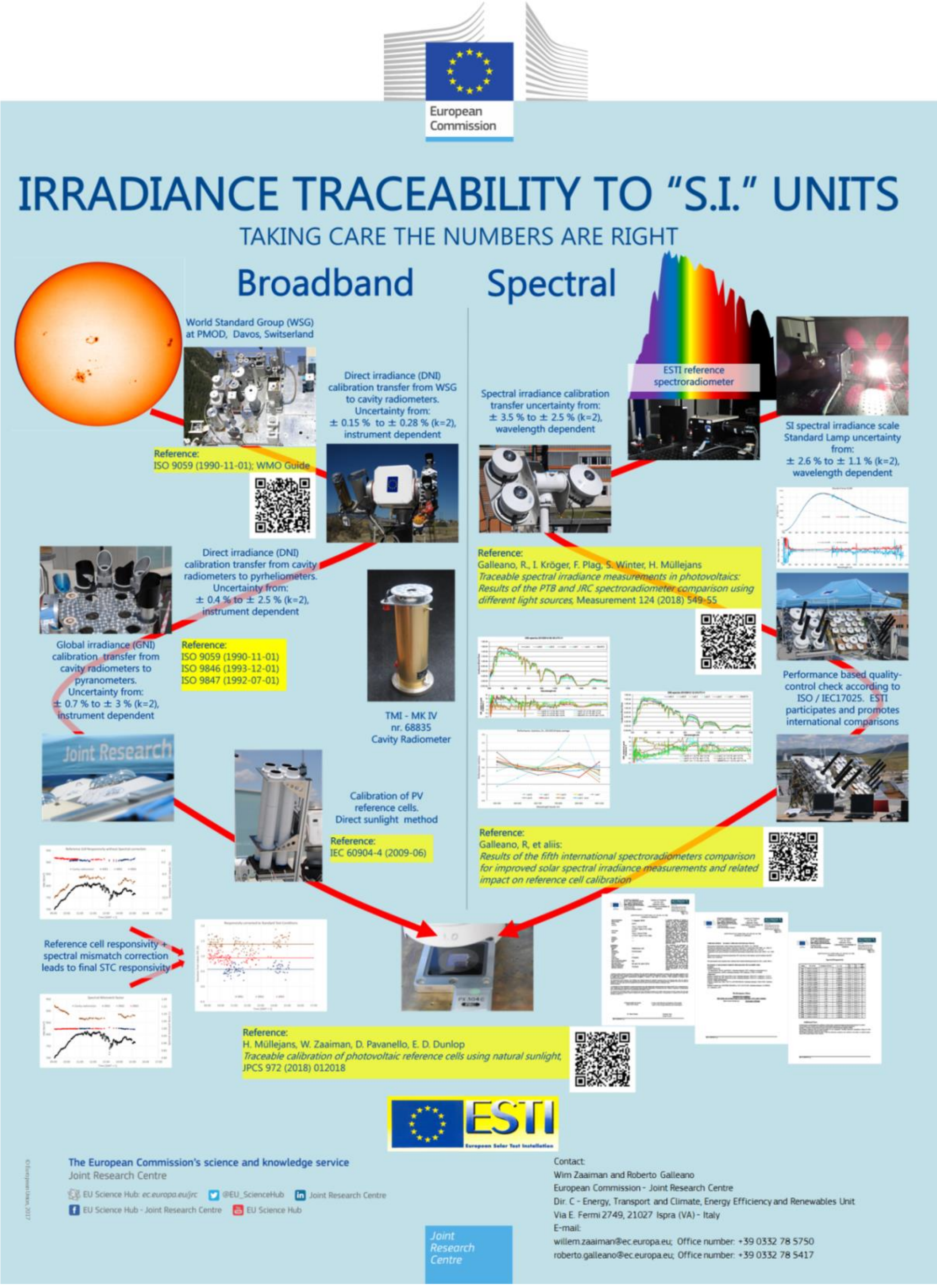

Figure 2: Overview of irradiance traceability chain at ESTI.

2.2 WRR and cavity radiometers

The WRR is a conventional primary (measurement) standard based on a group of cavity radiometers, named the World Standard Group (WSG), and transferred every five years to secondary (measurement) standards. ESTI holds three such secondary standards which it uses to transfer the calibration chain to PV devices according to IEC 60904-4. The methods implemented at ESTI are mainly the Global Sunlight Method (GSM) and Direct Sunlight Method (DSM). The former was developed at ESTI and is unique, whereas the DSM was originally pioneered by NREL and implemented at ESTI for comparison and validation purposes.

2.3 Spectroradiometers

The IEC 60904-4 makes it also possible to follow the traceability to black-body radiation via standard lamps (see Figure 1). This route was pioneered at AIST and is implemented at ESTI for comparison.

2.4 ESTI reference cell set

As primary calibrations are expensive in effort and costs, not all PV devices can be calibrated utilising them. Firstly, there is a size constraint which essentially limits the application of the above-mentioned methods to reference cells with an active area of typically 2 cm by 2 cm. A laboratory normally has one or a few of these cells, used as the laboratory primary reference. ESTI uses a set of five such cells (the ESTI reference cell set). This allows verification of their stability by cross comparison.

2.5 World Photovoltaic Scale (WPVS)

Several methods are available that have proven in the past to produce results consistent with each other within measurement UC. However, as is usual practise in international metrology at the highest level, a key comparison reference value (KCRV) can be assigned, even to a measurement standard, based on all valid measurements on the same device. In general, the weighted average is used, with the weighting provided by the measurement UC of the contributing results. This will provide a value which is more reliable than the individual values, as it contains information from all validated methods, thereby also reducing the uncertainty of this final average. This concept was the original idea at the basis of the WPVS, implemented in the 1995 as outcome of the Photovoltaic Solar Energy Project (PEP) of the Technology, Growth and Employment Working Group of the G7 summit [14]. However, only arithmetic averaging was used at that time. Furthermore, participants other than ESTI chose to maintain their own traceability with comparison to WPVS only for consistency. ESTI on the other hand decided to implement the WPVS and hence take full advantage of its benefits. In the following years ESTI developed the concept further, accumulating measurements from a variety of validated methods and finally (in 2008) implementing the weighted average approach, thus reducing the UC of the original WPVS from 1.9% to 0.25% (i.e. almost a factor 10). Now, ESTI is the keeper of the WPVS, which is constituted by the ESTI reference cell set (at present five cells). The uncertainty for solar irradiance measurements with these reference cells has now become the lowest available worldwide [15].

3 Intercomparisons measurements

In metrology, two measurement results are typically compared by the E_n number analysis [16] [17], according to the following equation:

$$En = \frac{X_{Lab} - X_{ref}}{\sqrt{(U_{95,Lab})^2 + (U_{95,ref})^2}}$$

with

X_{Lab} is the value reported by a laboratory

X_{ref} is the reference value or the value reported by the reference laboratory

$U_{95,Lab}$ is the combined uncertainty (with 95% confidence) of the first measurement

$U_{95,ref}$ is the combined uncertainty (with 95% confidence) of the reference laboratory or of the reference value.

$U_{95,diff} = \sqrt{(U_{95,Lab})^2 + (U_{95,ref})^2}$ is for extension the combined uncertainty of the difference X_{Lab} - X_{ref}

Essentially, the E_n number represents a metric that measures the distance between a measured value (X_{Lab}) and the reference value (X_{ref}) in terms of their uncertainties they both may have compared to the real (unknowable) absolute value of the quantity under measurement.

It is evident from the above equation that, when the difference X_{Lab} - X_{ref} is zero, the E_n number equals also zero whatever the uncertainty of the measurements. However, as in metrology the results of two measurements are never exactly the same, the agreement of X_{Lab} with X_{ref} is defined by those cases for which X_{Lab} is included in the range [X_{ref} - $U_{95,diff}$, X_{ref} - $U_{95,diff}$], i.e. the E_n number belongs to the interval [-1 ; 1] indicating consistency within declared uncertainties. If this is not the case, X_{Lab} is not consistent with X_{ref}.

In the case of equivalent measurements, the same approach can be applied, although there is no reference anymore, as both results can play the role of reference value.

This approach has been applied at ESTI and in measurement comparisons with ESTI partners for several years (see intercomparisons described in the following). In the case of a measurement by ESTI flagged as inconsistent with the reference value, further in-depth investigation follows to determine and eliminate, or if not fully possible at least mitigate, the cause of the discrepancy.

Moreover, for institutions participating to inter-laboratory comparisons that apply a quality system or have an ISO/IEC 17025 accreditation, the intercomparison itself is an implementation of the required periodical checks of the quality control system based on comparable laboratory performance and the E_n number approach is increasingly accepted as a suitable assessment method of the results.

3.1 Comparisons of broadband irradiance instruments

In the late 1970s, the WMO established the WRR as a conventional international standard for DNI measurement [18]. As mentioned in section 2.2, the WRR is a conventional, internationally recognised, detector-based measurement standard determined by the collective performance of electrically self-calibrated absolute cavity radiometers forming the WSG. The WSG is maintained at the PMOD/WRC at Davos, Switzerland. PMOD/WRC Davos has a mandate from the WMO to transfer the WRR to secondary radiometers.

To produce research-quality solar irradiance measurements, accurate radiometer calibrations traceable to an international primary standard are necessary. Maintaining the high precision of these calibrations/verifications is assured by comparisons at fixed time intervals. That's why every five years, the PMOD/WRC in Davos hosts an IPC for transferring the WRR to participating radiometers. ESTI has represented the European Commission in each IPC since 2000.

Annually, (except in IPC years) ESTI also participates in the NPC held at the National Renewable Energy Laboratory (NREL), Golden (CO), USA.

Since 1996, ESTI has developed its internal procedures to operate a selected group of absolute cavity radiometers with direct traceability to the WRR, thanks to the constant participation in the IPCs. These radiometers are therefore secondary measurement standards and as such they are part of the control radiometers during the NPC's at NREL.

ESTI participation to the above-mentioned radiometer comparisons fulfils its ISO/IEC 17025 accreditation, which also requires participation to such comparisons.

3.1.1 Cavity radiometer and pyrheliometer verification at NPC 2018

In 2018, ESTI participated to the US NPC organised by NREL (24 Sep – 5 Oct 2018 in Boulder, CO, USA) with its three cavity radiometers (codes: PMO-6 81109, PMO-6 911204 and TMI 68835). The purpose of the participation was to verify the stability of ESTI instruments as well as the US control radiometers. This was achieved by comparing the correction value determined at the NPC with respect to that of the last valid calibration, i.e. the Twelfth International Pyrheliometer Comparison, IPCXII (2015) [19] (Table 1). The stability of all three instruments was confirmed.

As the US and the ESTI cavity radiometers are all secondary measurement standards, these comparison measurements are merely used to check the instrument stability within the time period between one IPC and the next, but the results are not used as actual calibration values of the ESTI instruments. The latter are always calculated from the last valid calibration against the WRR (which is a primary measurement standard), i.e. currently against the IPC-XII value. Figure 3 shows the long-term stability of the three ESTI cavity radiometers during international inter-comparisons.

Table 1: Comparison of cavity radiometer stability in 2018.

	PMO6 81109	**PMO6 911204**	**TMI 68835**
IPC-XII (2015)	0.998320 ± 0.32%	0.999450 ± 0.41%	1.000714 ± 0.32%
NPC (2018)	0.998230 ± 0.39%	1.000130 ± 0.41%	0.999830 ± 0.41%
Difference	-90 ppm	+680 ppm	-884 ppm
E_n	-0.02	+0.12	-0.17

Furthermore, also ESTI secondary pyrheliometers are usually compared to the NREL reference standards during the NPC. This occurred also in 2018. The historical trend in the WRR correction factors (for pyrheliometer CH1 930018 this goes back 24 years) shown in Figure 4 and the E_n number analysis (not shown) confirm the stability of these instruments.

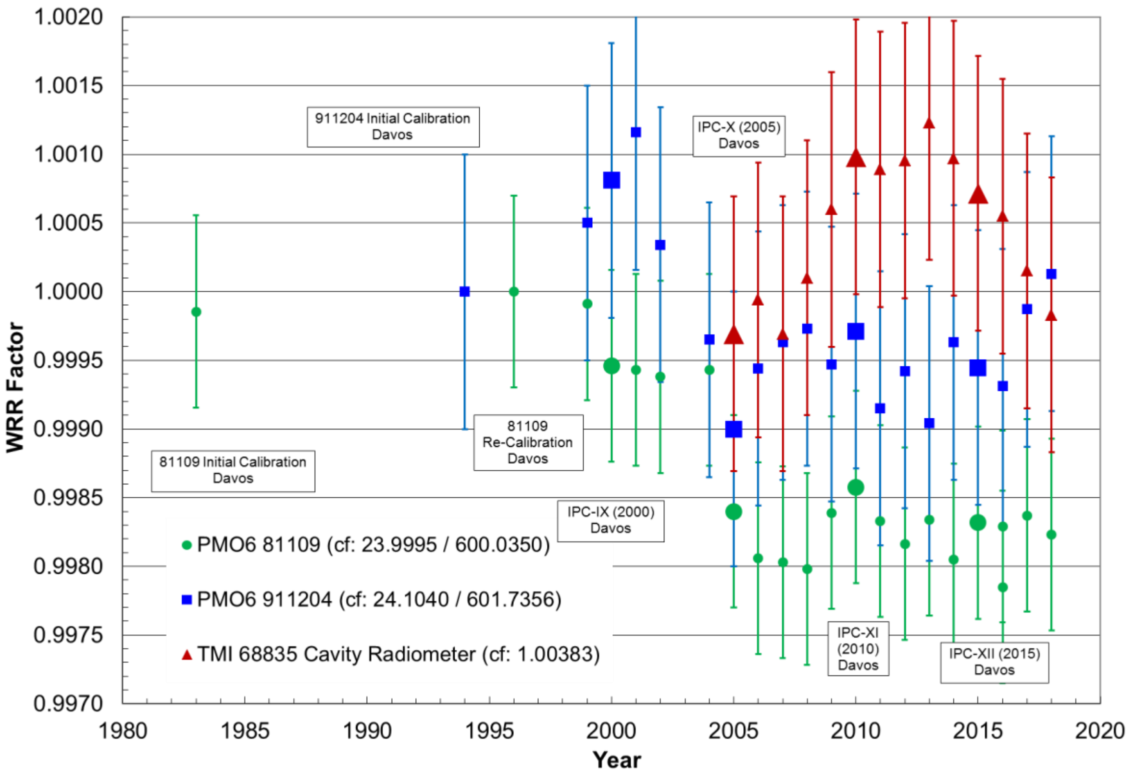

Figure 3. Stability of ESTI cavity radiometers as determined from international comparisons.

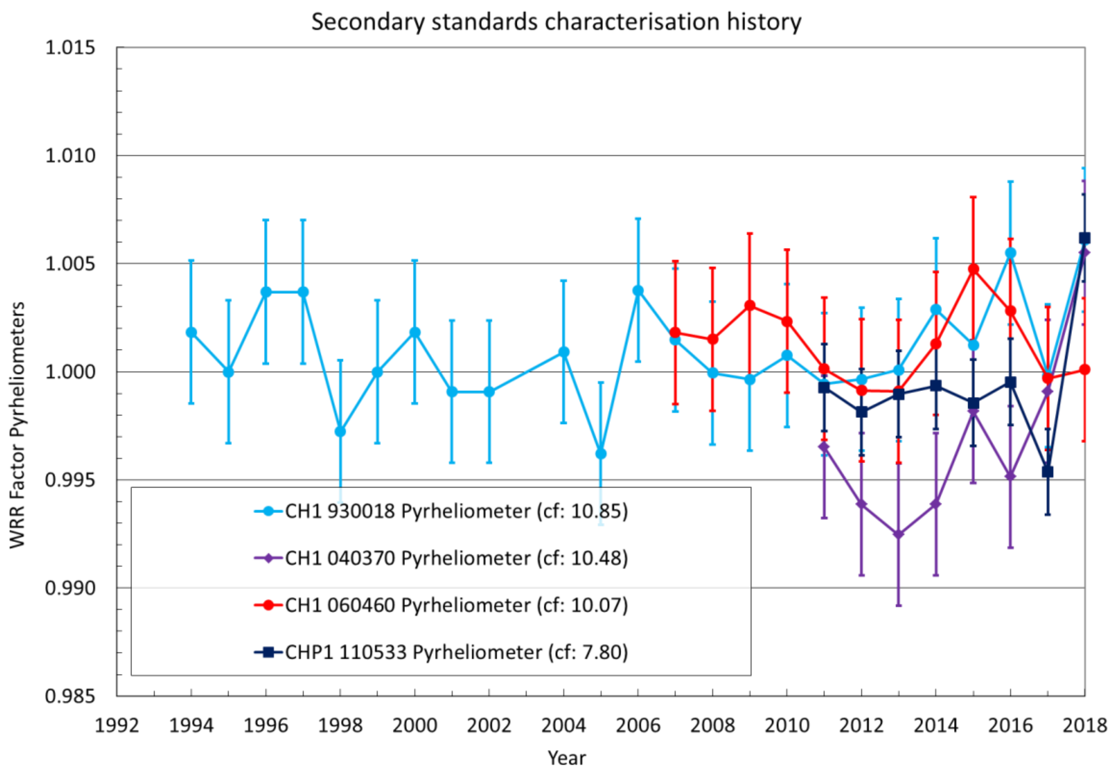

Figure 4. Stability of ESTI pyrheliometers as determined from international comparisons.

3.1.2 Pyranometer comparisons

Regarding the calibration of pyranometers, which are another type of broadband irradiance detectors based on a different operating principle compared to PV, ESTI additionally implemented the "Alternate method" [20, 21] in 2018 and then validated the results against the traditional method as well as against results from an ISO/IEC 17025 accredited peer laboratory (ISO-CAL, USA) for two pyranometers (CM22 060142 and CM22 060143). This showed that the "Alternate method" as implemented at ESTI is equivalent to the traditional one and all results fully agree within stated uncertainties.

Table 2: Results and E_n number analysis for calibration of two pyranometers with traditional and "Alternate method" at ESTI as compared to peer laboratory ISO-CAL.

	CM22 (060142)			**CM22 (060143)**		
	CF [μV/W/m²]	stdev [μV/W/m²]	$\boldsymbol{E_n}$	CF [μV/W/m²]	stdev [μV/W/m²]	$\boldsymbol{E_n}$
ESTI historical calibration	8.63	0.054	0.05	8.60	0.043	0.36
ESTI "Alternate method" (April 2018)	8.60	0.032	0.69	8.60	0.032	0.42
ISO-CAL USA (June 2018)	8.633	0.035		8.62	0.035	

3.2 Spectroradiometers comparisons

There is a growing request of harmonisation of good measurement practices and knowledge transfer in the field of spectrally-resolved solar radiation for solar energy applications (e.g. PV) in order to make them comparable and directly traceable to SI units. Moreover, there is a growing request for comparable, traceable and low-uncertainty (natural or simulated) sunlight spectrum measurements for PV energy yield estimate. The spectroradiometer intercomparison, whose results are summarised in this work, is thus a good opportunity to raise the awareness on these crucial measurements.

Nowadays, spectroradiometers with different operating principles (e.g. single-, double-stage rotating-grating monochromator or fixed single-grating polychromator with photodiode array or CCD detectors and filter radiometer-based instruments) are routinely used for sunlight spectrum measurements.

Due to the large variety of PV technologies, covering different wavelength ranges of the solar spectrum, new challenges for research centres and product manufacturers arise. This is mainly due to the increasing and crucial need to know the spectral composition of the natural or simulated sunlight used during PV calibration in comparison to the standard reference spectrum. The measurement spectrum is indeed needed with higher accuracy and over a extended wavelength range in order to meet the demand for higher accuracy of PV calibration. Moreover, the paradigm change in defining the price of PV modules and cells from €/(watt-peak) to €/(produced kWh) makes accurate and long-term in-situ spectral measurements a key parameter in energy-rating and energy-yield estimates.

Spectroradiometry is a key metrological discipline for accurate calibration of PV devices, particularly relevant for the following aspects:

- Spectral irradiance is one of the three parameters according to which solar simulators are rated as per the international standard IEC 60904-9 [22];

- Spectral mismatch correction typically represents the major source of uncertainty in measuring the performance of PV devices. Accurate measurements of natural or simulated sunlight spectral irradiance are essential in limiting the overall amount of the spectral mismatch, especially in those cases where the SRs of the DUT and the reference device significantly differ from each other;
- While PV devices are rated at the reference spectral irradiance [6], in real PV installations both the total as well as the spectral irradiance may differ significantly from STC and therefore accurate measurements of these two quantities plays an important role for energy yield estimation;
- Comprehensive knowledge of both repeatability and reproducibility of spectral irradiance measurements is also key to a correct uncertainty evaluation for PV device measurement, which is also mandatory for ISO/IEC 17025 accreditation.

3.2.1 PTB-JRC intercomparison

A high-level intercomparison between the spectroradiometers of ESTI (two instruments) and PTB (one instrument) was made under natural as well as simulated sunlight. From the detailed analysis, it was concluded that measurement results of the three instruments agree within their stated UCs for most wavelengths. Some discrepancies are due to different resolution and the noise level at low signals. Some systematic differences in the UV region of the spectrum require further investigation [23].

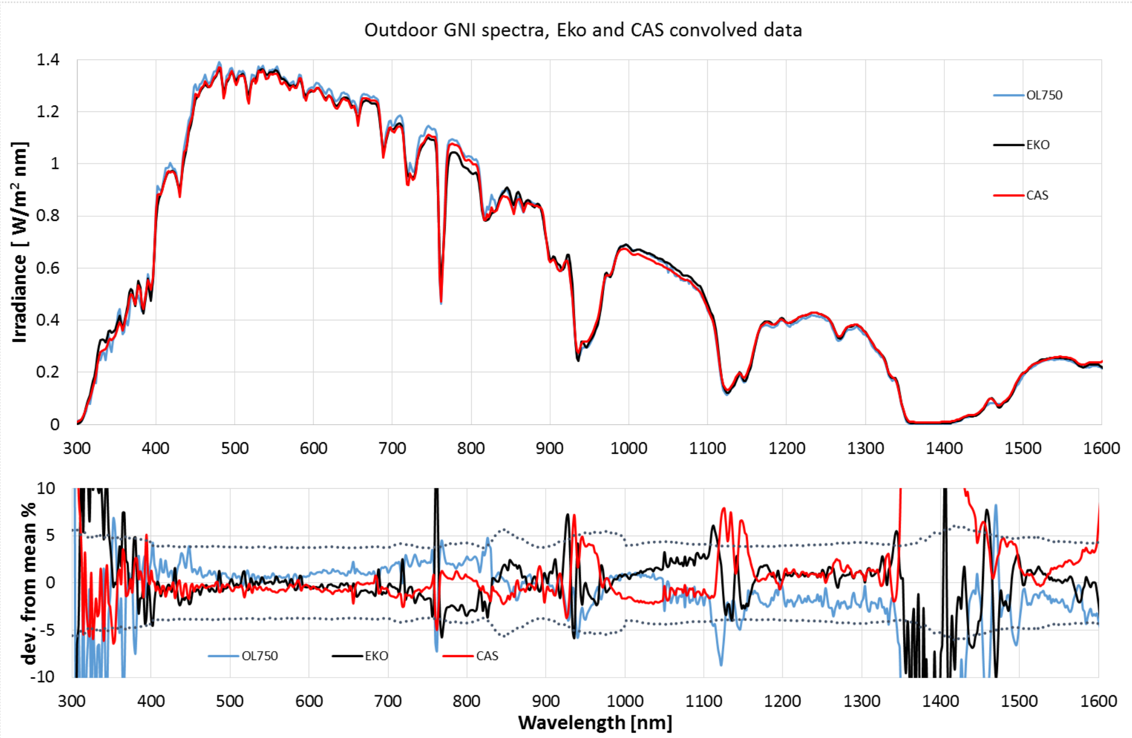

Figure 5. Comparison of the global spectrum of natural sunlight as measured by two spectroradiometers from ESTI and one from PTB.

3.2.2 International Spectroradiometer Intercomparison (ISRC) 2018

ESTI is organising and leading the ISRC since 2011, usually in various localities in the Mediterranean Basin (either Italy or Spain). These intercomparisons gather research institutes, universities and commercial partners with the aim of sharing good laboratory practices, improving measuring techniques and measurement equivalence of total and spectrally-resolved solar radiation. In 2018 the intercomparison was held at the "Instituto Nacional de Técnica Aerospacial" (INTA) in Torrejón de Ardoz, Madrid, Spain from 4th to 8th June. Table 3 summarizes participating institutions and the main characteristics of the instruments. The ISRC 2019 is planned to be held at the Observatoire Astronomique de Saint-Véran "AstroQueyras", department of Haute-Alps, in France.

In order to harmonise European wide determination methods of solar spectral resource, ESTI provides through the ISRC the calibration measurement standard traceable to SI units and also to the WRR, against which all the other participating instruments are compared. The first ISRC in 2011 involved only three Member States, with eight participating in 2018. The goal is to extend this activity involving participants from all 28 EU Member States.

So far the scientific output of the ISRCs includes seven conference contributions, four papers published on peer reviewed journals and another one submitted and under review. The good scientific production rate and the increasing participation from European and even non-European partners testify the interest of the PV community to the subject. Moreover, the participation to intercomparisons and/or round robin exercises is required for ISO/IEC 17025 accredited laboratories as a factual-based quality-control assessment.

Table 3. Participants to ISRC 2018.

Institute	Country	Instrument	Wave-length range [nm]	Global / Direct
AIT	Austria	MAYA 2000 Pro & NIRQuest 512-1.7	300-1600	GNI[2]
Loughborough University	UK	Avantes Avaspec-2048 X	300-1100	GNI
CEA INES	France	Avantes AvaSpec-ULS2048CL-EVO (CMOS) & Avantes AvaSpec-NIR256-1.7	300-1600	GNI
Radboud University / ReRa Solutions	South Africa	EKO MS711 & MS712	300-1700	GNI
DTU	Denmark	EKO MS711	300-1100	DNI[3]
JRC	EU	EKO MS701 & MS710 & MS712	300-1700	GNI / DNI
EKO	The Netherlands	EKO MS711 & MS712	300-1700	DNI
RSE	Italy	Spectrafy SolarSIM-D2	300-4000	DNI
INTA	Spain	Avantes AvaSpec-ULS2048L / XL	280-900	GNI / DNI
INTA - SPASOLAB	Spain	IS320D CAS140 CT	300–1550 1550-2188	N/A Only Indoor
UEX	Spain	Stellarnet Black-Comet UV-Vis Avantes AvaSpec-ULS2048L / XL	280-900	GNI GNI / DNI
Alitec srl	Italy	Own product to calibrate		---
ENEA	Italy	Stellarnet EPP2000 VIS & NIR	300-1700	GNI / DNI
UCY	Cyprus	Spectrafy SolarSIM-D2	300-4000	DNI
SERIS	Singapore	Avantes Avaspec-3648-USB2	300-1100	GNI

[2] Global Normal Incidence
[3] Direct Normal Incidence

Due to the differences among various instruments in measurement timing, bandwidth and spectral resolution, specific procedures for instruments synchronisation and data acquisition and analysis were developed in order to make the spectroradiometers' output comparable to each other. Prior to the intercomparison each participant calibrated its own spectroradiometer(s) following its usual procedures. This allowed the evaluation of each instrument performance together with its traceability chain and calibration procedure. Indeed, some spectroradiometers were calibrated by an external accredited calibration laboratory, while others were calibrated either in house using a calibrated radiometric standard lamp or at the manufacturer.

All participating instruments were mounted on high-accuracy solar trackers in order to reduce errors due to instruments pointing. In parallel to the intercomparison, ESTI cavity radiometers were also in use as reference instruments for broadband irradiance data ensuring the direct link to SI units. For clear-sky conditions, the corresponding output data obtained from SMARTS model were used for consistency check purposes.

The dissemination activity performed by JRC-ESTI in the framework of the spectroradiometer intercomparisons is fundamental to maintain a reliable and traceable connection of the solar spectral measurement performed in the European PV community to the SI units. As well, such an activity is crucial to improve measurement results comparability among participating institutions. Due to bad weather conditions, the ISRC 2018 was run mainly indoor using an AM0-like solar simulator and only partially outdoor during the single day with decent weather. Data from this measurement exercise are being analysed and circulated to the participants to increase awareness regarding accuracy, stability, repeatability and reproducibility for their respective instruments. The final goal is to publish the comparison results as a contribution to a PV conference and/or as a scientific paper in a peer-review journal.

Figure 6, Figure 7 and Figure 8 show some examples of acquired spectra during ISRC 2018 where the acquired spectra are superimposed one on top of each other for a quick and preliminary spectra quality evaluation (upper graphs in the figures). Figure 6 contains data from measurements made on a high-intensity solar simulator for characteirisation and calibration of space cells; Figure 7 and Figure 8 show data from outdoor solar DNI measurements. For this exercise, analyses of the wavelength-by-wavelength differences relative to reference spectrum peak irradiance were performed and reported in the lower graphs in the figures.

Previous data analysis has focussed on the differences in absolute spectral irradiance among participating instruments. A different approach can be used to separate systematic effects (e.g. arising from instrument calibration or from instrument time drift) from non-linearity, internal stray light or distortion as outlined previously [24]. This is important in solar spectrum measurement applied to PV field, where a correct measurement of the (shape of) the incoming sunlight spectral distribution is fundamental, whereas the total irradiance is usually measured by other means, often also with lower UC (e.g. cavity radiometers, reference solar cells, pyrheliometers, pyranometers, etc.).

In order to compare solar spectra acquired by 'fast' and 'slow' measuring instruments, several sets of average spectra, measured during 7-minute acquisition time series, were analysed. During the time series, the irradiance must vary less than 1% in order to consider the spectra series 'stable' and flagged for analysis. The stability constraint avoids adding errors arising from fast-changing weather conditions affecting the output of spectroradiometers in different ways. This constraint limited the useful sky conditions to clear or almost clear. Several analyses were performed on output data in terms of both absolute spectral irradiance and spectral shape deviation.

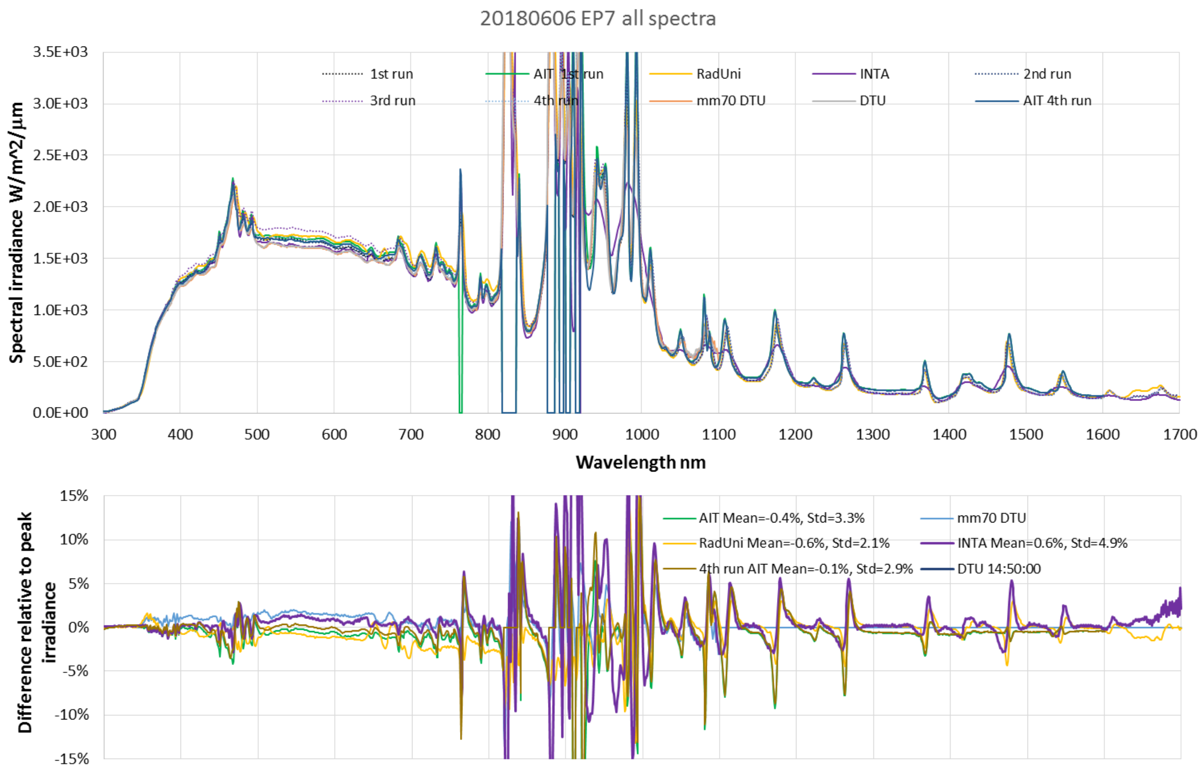

Figure 6: Example of spectra comparison.

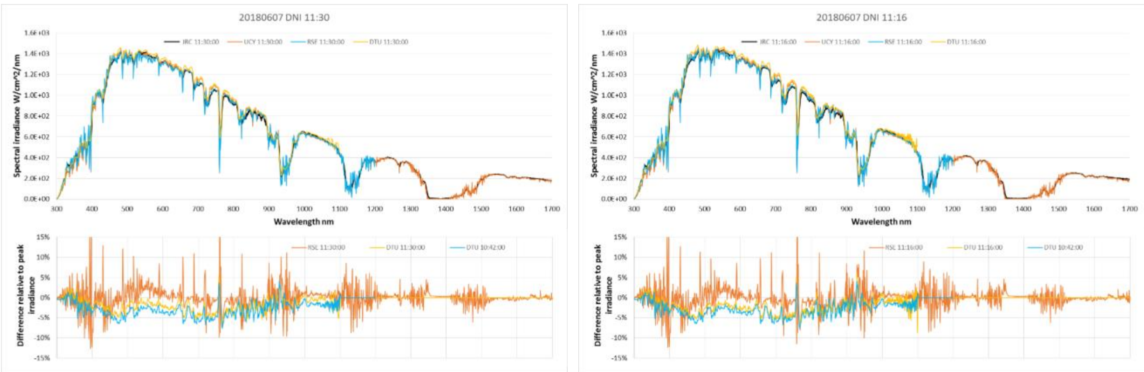

Figure 7: Example of spectra comparison.

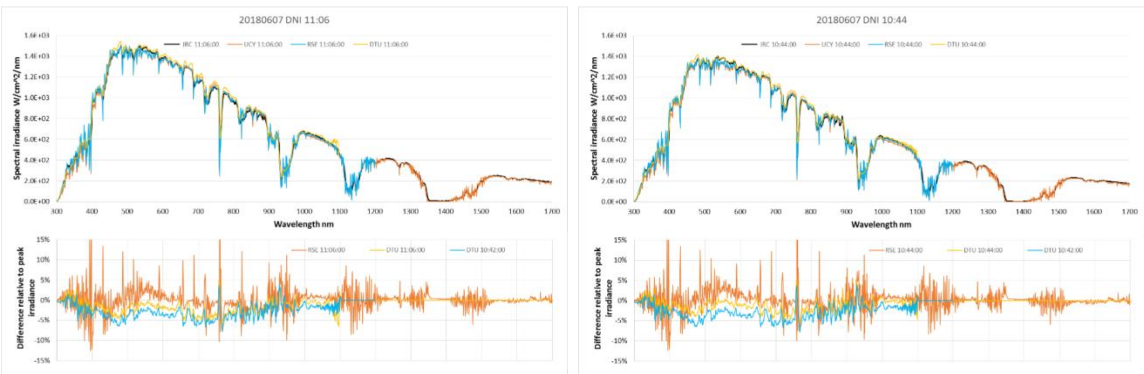

Figure 8: Example of spectra comparison.

3.3 PV device calibration comparisons

The ESTI reference cell set (comprising five solar cells) constitutes the primary reference of PV reference devices for the ESTI laboratory. Every year the stability of the five cells in the set is verified and then the set is used to calibrate the about 30 other ESTI PV reference cells. The latter constitute secondary references for the ESTI laboratory (see Figure 1 for definition in the traceability chain) and are used in routine measurements in the laboratory. Furthermore, ESTI regularly compares the calibration of PV reference devices with its peers, both in bilateral intercomparisons as well as in round-robin comparisons with multiple peers.

3.3.1 Annual calibration of ESTI secondary references

In the annual calibration the almost 30 secondary references of the ESTI laboratory are calibrated against the primary reference (ESTI reference cell set). Such measurements, called secondary calibrations, require less effort and are faster than the primary calibrations against non-PV devices (see sections above).

3.3.1.1 Stability of ESTI reference cell set

The first step for ensuring a reliable calibration of the secondary references is in fact to check the stability of the primary reference. Therefore, the five cells of the ESTI reference cell set are calibrated against each other, i.e. taking one of the cells in turn as the reference device and calibrating the other cells against it. The results are then compared to the previous assigned calibration value (CV) for each cell. As the set comprises five cells of different type, the drift of any member of the set can be detected by this wide cross comparison. Only if all cells in the set drifted exactly by the same amount relatively to each other and to all possible combinations, the drift would pass unnoticed; however, this is highly unlikely. As an example, Figure 9 shows the results of this check for the cell PX201C (a member of the set) over the last ten years with respect to the assigned reference value. The verification shows that the results are fully consistent, as the variation among the measured values (blue dots) is much less than the measurement UC as shown by the error bars.

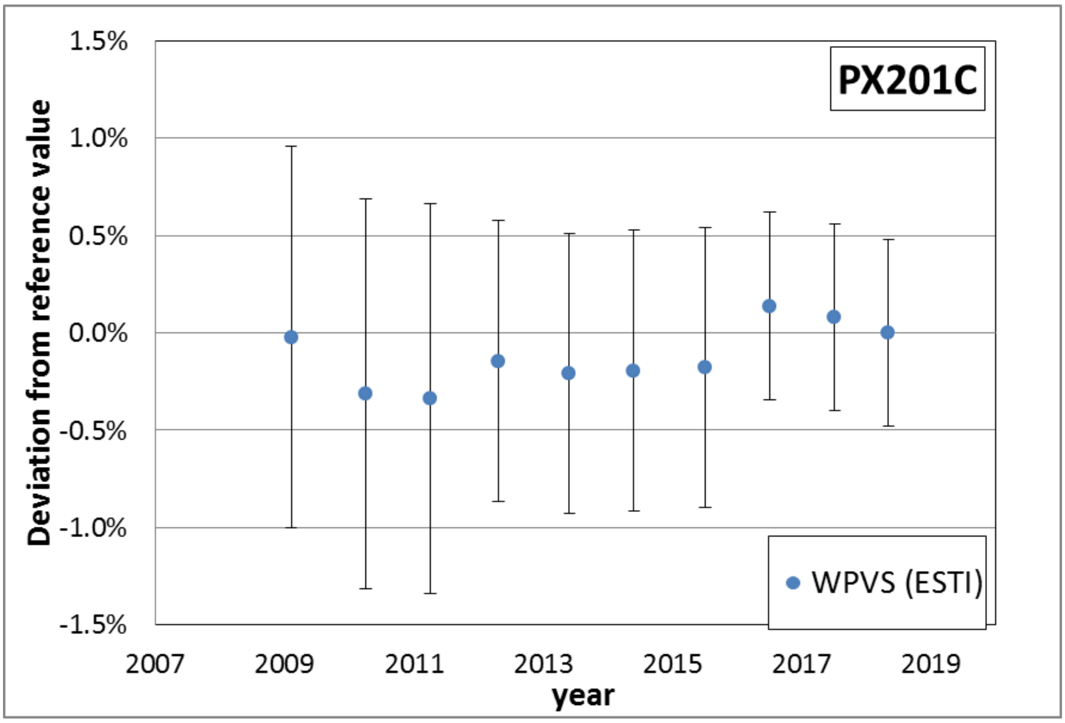

Figure 9. Stability of one reference cell within the ESTI reference cell set.

3.3.1.2 Calibration transfer to secondary references

Once the stability of the ESTI reference cell set has been verified, all other ESTI reference cells are calibrated against at least two members of this set, using the WPVS assigned CV for the primary references as that is based on primary calibrations and have lower measurement UC. As an example the yearly calibration of one secondary reference cell (PX305C) is shown in Figure 10. Again the yearly variation is much less than the measurement UC, showing that the cell itself is stable over time and that the measurements at ESTI are reproducible over time. In fact, any noticeable deviation in the results would be flagged for further investigation before releasing the respective calibration certificate.

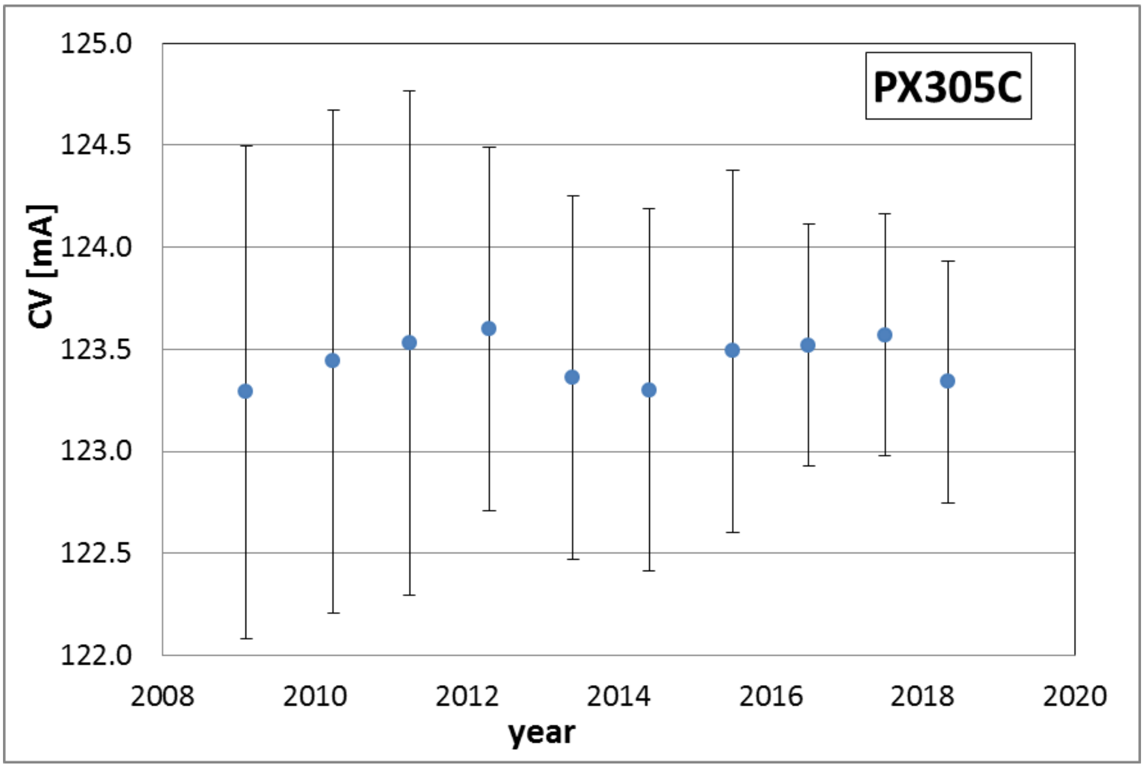

Figure 10. Stability of one reference cell in use at ESTI for routine measurements (typically for transfer of traceability to external reference cells).

3.3.2 Bilateral intercomparisons

As a further check on the reliability of the calibration results obtained by ESTI, bilateral calibration intercomparisons are regularly made with peer laboratories around the world. This includes reference cells as well as full-size PV modules. Such intercomparisons are vital to guarantee the world-wide equivalence of PV measurement results, but as already mentioned they are also a requirement under the ESTI ISO/IEC 17025 accreditation as calibration laboratory.

In the following, the comparison of results will be typically done using the concept of E_n number, which is the comparison's most appropriate metric in metrology. When two measurements are performed by two institutions (or for that matter by applying two different methods), each has to quote its result together with the expanded measurement uncertainty UC(95%), i.e. covering an interval which is expected to contain the true value with a probability of 95%. The assignment of this measurement UC is far from trivial and requires skills and experience to setup and run dedicated experiments assessing sources of measurement UC contributions as well as their combination. ESTI has been traditionally very active in this area [25] and is working as well on transferring the acquired knowledge of UC calculation.

3.3.2.1 NREL

Since many years there has been fruitful and intense collaboration with the US reference laboratory for PV calibration, NREL, by exchanging best practices on calibration methods and procedures as well as directly comparing the calibration of actual PV devices. In 2018, two ESTI reference cells were calibrated at NREL and compared to the results from the prior calibration at ESTI (Table 4) with satisfactory agreement.

Table 4. Comparison of the CVs together with UCs of two PV reference cells between ESTI and NREL.

ESTI code	**CV (ESTI) [mA]**	**CV (NREL) [mA]**	E_n
PX505C	150.42 ± 0.72	150.71 ± 0.93	-0.25
PX506C	154.93 ± 0.74	155.89 ± 0.96	-0.79

3.3.2.2 PTB

The collaboration with the group of PTB, the German NMI, that deals with PV reference cells calibration is another long-lasting partnership with ESTI. Over the years, it has involved staff exchanging (visiting scientists for one month), best practices on PV calibration methods and procedures and comparison of real calibration of actual PV devices. In 2018, three PTB reference cells were calibrated at ESTI and compared to the results from the prior calibration at PTB (Table 5) showing satisfactory agreement.

Table 5. Comparison of CVs together with UCs for three PV reference cells between ESTI and PTB.

ESTI code	**CV (ESTI) [mA]**	**CV (PTB) [mA]**	E_n
SR81	140.40 ± 0.67	139.47 ± 0.67	0.98
SR82	36.35 ± 0.55	35.84 ± 0.19	0.88
SR83	149.86 ± 0.72	149.28 ± 0.75	0.56

3.3.2.3 ISFH

The German laboratory ISFH was recently accredited for PV reference cell calibration under ISO/IEC 17025. In 2018, two reference cells from ISFH were calibrated at ESTI and compared to the results from the prior calibration at ISFH (Table 6), showing agreement. Furthermore, a detailed comparison was done on the SR measurement, which is required to correct the spectral mismatch mainly arising from the difference of the simulated sunlight spectrum used during calibration to the reference spectrum tabulated by the IEC 60904-3 [6]. The comparison was made on a wavelength-by-wavelength basis using interpolated values to allow compare the same wavelengths and again the E_n number assessment (Figure 11).

Table 6. Comparison of CVs together with UCs for two PV reference cells between ESTI and ISFH.

ESTI code	CV (ESTI) [mA]	CV (ISFH) [mA]	E_n
SS81	149.61 ± 0.93	149.53 ± 1.40	0.05
SS82	146.25 ± 0.70	146.51 ± 1.40	0.17

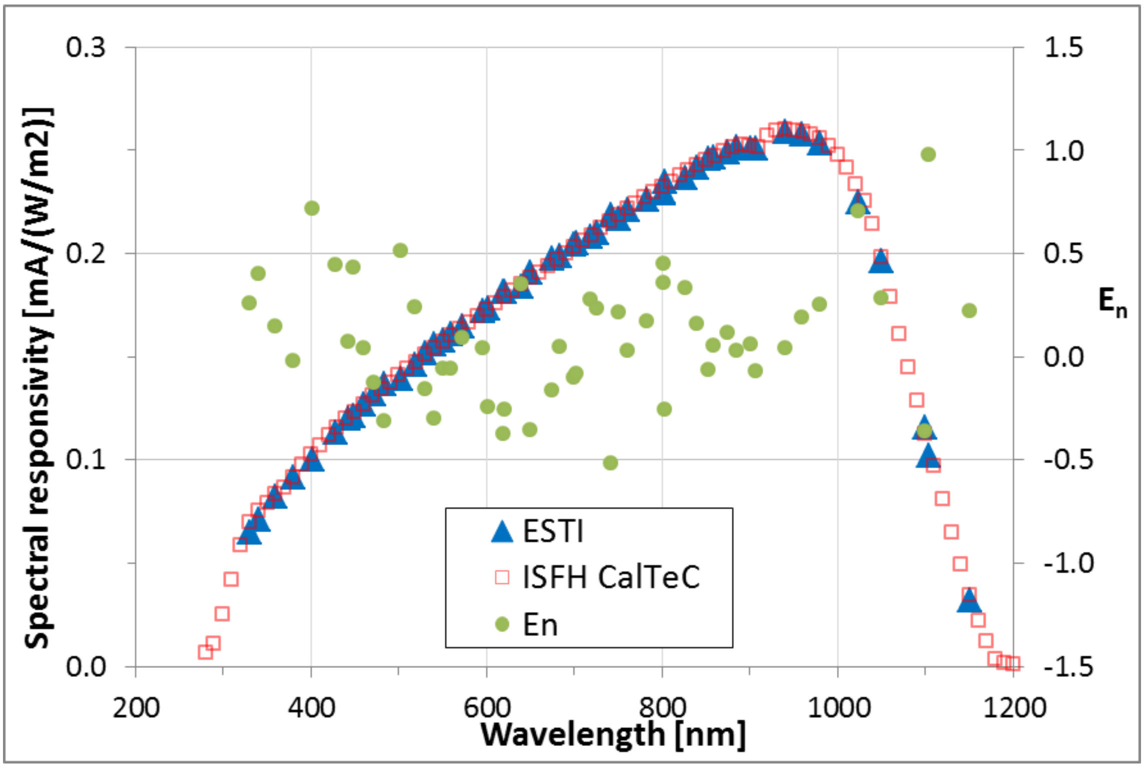

Figure 11. Comparison of SR for PV reference cell SS82 between ESTI and ISFH.

3.3.3 Round-robin intercomparisons

Round-robin measurement campaigns comprise more than two participants and are set so that the devices to be measured are sent to the next laboratory in the sequence, without going back to the initiator until the very end of the campaign itself. Sometimes the expertise level of the participants is varied, ranging from peer laboratories to those at a lower level or even newly entering the PV field. The round-robin exercises between peer laboratories give more easily a broader overview of compatibility between their measurement capabilities, as the effort required to achieve the same with bilateral comparisons would be much larger. In the case of participants of different expertise level, round-robins are extremely useful to spread good measurement practices and to periodically check the laboratories procedures (even at the reference laboratory). The results of two example round-robin intercomparisons, one run between 2016 and 2017 and concerning PV reference cells calibration and the other one on full-size PV modules calibration run between 2015 and 2017, are reported. Further round-robin exercises on bi-facial PV devices are ongoing and will be reported in the future.

Within the EURAMET ENG55 "PHOTOCLASS" project several round-robin intercomparisons were made, which ranged from electrical performance (including the one reported in 3.3.3.1) over temperature coefficients to linearity and covered PV devices from reference cells to full-size modules passing through two intermediate sizes and interconnections of PV devices. The aim of the project was to develop, implement and improve an advanced metric based on energy rating. In order to do this, new and improved measurement methods for PV device characterisation were necessary and put in place at ESTI. Therefore, not all the measurements made for this project were fully covered by the ISO/IEC 17025 accreditation of the ESTI laboratory, not even under its flexible scope. An example of this are the linearity measurements via the two-lamp method. The results were released on ESTI calibration certificates (but not under the accreditation scheme) with a total of 17 certificates.

3.3.3.1 Reference cells

Two PV reference cells of different technology (crystalline silicon and gallium-arsenide) were calibrated by nine laboratories within the European PHOTOCLASS project [26]. The results (Figure 12) were evaluated by calculating the deviation of each participant from the weighted mean. As the weighted mean is contained within the UC interval of each single measurement (as already visually shown in Figure 12 by the value 1 in the left plots), the overall data set is fully consistent. The E_n analysis shown in the right-hand plots confirms this statement, as no value is outside the range [-1;1]. This proves that the calibration results from all participating laboratories agree within their stated UCs and therefore can all be used as valid CVs.

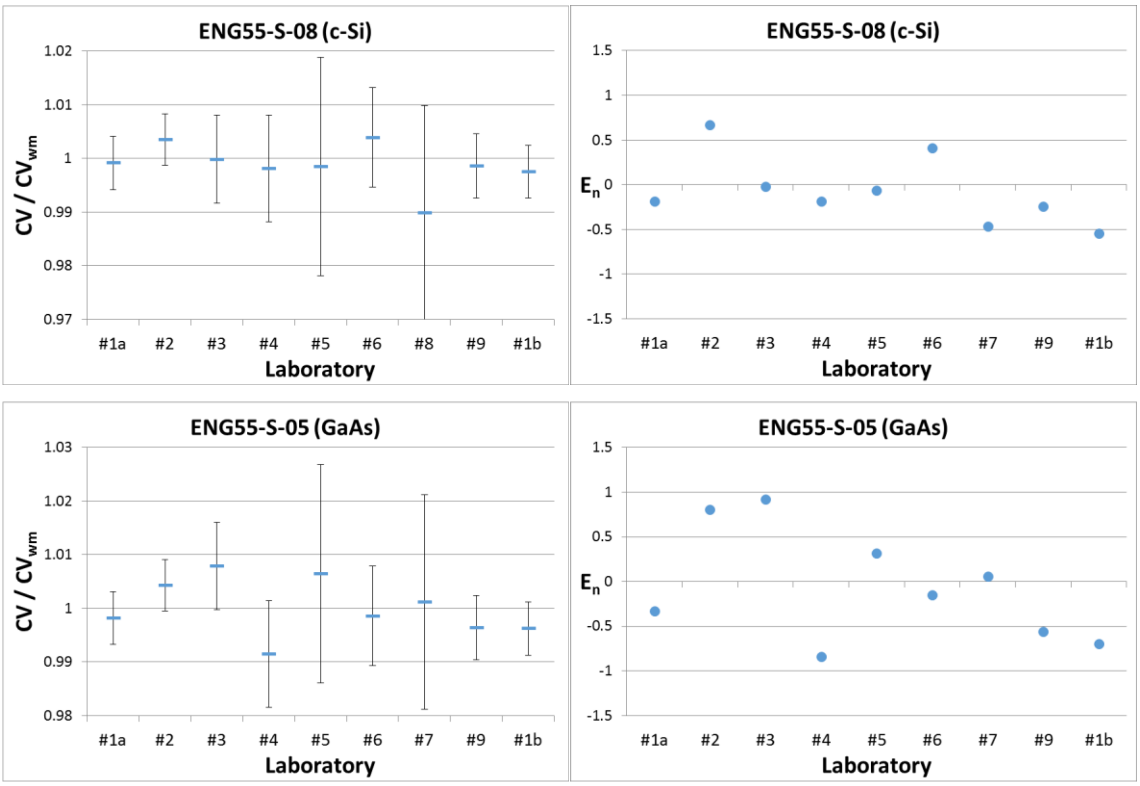

Figure 12. Results of round-robin measurements of two reference cells of different technologies. Left-side: Results of participants (dashes) with stated measurement uncertainties (error bars) and normalised to the weighted mean value. Right-side: E_n number corresponding to the left-side results towards the weighted mean.

3.3.3.2 PV modules

Seven full-size PV modules were calibrated in a world-wide intercomparison between four reference laboratories for PV calibration: NREL, AIST, FhG-ISE and ESTI [27]. While for PV reference cells the comparison is usually limited to the short-circuit current or CV of the cells (see examples above), as this parameter only is used when they are employed to measure the incident irradiance in other PV device calibrations, for PV modules the full current-voltage characteristics (I-V curves) are measured. From these, various relevant parameters can be extracted such as the short-circuit current (I_{SC}), the open–circuit voltage (V_{OC}) and the maximum power (P_{MAX}). In the intecomparison all these parameters were compared in detail for all seven modules. As an example, the comparison for maximum power calibration is reported (Figure 13). Again, the relative deviation from the weighted mean is shown with the respective error bars for each measurement. Consistency was found for all devices.

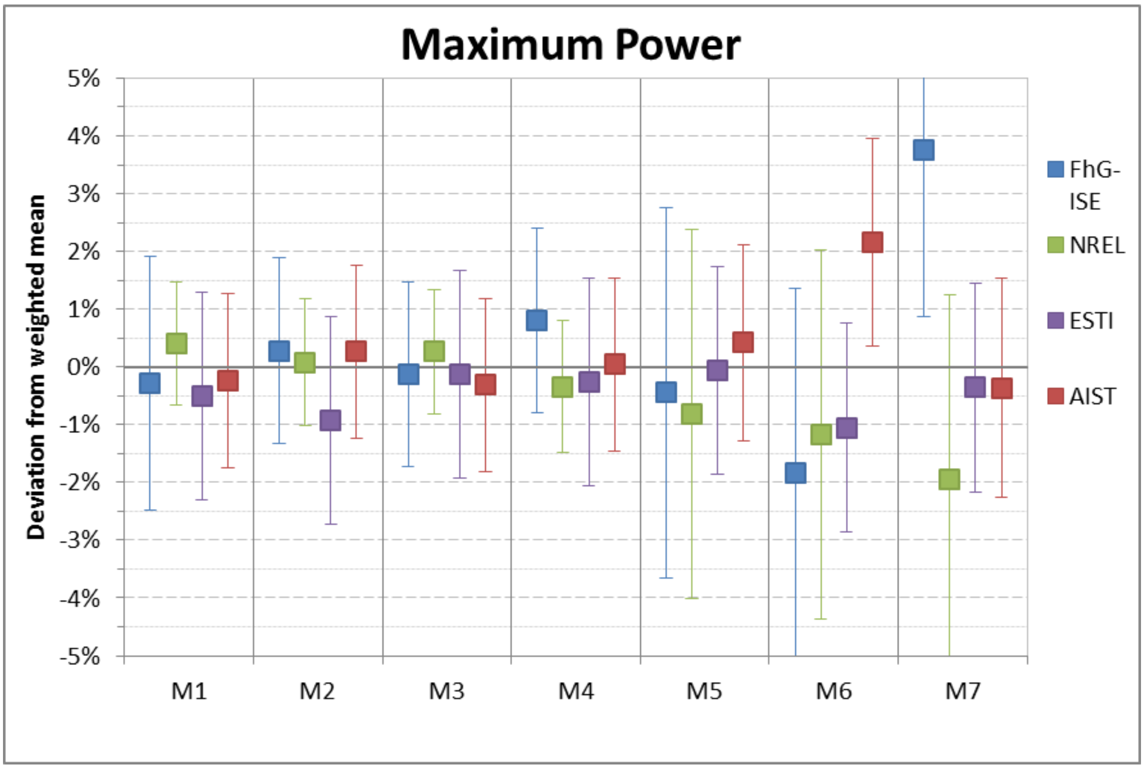

Figure 13. Results of P_{MAX} calibration measurements of the seven PV modules of different technologies included in the intercomparison between NREL, AIST, FhG-ISE and ESTI.

4 Generation of PV reference material

Based on the calibration chain available at ESTI (see section 2), transfer of the traceability chain to downstream PV calibrations are also made for clients and partners. Essentially, all laboratories for PV measurements require to have the unbroken traceability chain. However, the effort to ensure it in a reliable way is such that only few laboratories in the world have all of it in house (as ESTI does). Therefore, one service that ESTI provides with its unique position is to calibrate secondary references for external clients issuing a calibration certificate under its ISO/IEC 17025 accreditation and thereby providing the necessary traceability chain to the client.

Furthermore, the measurement capability of PV laboratories has to be periodically assessed in proficiency testing. This does not concern the top-level calibration institutes (such as ESTI), as in this verification aspect they would essentially be covered by calibration intercomparisons between peer laboratories, but rather all those test laboratories who routinely measure performance of PV devices at a somewhat lower level in the traceability chain. These laboratories have to be evaluated against a reference, which is usually provided by one of the top-level calibration institutes, e.g. ESTI.

4.1 Proficiency testing

ESTI has recently served as the reference laboratory in two cases. The devices under test were calibrated at ESTI and the calibration result was used to assign the reference value to the device (including uncertainty). All participants then measured the devices and their results were evaluated against the reference value through E_n number approach.

4.1.1 High-efficiency crystalline silicon PV modules

The measurement of high-efficiency crystalline silicon PV modules poses a challenge to PV calibration, as the inherent capacitance of these devices complicates the I-V curve measurement using pulsed solar simulators. Various solutions have been proposed as a workaround. Such methods have been evaluated against the reference value provided by ESTI and based on measurements under natural sunlight (Table 7) [28], which do not suffer from the time limitations due to the continuous nature of the light source. By validating the methods against the reference value provided by ESTI, they can now be used in test laboratories and PV industry.

Table 7. E_n numbers comparison of the results for maximum power of high-efficiency PV modules and obtained by proficiency testing participants with respect to the reference value as measured by ESTI.

E_n	Lab #1	Lab #2	Lab #3	Lab #4	Lab #5	Lab #6	Lab #7
Module #1	0.04	0.80	0.92	0.84	-0.25	0.09	0.89
Module #2	0.20	0.89	0.87	0.83	-0.15	0.19	0.84
Module #3	0.22	0.56	0.64	0.61	-0.36	-0.21	0.63
Module #4	0.15	0.52	0.45	0.46	-0.42	-0.33	0.42
Module #5	0.12	0.34	0.37	0.39	-0.17	-0.24	0.08
Module #6	0.24	0.21	0.43	0.43	-0.21	-0.20	0.14
Module #7	0.66	0.35	0.49	0.54	-0.01	0.57	-0.01
Module #8	0.78	0.57	0.78	0.90	0.27	0.85	0.21

4.1.2 Multi-junction PV cells

Monolithic multi-junction (MJ) PV devices are formed by the superposition of two or more photoactive layers of semiconducting p-n junctions, each of which is usually responsive to a different spectral range of the incident light. In monolithic structures, such layers (or junctions) are electrically connected in series, which implies that the electric charges created by the conversion of light inside the photoactive junction have to cross all the device material (and therefore its other junctions) in order to be available for collection at the terminals of the PV device. In some cases, electric charges created in one of the junctions of MJ PV devices (usually the one responsive to photons with higher energy, i.e. towards the blue region of the spectrum) can recombine within the junction itself and emit new photons, which can in turn travel through the material and couple with the junction(s) responsive to less energetic photons altering their light conversion process. When this happens, the recombined charges are removed from the process of light conversion into electricity. This usually results in a lower conversion efficiency of the MJ PV device, as the maximum electric current flow through the entire MJ PV device is ruled by the junction that allows the smallest electric current through it (therefore called limiting-junction). As the limiting junction is typically the one responsive to higher energy, reducing the amount of its effective converted charges implies usually a reduction in the total amount of electricity that can be produced by the MJ PV device and so in its overall conversion efficiency.

Hence, the measurement of monolithic MJ PV devices poses particular challenges in both I-V curve and SR cases, as the electric charges have to pass through (all) other junction(s) due to their series connection. Therefore, such measurements require special instrumentation and procedures, e.g. proper narrowband bias light together with appropriate compensating bias voltage during spectral responsivity measurement. Furthermore, the devices that were specifically investigated in this proficiency testing are made of two junctions (for which they are named double-junction or tandem PV devices) consisting of amorphous and micro-crystalline silicon. These materials are known to have some inherent instability. Therefore, ESTI had to first stabilise the devices following international standard procedures and then calibrated them. The devices were then circulated with a round-robin approach to the twelve participants of the proficiency test, not all of which had the expertise nor all the facilities to fully measure MJ PV devices. However, this was part of the campaign and one of the reasons for which ESTI was chosen as its reference laboratory, as good practice and expertise in MJ PV device measurements are both far from being routinely available at many laboratories in the world. At the end of July 2017, the devices were returned to ESTI for the final calibration that had to close the proficiency test. As the whole exercise lasted more than 1.5 years, ESTI first calibrated them as received (following the same instructions given to all participants) and then after repeating the initial stabilisation procedure. An example of the results from all participants are shown for one device in Figure 14. All the results (including those by ESTI at the end of 2017) were compared and are shown in terms of their deviation from ESTI original calibration value generated at the beginning of the proficiency test (corresponding to the horizontal axis in the plot). From the compiled results (whose detailed data analysis was finalised by ESTI in 2018) a variety of conclusions can be drawn. These include the proficiency of the participants to measure MJ PV devices and the stability of the circulated devices over time. For example, the shown device clearly changed during the round-robin because after its return to ESTI the first measured maximum power value (the green triangle just after the vertical blue-dashed line) was more than 4% higher than at the beginning. After stabilisation the maximum power returned to its original value, proving that the stabilisation procedure required by the IEC standards is reproducible. It also shows that it is necessary, although not sufficient, to reliably calibrate this type of devices.

Due to the observable change of the devices, the participants measuring towards the end typically found higher values of the maximum power compared to the ESTI original value. All these observations will be evaluated in more detail using all available information and published in a peer-reviewed paper currently under preparation.

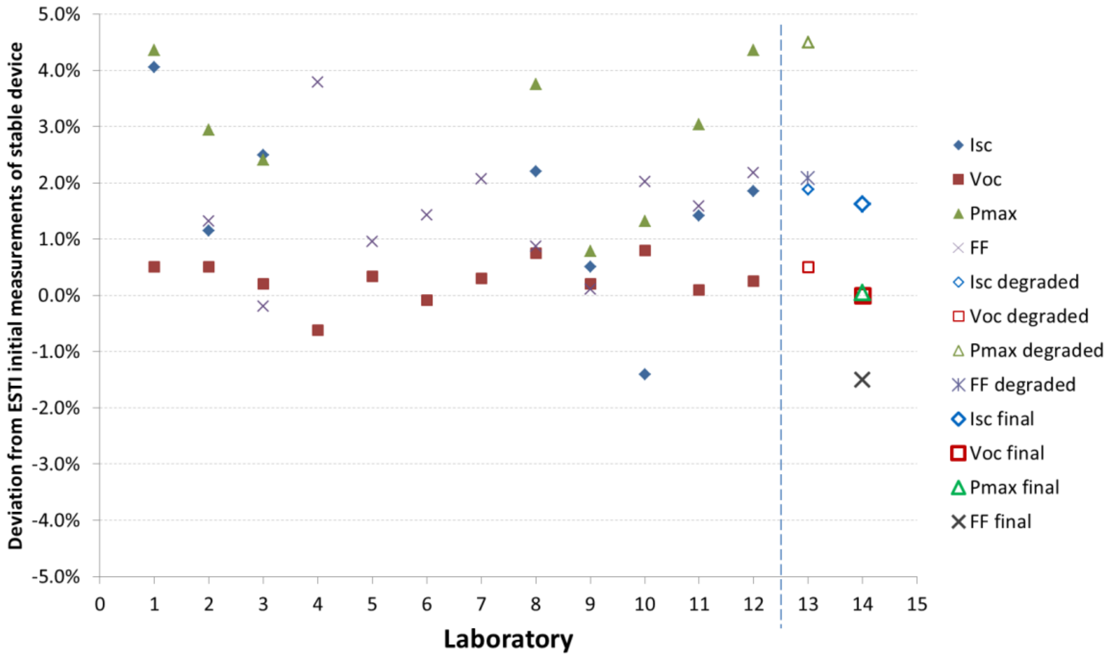

Figure 14. Results of proficiency test of MJ PV device measurements shown as deviations from the original reference value provided by ESTI at the beginning of the round robin.

4.2 Reference devices for clients and partners

In 2018 ESTI calibrated a number of reference devices for clients and partners. Table 8 gives an overview. A short description of each case is given in the following sub-sections.

Table 8. Overview of ESTI calibration certificates for clients and partners under its ISO/IEC 17025 accreditation as calibration laboratory.

Client	ESTI job code	Number of calibration certificates issued
CENER (Spain)	DC-18-TY DC-18-UG	3 5
UCY (Cyprus)	DC-18-UE	2
PV Lab (Germany)	DC-18-UH	5
CSIR Energy Centre (South Africa)	DC-18-UM	2
EURAC Research (Italy)	DC-18-TQ DC-18-UQ	1 3
Loughborough University (UK)	DC-18-UO	5

4.2.1 CENER

JRC-ESTI has been providing PV reference cell calibration to CENER (the Spanish National Renewable Energy Laboratory) since the beginning of 2001. The work reported here was covered under a Memorandum of Understanding (MoU) as of January 2007. CENER uses these PV reference cells calibrated at ESTI to further calibrate PV devices for its clients. Hence, essentially ESTI provides the traceability chain for irradiance measurements (see section 2) to CENER and, through it, to its clients. This is in the framework of international harmonisation of PV device calibration and their traceability.

4.2.2 PV Lab

JRC-ESTI is collaborating with the German independent laboratory PV Lab in the field of PV solar energy for technology monitoring. This work is in support of the European Regions. ESTI provides PV Lab with traceable calibration of their PV reference solar devices, which are then used in their regional projects. This is in the framework of international harmonisation of PV device calibration and their traceability.

4.2.3 CSIR Energy Centre

JRC-ESTI is collaborating with the Council for Scientific and Industrial Research (CSIR) Energy Centre PV testing Facility, which is envisaged to be the premier PV research and testing laboratory in South Africa for the local provision of credible safety, reliability and performance measurements of PV modules and systems. CSIR will use PV reference devices calibrated at ESTI to further calibrate PV devices for its clients. Hence, also in this case ESTI provides the traceability chain for irradiance measurements to CSIR and, through it, to its clients. This is in the framework of international harmonisation of PV device calibration and their traceability.

4.2.4 Loughborough University

JRC-ESTI is collaborating with the Applied Photovoltaic Research Laboratory of the University of Loughborough in both material assessment, through measurements of PV performance, and technology monitoring. ESTI provides the University of Loughborough with traceable calibration of their reference PV devices, which are then used in their regional projects. This is in the framework of support to European universities for the traceability of solar irradiance measurements.

4.2.5 University of Cyprus

JRC-ESTI provides the University of Cyprus with traceable calibration of their reference solar cells and PV modules. This is in the framework of support to European universities for the traceability of solar irradiance measurements.

4.2.6 EURAC Research

ESTI is collaborating with the laboratory EURAC Research (based in Bolzano, Italy) in the field of PV solar energy for technology monitoring. This work is in support of the European Regions. ESTI provides EURAC Research with traceable calibration of their PV reference solar devices, which are then used in their regional projects. This is in the framework of international harmonisation of PV device calibration and their traceability.

5 Verification and validation of prototype PV devices

The ESTI laboratory also serves as an independent reference laboratory for the verification and validation of prototype PV devices, based on its experience and measurement capability. Since many years, ESTI co-authors the world record efficiency tables published twice a year in *Progress and Photovoltaics* [11, 12] and is one of the few world laboratories recognised as fully capable of independently verifying claims on exceptional performance of PV devices.

The most recent claim verified by ESTI occurred in 2018 and requests for two more concerning the emerging technology of perovskite (see also section 7.3.4) have been very recently received and will be reported in the future.

5.1 Co-authorship on world record PV efficiency tables

Based on the long term experience and the high level for PV device calibration at ESTI, it is currently co-author on the world record efficiency tables published twice yearly [11, 12]. Results submitted for inclusion in the tables are critically reviewed by the board of authors.

5.2 Innovative hybrid PV device

An innovative hybrid PV device, combining crystalline silicon technologies and a traditional thin-film technology was proposed and filed for patent. ESTI was asked by a potential investor to independently assess the electrical performance of the device for comparison with the manufacturer’s claims made. Prototype devices were delivered to ESTI, measurements made on them and the results provided to the contractor.

6 Deployment of knowledge

Thanks to the expertise and knowledge on PV built since its foundation, ESTI is regularly approached to help in the broadest dissemination of its knowledge, in particular when it comes to set up (also from scratch) and improve PV test laboratories, their ISO/IEC 17025 accreditation and/or their proficiency.

6.1 CSIR SA

Among these requests, in the course of 2018 a collaboration was agreed between the JRC and the Council for Scientific and Industrial Research (CSIR), Energy Centre PV Testing Facility, which established to support the development of solar technologies in South Africa. The facility is envisaged to positively contribute to the deployment of PV by providing support for local and national policy makers, as well as project developers and engineering, procurement and construction contractors.

In addition to the calibration services for the CSIR PV reference devices, thus providing traceability to the SI units as already described above, the JRC offered that ESTI could provide assistance in the following fields:

- CSIR preparation for ISO/IEC 17025 accreditation

  ESTI could share its approach to quality, procedures and objectives and help in determining the uncertainty calculations for specific tests that would be performed at CSIR, thanks to the many years of experience that ESTI has spent in operating under the ISO/IEC 17025 scheme. By this, ESTI is meant to help the CSIR Solar PV Testing Facility in setting up their ISO/IEC 17025 system, including hosting the quality officer from CSIR to discuss with ESTI quality officer.

- Training to IEC 60904, IEC 61215 and IEC 61853 international series of standards

  The ESTI laboratory could host members from the CSIR Solar PV Testing Facility for training in specifics of the individual IEC standards belonging to the above-mentioned series, due to the significant contribution ESTI staff gave to their development and improvement.

- Calibration of PV modules and participation in round-robin testing of PV modules

  ESTI could provide bi-lateral intercomparisons with the CSIR Solar PV Testing Facility, which would benefit from ESTI's unique traceability chain and from the full incorporation of the World Photovoltaic Scale (WPVS) into it. As previously outlined, such intercomparisons are required as benchmarking activity under the ISO/IEC 17025 scheme and would build confidence in the CSIR performance measurements of PV modules for both the South African accreditation body and all the clients of the CSIR Solar PV Testing Facility. At a later stage, ESTI could introduce the CSIR Solar PV Testing Facility to international round-robin testing through its extensive peer laboratory collaborations.

- Determination of measurement uncertainty for the I-V characteristics

  ESTI offers to provide guidance based on details of its own uncertainty methodology and calculations, also published in the scientific literature, using these as a good starting point for the determination of the final uncertainty of the I-V characteristics of the CSIR Solar PV Testing Facility.

6.2 Workshop with Politecnico di Milano

On Wednesday 14th November 2018 the third annual training workshop on the Integration of Photovoltaics in the Mediterranean Electricity Markets was held at the JRC premises jointly organised with the Politecnico di Milano. Some 50 participants from 14 Mediterranean and African countries representing utilities, energy purchasers, economists, local and national governments and administrations attended the workshop.

Presentations from JRC staff were made concerning

- The state-of-the-art of PV technologies;
- The situation of African PV deployment with particular emphasis on the Mediterranean countries;
- The applications and potential for the JRC PVGIS model to help planning deployment, management and monitoring of distributed installations;
- The role that international standards play in ensuring the reliability and quality of supply from renewable energy sources.

In addition an extensive tour of the dedicated facilities at the EST laboratory for characterisation and verification of PV technologies was a key feature for the participants.

7 Pre-normative research

The ESTI laboratory is involved in a variety of activities which can be classed as pre-normative research. On the one hand, measurement methods and procedures are investigated, either by devising new approaches or by improving upon existing ones. On the other hand, new and emerging PV technologies are also investigated from a metrological point of view. Often these devices have particular properties, which may lead to artefacts and unreliable results when conventional measurement techniques are applied. Therefore, the actual interaction between the devices under test and the procedures to measure them is investigated aiming at finding solutions for reliably achieving correct and reproducible results.

7.1 Measurement methods

ESTI has been partner in two EURAMET-founded metrology projects. The first was the ENG55 "PhotoClass" [29], which started in 2014 and ended in 2017, and the second, the "PV-ENERATE" [30], is one born from the knowledge foundation set in the previous project and is running since 2017 until 2020. In particular PhotoClass investigated several metrological aspects for the energy rating of PV devices. Some of the ESTI research continued also after the end of the project under institutional funding and is being included, for example, in the improvement of some of the IEC standards that are currently under revision with JRC-ESTI leadership.

7.1.1 Temperature coefficients (TCs)

The correct temperature measurement of the PV device and the dependence of the DUT electrical performance on temperature is the second most important parameter for evaluating the PV device energy rating, the most important being the total irradiance (already dealt with extensively above). During the PhotoClass project, ESTI extended its TC measurement capabilities in both temperature range and usable set-ups [31], so that state-of-the-art facilities are now available for PV devices ranging from reference cells to full-size PV modules.

7.1.1.1 Intra-laboratory validation of ESTI TC measurements and procedures

Traditionally, the TCs were measured at ESTI with a pulsed solar simulator (in this validation labelled GPS) where the DUT was enclosed in a thermally-isolated cabinet with a glass front door. The internal temperature of the cabinet was increased by electric resistive heating. This approach had a couple of drawbacks; firstly, the relative long time required to achieve temperature stabilisation and thus to complete the measurement of one device (typically just under a day), and secondly the relatively poor spectral irradiance of the solar simulator that was necessarily leading to significant additional contributions in the measurement UC, as the spectral mismatch of most typical PV devices (crystalline silicon) changes with temperature but could not be corrected for with this facility and procedure due to difficulties in reliably measuring such poor spectral irradiance.

This issue had been successfully overcome before PhotoClass by implementing TC measurements under natural sunlight. However, the outdoors conditions under which a TC measurement can be easily and rapidly achieved are limited during the year. Therefore, during the PhotoClass project the same approach developed for the outdoor system was implemented and validated at the unique large-area steady-state solar simulator present at ESTI (APOLLO). Furthermore, the TC measurements were implemented also at the steady-state solar simulator (WACOM) dedicated to reference cells calibration, through a procedure specifically developed for it [31]. In the case of continuous (natural or simulated) sunlight, the heating is achieved and controlled by using the incident irradiance itself, a procedure that leads to typical measurement times of about 20 minutes, so that several devices can be measured on the same day one after the other. The spectral irradiance of the natural sunlight is almost perfectly matched to the reference spectrum under permissible measurement conditions, so that all uncertainties due to spectral mismatch are negligible [31]. The APOLLO steady-state solar simulator available at ESTI has a much better spectral match than the GPS solar simulator, thus reducing the spectral mismatch contribution to the measurement UC. After the methods were fully implemented, an extensive intra-laboratory validation was carried out [31] with the use of E_n number assessment, keeping the outdoors results as reference due to the closer measurement conditions to the reference spectrum. Table 9 shows the three principal TCs for a series of devices (from reference cells to PV modules) measured on all possible systems available at ESTI for each type of device. The detailed analysis with E_n numbers (not shown here) showed that all methods yield equivalent results and therefore are fully validated for use.

Table 9. Results of the determination of TCs (α for short-circuit current, β for open-circuit voltage and δ for maximum power) for a range of PV modules and cells obtained by various measurement set-ups at ESTI including the measurement uncertainties.

Device	Setup	α [%/K]	UC α [%/K]	β [%/K]	UC β [%/K]	δ [%/K]	UC δ [%/K]
ADX00	OUTDOOR	0.0568	0.0129	-0.3548	0.0765	-0.4631	0.0776
	GPS	0.0853	0.0576	-0.3543	0.0223	-0.4233	0.0618
	APOLLO	0.0517	0.0152	-0.3291	0.0287	-0.4268	0.0324
GC01	OUTDOOR	0.0526	0.0129	-0.3501	0.0765	-0.4696	0.0776
	GPS	0.1176	0.0576	-0.3639	0.0223	-0.4157	0.0618
	APOLLO	0.0518	0.0152	-0.3319	0.0287	-0.4360	0.0324
ZZ71	OUTDOOR	0.0425	0.0129	-0.3510	0.0765	-0.4678	0.0776
	GPS	0.0771	0.0576	-0.3535	0.0223	-0.4199	0.0618
	APOLLO	0.0318	0.0152	-0.3225	0.0287	-0.4332	0.0324
TD81	OUTDOOR	0.0621	0.0129	-0.3418	0.0765	-0.4677	0.0776
	GPS	0.0943	0.0576	-0.3471	0.0223	-0.4289	0.0618
	APOLLO	0.0612	0.0152	-0.3427	0.0287	-0.4624	0.0324
AY81	OUTDOOR	0.0589	0.0125	-0.3121	0.0765	-0.2386	0.0776
	GPS	0.0659	0.0071	-0.3234	0.0223	-0.2045	0.0234
	APOLLO	0.0668	0.0072	-0.3130	0.0287	-0.2292	0.0296
NUF2	OUTDOOR	0.0450	0.0060	NA	NA	NA	NA
	GPS	0.0782	0.0575	NA	NA	NA	NA
	APOLLO	0.0493	0.0147	NA	NA	NA	NA
PX305C	OUTDOOR	0.0401	0.0060	NA	NA	NA	NA
	GPS	0.0654	0.0575	NA	NA	NA	NA
	WACOM	0.0470	0.0144	NA	NA	NA	NA

The validated methodologies were approved by the accreditation body that delivers to ESTI its ISO/IEC 17025 accreditation certificate as calibration laboratory and it was included in the flexible scope of ESTI accreditation scheme in 2016. The advanced UC calculation done for this validation also improved the ESTI best measurement capability for TC measurements, as it proved that some UCs were overestimated and could be (and actually were) reduced.

7.1.1.2 PhotoClass round-robin of TC measurements

The next step was to compare the TC measurements with peer laboratories. Such comparisons have historically been sparse in the PV community and when reported had shown significant inconsistencies. In the more recent PhotoClass RR, on the other hand, a full consistency between all participants was found for the TC of the short-circuit current and for several devices of very different size and PV technology [32]. Figure 15 shows the RR results including their uncertainties for the six participants (amongst them ESTI), which already visibly are consistent. This was again confirmed by E_n number analysis (not shown here). This is significant improvement over previously published results. Work is already in progress at ESTI to extend this achievement to the TCs of short-circuit current, open-circuit voltage and maximum power for a range of full-size PV module technologies.

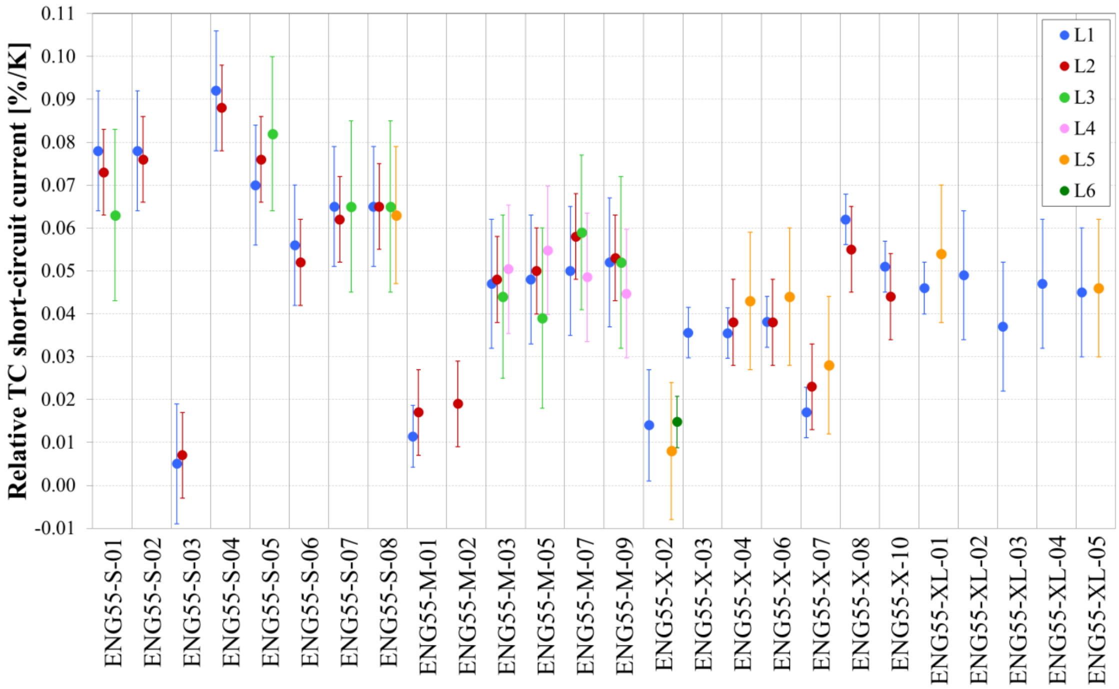

Figure 15. Comparison of the results for TC of I_{sc} in the PhotoClass round robin.

7.1.1.3 Building integrated PV: towards higher temperatures

In building integrated PV (BIPV), the PV devices may reach higher temperatures due to the reduced natural cooling as a consequence of the building integration. Therefore, it is important to extend the temperature range beyond the 75 °C limit required by the standard IEC 61853-1 for the conventional power matrix [33]. ESTI was able to extend the measurement range on the APOLLO solar simulator under specific conditions and within a reasonable measurement time well above this temperature, currently up to 85 °C. Figure 16 shows on the left examples of measured current-voltage characteristics at three different temperatures and on the right the maximum power over the full temperature range 25 °C to 85 °C. From this the TC δ is extracted as slope of the linear fit that is built on the measured data set.

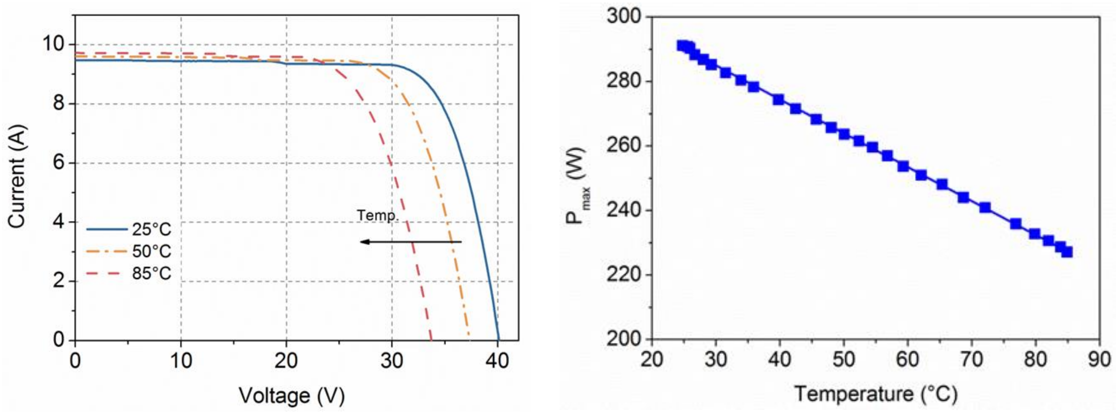

Figure 16: Characterisation of PV module over extended temperature range: current-voltage characteristics at three different temperatures (left) and TC of maximum power (right).

7.1.2 Linearity

The concept of linearity of a PV device is usually used within the PV community as synonym of the proportionality of the PV device short-circuit current with respect to the incident irradiance, even though the IEC standard that derives its name from it deals also with more general linear dependences (e.g. linear dependence of maximum power on temperature, as shown just above). This is of importance as PV reference devices are calibrated at STC, which correspond to an irradiance of 1000 W/m^2, but are then used to measure for example the power matrix [33] at irradiances between 100 W/m^2 and 1100 W/m^2. Deviation of the short-circuit current of the reference device from the proportionality to the incident irradiance will directly contribute to measurement uncertainty.

7.1.2.1 JRC project leader IEC 60904-10

The linearity of PV devices is defined and assessed in the IEC 60904-10 [34]. The current ed. 2 has some shortcomings. The first and more important for the correct measurement of PV devices at any irradiance other than 1000 W/m^2 is that the linearity, as intended by the common practice and use in PV mentioned above, is not defined as proportionality but rather as a generic linear relationship that applies as such to many dependences of the electrical parameters (such as short-circuit current or maximum power) on the environmental parameters (such as irradiance or temperature). Secondly, one method allowed to assess the linearity of short-circuit current towards irradiance, namely the two-lamp method, is only described experimentally without the required data analysis to obtain information from it that could be useful and above all comparable to the other methods allowed by the same standard. Therefore, the IEC 60904-10 is currently under revision and the (technical) project leadership has been assigned to ESTI.

7.1.2.2 Linearity Round Robin

Dealing with energy rating of PV technologies, the PhotoClass project included a RR intercomparison on linearity measurements [35].The APOLLO solar simulator at ESTI, which consists of 11 equivalent lamps that can be controlled individually in power and shuttering, was used to verify and include the two-lamp method in the RR. In order to do this, ESTI had also to develop the missing data analysis (see 7.1.2.3) so to compare its own results to those obtained by the other participants, who used other independent methods including SR. In general, a certain scatter of results between all participants was observed, partly coupled with relatively large measurement uncertainties (see one example in Figure 17). The data are not fully consistent, which is currently subject to further investigation. However, it is noted that the results from the two-lamp method are in fact in between those of the other methods.

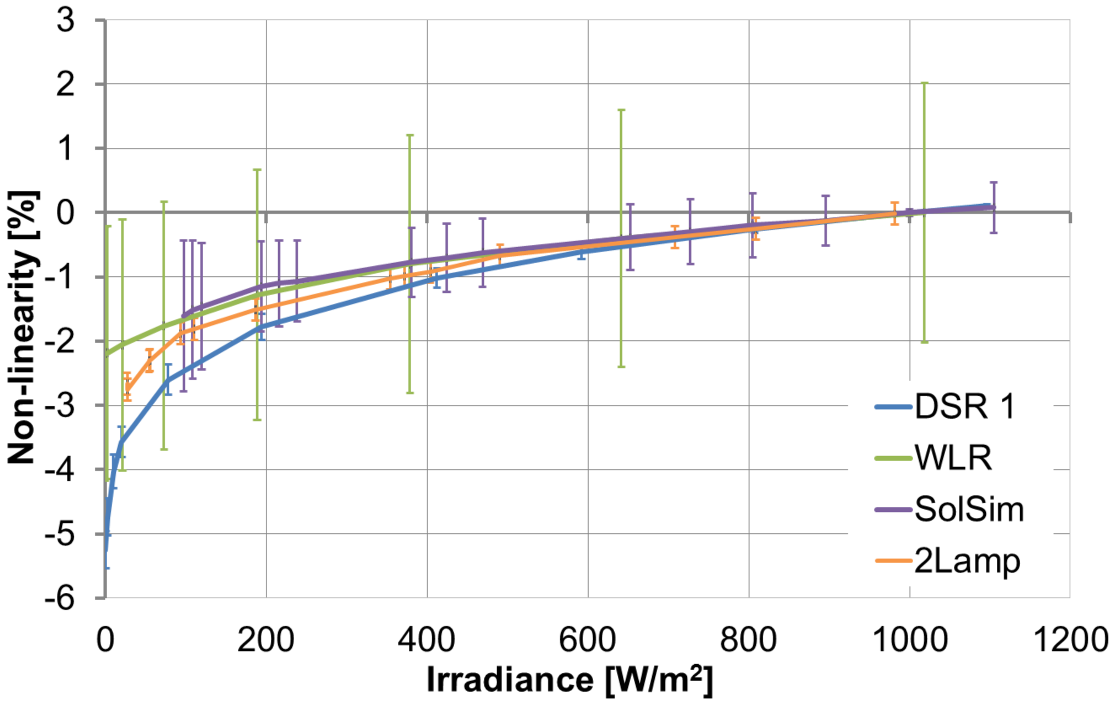

Figure 17. Comparison of the results for non-linearity of a PV reference cell obtained by various methods in the PhotoClass round robin. The data for the two-lamp method (2Lamp) were obtained by applying the analysis reported in 7.1.2.3.

7.1.2.3 ESTI improvement of the two-lamp method

The PhotoClass RR on linearity measurements gave the possibility to ESTI to develop the necessary data analysis to compare results from the two-lamp method (basically applied only at NREL and as simple pass/fail test) to all other methods allowed by the standard IEC 60904-10 [34]. This subsection aims to giving some additional information on this achievement, although without giving full details that can be found in the literature references given in this whole section.

The plain application of the two-lamp method as currently described in IEC 60904-10 ed. 2 [34] to a reference cell that in the PhotoClass RR was known to be non-linear (Figure 17) yields the upper data points (blue diamonds) in Figure 18. During the PhotoClass project, ESTI has implemented this method on the APOLLO solar simulator. A completely new data analysis had also to be developed to combine the local non-linearities to a global non-linearity, shown as the lower curve (with red dots) in Figure 18 [36]. This produced the advantage that the results from the two-lamp method can now be compared directly to all other methods and thereby checked for consistency.

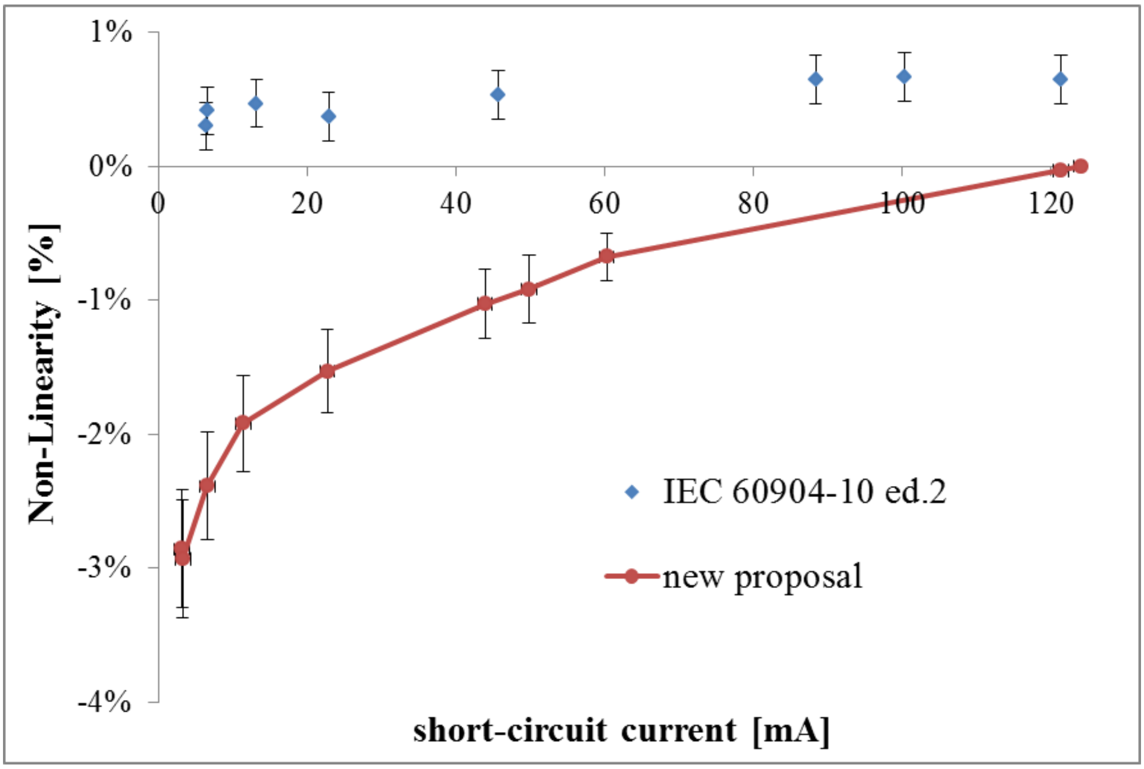

Figure 18. Comparison of the results for non-linearity of a PV reference cell (same device as in Figure 17) according to current standard IEC 60904-10 ed.2 and the proposal for data analysis as developed at ESTI.

7.1.2.4 Towards the N-lamp method

The two-lamp method is very attractive as it is simple to implement, it provides measurement results in relatively short time (less than one day per device) and is a primary method, i.e. it does not require any reference device nor *a priori* knowledge about the DUT. Therefore, ESTI is working to further develop the scheme towards what it calls the "N-lamp method", which is ideally and naturally suited to determine the non-linearity of PV devices on the APOLLO solar simulator [37], as well as on any other set-up where more than two light sources are available. The final significant result is detailed non-linearity information over the entire irradiance range of interest in PV (from 100 W/m^2 to 1100 W/m^2) in steps of roughly 100 W/m^2 (as would be very useful for the power matrix measurements [33], for example). Figure 19 shows the irradiance dependence of the parameter R that has been introduced into this advanced methodology and strictly linked to the non-linearity of the PV device. Furthermore, the procedure and data analysis developed for the N-lamp method would reduce significantly the measurement UC (compare Figure 19 to Figure 18 which are for the same devcie). Most importantly this quantitative information about linearity can be used to quantitatively correct measurements for the effects of non-linearity via the parameter R, in the same way a correction is made for the spectral mismatch factor according to the IEC 60904-7 [38]. The uncertainty of the correction is more than ten times less than the actual effect in the example shown.

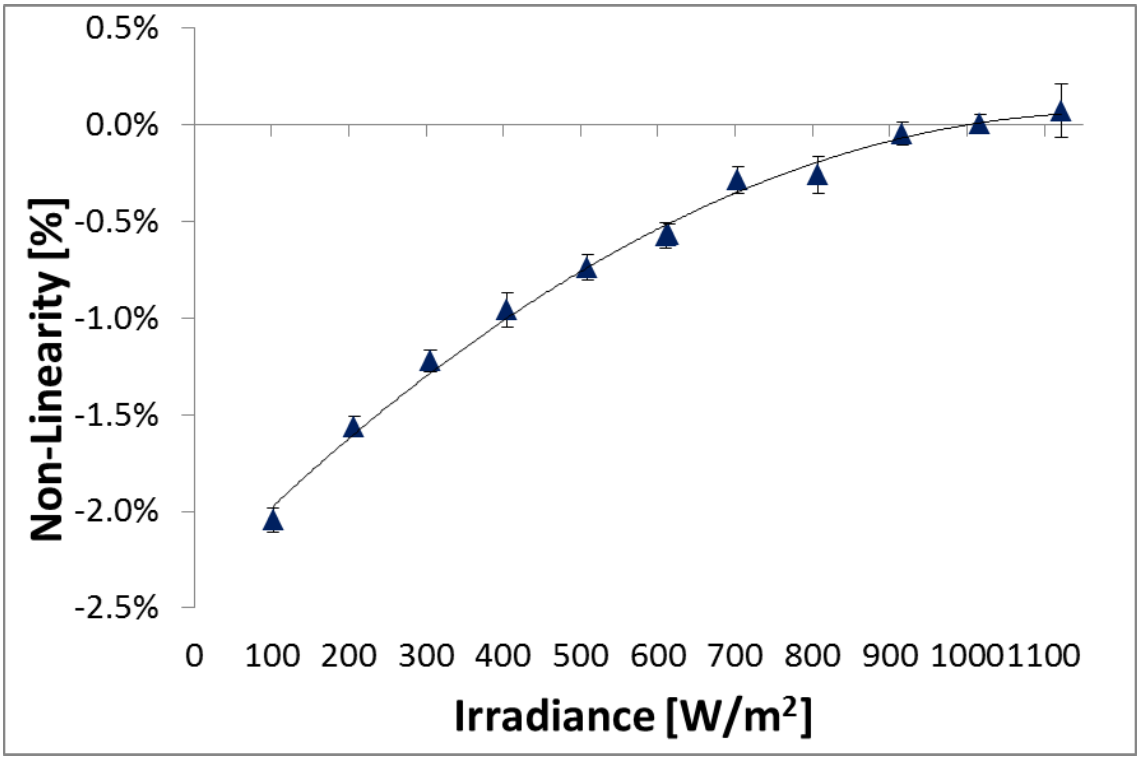

Figure 19. Comprehensive determination of PV device non-linearity with the N-lamp method on the same device as for Figure 17 and Figure 18.

7.2 Bifacial PV devices

The market share of bifacial crystalline Si PV modules has grown significantly over the last years, because they can produce additional output energy in comparison to conventional (monofacial) PV modules. This is achieved by the fact that both sides of the PV module, front and rear, are exposed to solar radiation and can thus absorb it, also utilising the light scattered from the ground and surroundings on the back side of the module. The International Technology Roadmap for Photovoltaic (ITRPV) anticipates that the bifacial concept is expected to grow to a 10% market share in 2018, 15% in 2020 and to gain close to 40% market share in 10 years [39].

There is little additional effort required to turn an advanced crystalline silicon cell architecture into a bifacial PV device. The main bifacial cell technologies are passivated emitter rear cell (PERC), passivated emitter rear locally-diffused (PERL), passivated emitter rear totally-diffused (PERT) and based on heterojunction with intrinsic thin layer (HIT) and different subsection, depending on the employed materials and production tools. For a PV module to become bifacial, the rear cover must be made of transparent material, for example glass or transparent plastic backsheets [40].

Currently, there is no international standard for measuring the I-V characteristics of bifacial modules. However, the draft technical specification IEC TS 60904-1-2 developed at the IEC TC 82 specifically on this type of devices is currently close to its publication [41] (due early 2019).

Along with the development of the IEC technical specifications, different approaches have been developed and proposed for indoor [42, 43, 44, 45, 46, 47] and outdoor (under natural sunlight) [48, 49] measurement of bifacial PV devices (cells and modules). They are schematically summarised in Figure 20. Most of them were finally included in the draft IEC technical specification and all of them have been tested also at ESTI.

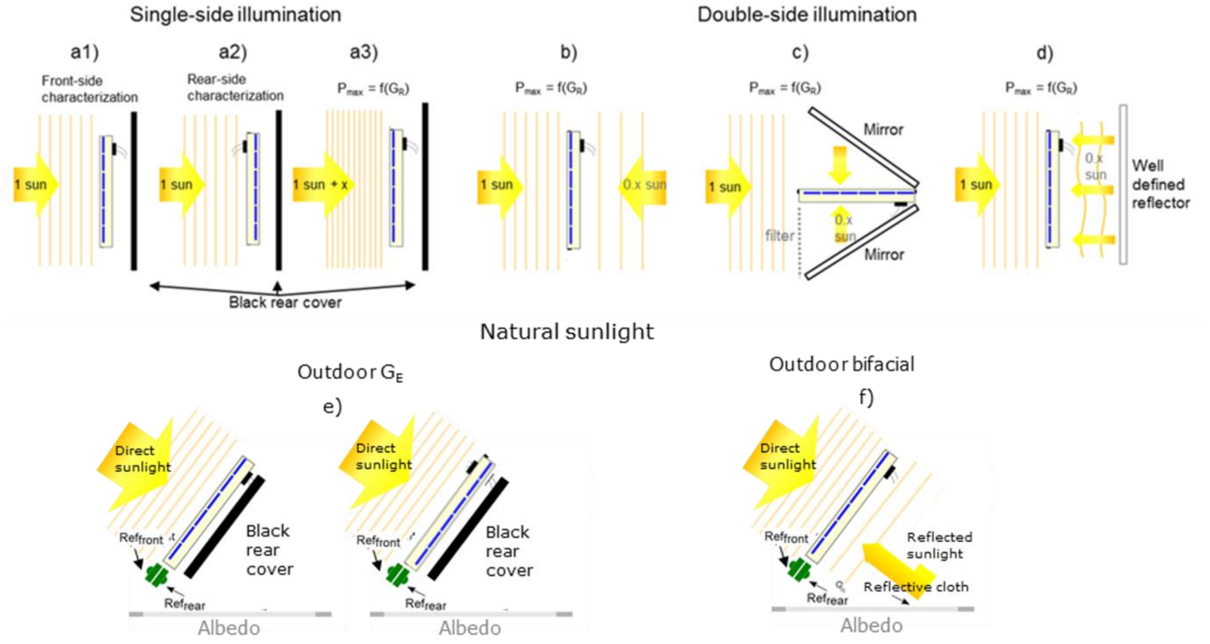

Figure 20: Schematic representation of the different approaches proposed for the bifacial PV modules testing (single-side illumination methods: indoor a1, a2, a3 and b) and outdoor e); double-sided illumination methods: indoor c) and d) and outdoor f)).

7.2.1 IEC TS 60904-1-2

ESTI was member of the project team to develop the technical specifications IEC TS 60904-1-2 [41], which is due to be published early 2019.

7.2.2 Indoor set-up

The most convenient measurement for bifacial PV devices is indoors as the environment can be controlled more easily than outdoors.

7.2.2.1 Single-side illumination: equivalent irradiance method

The first verified indoor approach is based on the individual measurement of both sides of the device at STC (Figure 20 a1 and a2) by means of a single-sided illumination or single-source solar simulator with adjustable irradiance level (both pulsed or continuous large-area solar simulators) and this is currently the most used method for characterisation of bifacial PV modules [50, 51]. As for all high-efficiency PV modules, also for bifacial PV modules the capacitance effects can show up and as such should be managed (see section 4.1.1).

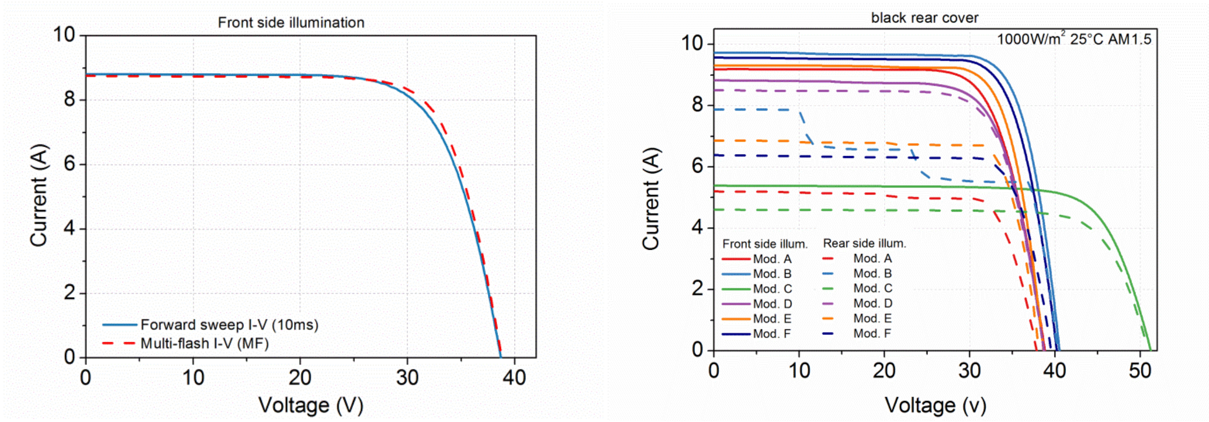

Figure 21: I-V curve of a bifacial PV module measured with single-flash forward sweep and with MF method using a pulsed solar simulator (left). Front and rear-side I-V curves of commercially available bifacial Si PV modules measured with MF method in a pulsed solar simulator. Note the different bifacialities and the kinks in the rear side curves due to partial self-shading on the rear due to junction box, label and frames.

Figure 21 (left) shows the I-V curves of a typical bifacial PV module measured at ESTI with usual single flash (10 ms) and with multiflash (MF) methods at the same pulsed solar simulator. In general, for commercial modules, a difference of 2% to 3.5% is obtained. During these measurements, the side of the module not facing the solar simulator was covered by either a non-reflective or a black absorbing material in order to reduce the back-reflected light. The I-V curve of the illuminated side is then measured (first front side and subsequently rear side). The right plot in Figure 21 shows the front-side and rear-side I-V curves of commercial bifacial PV modules measured at ESTI under STC with a black cover on the rear side.

The bifaciality characteristics of such PV devices refers to the ratio between the main I-V characteristics of the rear and front side, typically at STC. This has been quantified with reference to bifaciality coefficients for the short-circuit current, φ_{Isc}, the open-circuit voltage, φ_{Voc} and the maximum power, φ_{Pmax}. The latter is defined as:

$$\varphi_{Pmax} = \frac{P_{\max \text{Rear}}}{P_{\max \text{Front}}}$$

where $P_{maxRear}$ and $P_{maxFront}$ are the module maximum power measured when illuminating only the rear and the front side at STC, respectively. The coefficients are usually expressed as percentages. The bifaciality factors are calculated and then the measurement at equivalent irradiance level can be performed as defined in the IEC TS 60904-1-2 (Figure 20 a3). Figure 23 and Table 10 show the measurements and data of measured maximum power at STC and equivalent irradiance levels for a representative bifacial module.

7.2.2.2 Double-sided illumination

The second approach is based on the simultaneous illumination of both sides of the bifacial device with 1000 W/m^2 on the front and at least two consecutive different rear side irradiance levels. Different set-ups were considered including the measurement with a double-source solar simulator (Figure 20 b), tilted mirrors (Figure 20 c) [46, 47, 52] or by using a diffuse reflector with known reflectivity placed at a specific distance behind the module (for example, a reflective white rear sheet as shown in Figure 20 d).

7.2.2.2.1 Reflective rear panel

This setup (Figure 22) allows for a simultaneous measurement of both sides with a single flash from the front and consists on a reflective rear surface parallel to the module [45, 53, 54]. However, it shows several problems such as rear irradiance non-uniformity, need of the specifications of the reflector's material and positioning which would result in a difficult implementation.

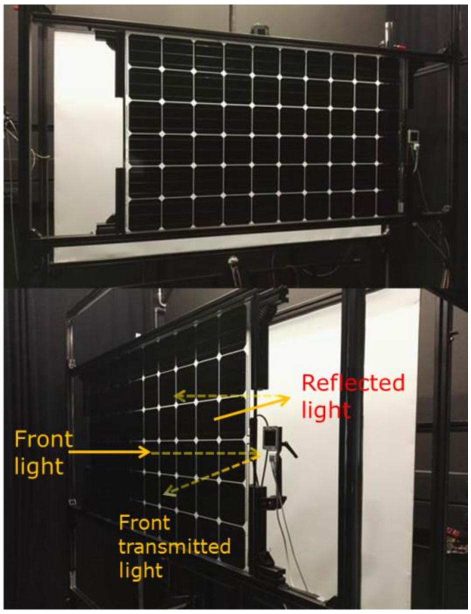

Figure 22: Experimental setup for double-sided illumination using a well-defined reflector on the rear.

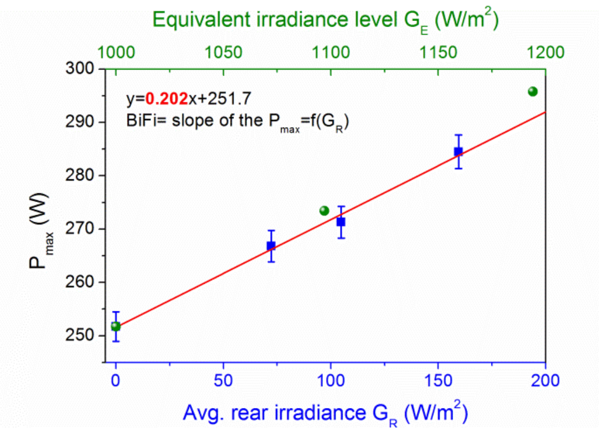

Figure 23: P_{max} as a function of average irradiance level on the rear side G_R (for double-side illumination) and its single-side equivalent irradiance. The red line is the linear fit of the values and the green circles are the measured values at equivalent irradiance level of 100 and 200 W/m^2.

Table 10. Output power values measured with single-side equivalent irradiance level method (P_{max} G_E) and with a double-sided illumination method using reflective rear panels (P_{max} $BiFi_{GR}$).

φ (%)	G_R (W/m²)	G_E (W/m²)	P_{max} G_E (W)	P_{max} $BiFi_{GR}$ (W)	ΔP_{max} (%)
98	0	1000	251.7	251.7	+0
	100	1098	273.4	271.9	+0.5
	200	1196	295.8	292.1	+1.3

Despite a high rear-side irradiance non-uniformity around 20% on average for full-size modules (10% for mini-modules), higher than the technical specification requirement for double-sided illumination, similar results for P_{max} are obtained with respect to the single-side equivalent irradiance method [55]. This result agrees with previously reported works that showed that the non–uniform irradiance affects I_{sc} and the voltage region from 0 to V_{mpp} but to a much lesser extent the $P_{max.}$ The suitability of this method for the measurement of bifacial PV Modules need to be confirmed with more tests in different module types and the rear-side irradiance should be improved by mean of new designs and materials of the rear reflector.

7.2.2.2.2 LED simulator

The setup consisting of a double-source solar simulator is considered in the draft technical specification IEC TS 60904-1-2 as a suitable method for double-sided illumination. However, this approach presents some problems at the PV module scale such as the logistics of timing two flashes, controlling the reflection from the environment and the added cost of using two controlled light sources instead of one [43, 45].

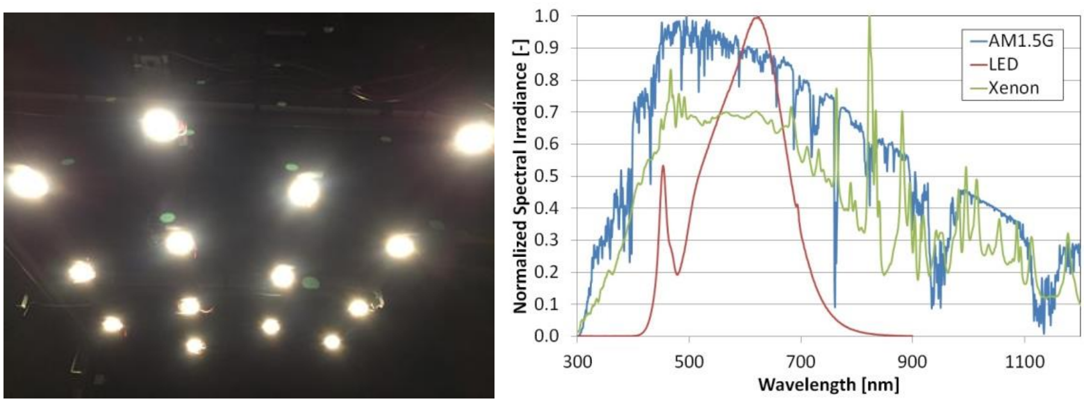

Figure 24: Prototype of LED solar simulator (right) and Solar spectrum AM1.5G, spectrum of the 4000K LED simulator at 350 W/m2 and spectrum of a xenon Class AAA solar simulator at 1000 W/m².

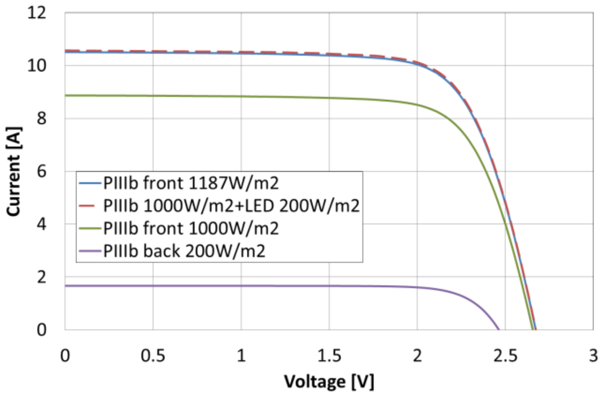

Figure 25: IV curves measured with the equivalent irradiance single-side method and double-side illumination method. Front side only at STC and rear side at 200 W/m^2 IV curves are also shown for reference.

The prototype LED simulator developed at ESTI (Figure 24) has demonstrated very good performance, enabling illumination of the rear side of a bifacial module at variable light levels to above 300 W/m^2. When combined with a commercial Class AAA pulsed solar simulator for the characterisation of a bifacial mini-module, double-side illumination produces similar results to those obtained with the Class AAA solar simulator using equivalent irradiance and single-side illumination (<1% difference). The non-uniformity below 5% means it meets the requirements of draft IEC TS 60904-1-2 [41] for use with bifacial modules. The spectral match to AM1.5G is outside Class C, but this may be compensated by a mismatch correction, or using the effective irradiance method. The uniformity of the LED simulator may also be readily adjusted, by changing the geometry or by varying the powering of individual LEDs, which may enable the performance of bifacial modules to be evaluated over the full range of outdoor conditions. The modular simulator design means that extension of the area to allow measurement of full size 60-cell modules will be straightforward and at low cost. Further details can be found in [56].

7.2.3 Outdoor set-up

Two outdoor approaches have been proposed consisting of an outdoor single side illumination with equivalent irradiance levels measurements (Figure 20 e) [49] similar to the indoor method and a double-side illumination with reflective cloth or surfaces in order to change the albedo from the ground included in the draft technical specification IEC TS 60904-1-2 (Figure 20 f) [41, 48]. Basically, in the latter method, besides the STC measurement at 1000 W/m^2 (G_R = 0 W/m^2), AM1.5G and 25 °C, P_{max} of the module shall be measured at 1000 W/m^2 ± 10% on the front side (or corrected to this value), plus different rear side irradiance levels G_{Ri} (i=1, 2 ,3…, for instance, G_{R1} < 100 W/m^2, 100 W/m^2 < G_{R2} < 200 W/m^2 and G_{r3}> 200 W/m^2). [57]

The Outdoor set-up for measurement of bifacial PV modules is shown in (Figure 26), where white stones have been placed on the surroundings to increase the albedo. Also indicated are the positions of 9 irradiance sensors on the rear side used to determine the uniformity of the rear side irradiance. The draft technical specification IEC TS 60904-1-2 requires that the rear side irradiance uniformity is better than 10%. This has been found to be achievable under certain conditions and certain times of day (see Figure 27**).**

The Current-voltage characteristics of a 4-cell mini-module have been measured both indoors and outdoors in order to compare the results for both single sided illumination and double sided illumination (Figure 28). The current is normalised to the value of the indoor measurement at 1000 W/m^2. Indoor and outdoor measurements are found to agree closely for both the single sided illumination and double-sided illumination cases, demonstrating that the outdoor method can be usefully performed as long as rear side uniformity is below 10%.

Figure 26: Outdoor set-up for measurement of bifacial PV modules.

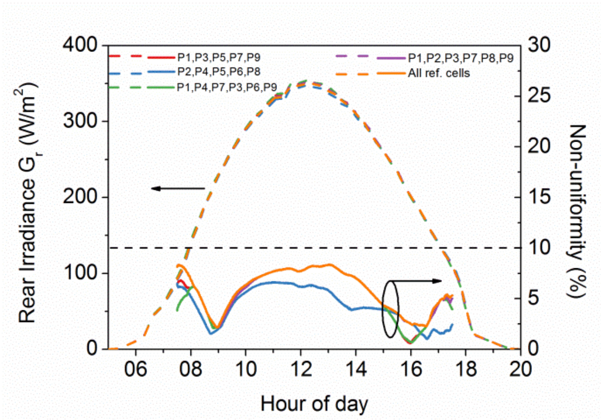

Figure 27: Variation during the day.

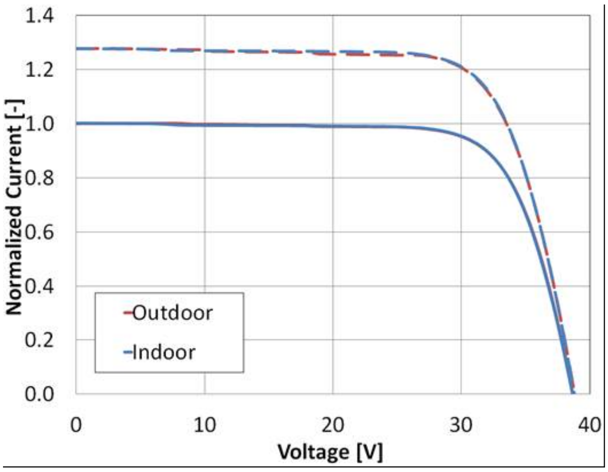

Figure 28: Current-voltage characteristics.

7.3 PV devices: Emerging technologies

7.3.1 IEC TR 63228: standardisation activity on emerging PV technologies

In the pre-normative context ESTI participated in an international group of experts working on the preparation of a document containing guidelines for assessing emerging PV technologies. The main aim was to reach broad consensus with other internationally accredited laboratories on measuring efficiencies of these devices. A contribution to the definition of best-practice methods for the measurements of emerging PV devices has been given through the preparation of a new IEC Technical Report on the "Measurement Protocols For Photovoltaic Devices based On Organic, Dye-sensitized Or Perovskite Materials", has been voted positively and will be published in 2019.

7.3.2 Organic PV: calibration and power matrix of large-area organic PV modules and mini-modules from two different manufacturers

The main objective of these collaborations was to receive devices to characterize at ESTI (following the protocol developed previously [58]) and to improve the measurement protocols of both parties. An initial STC calibration of the devices at a solar simulator and a subsequent energy rating study based on indoor power matrix measurements has been initiated and currently running according scheduling (Figure 29).

The manufacturers are two European companies working in the organic PV sector. The devices are roll-to-roll printed organic PV (OPV) devices based on different new organic materials. The modules have an area of 30x200 cm^2 and 24 cells in series. The smallest mini-modules have area 10x15 $cm^2$and 8 cells in series.

The results of the measurements of these devices have been presented in a series of conferences and papers:

- EU PVSEC 2017: "Power matrix measurements and energy rating analysis of organic PV mini-modules" [59];
- EU PVSEC 2018: "Indoor Calibration of Large Area Organic PV Modules" [60]
- SEPV 2018: "Energy rating study of three different organic PV devices in five different climatic conditions: a comparative study with other PV technologies"

Currently the large area OPV module under study has been setup outdoor under natural sunlight and I-V curves are repeatedly measured during the day every 5 minutes. An energy rating study of this device kept outdoor at different weather conditions is the main aim of this experiment. Periodically (once a month) an STC calibration of the device is performed indoor under solar simulator illumination in order to study the long term stability.

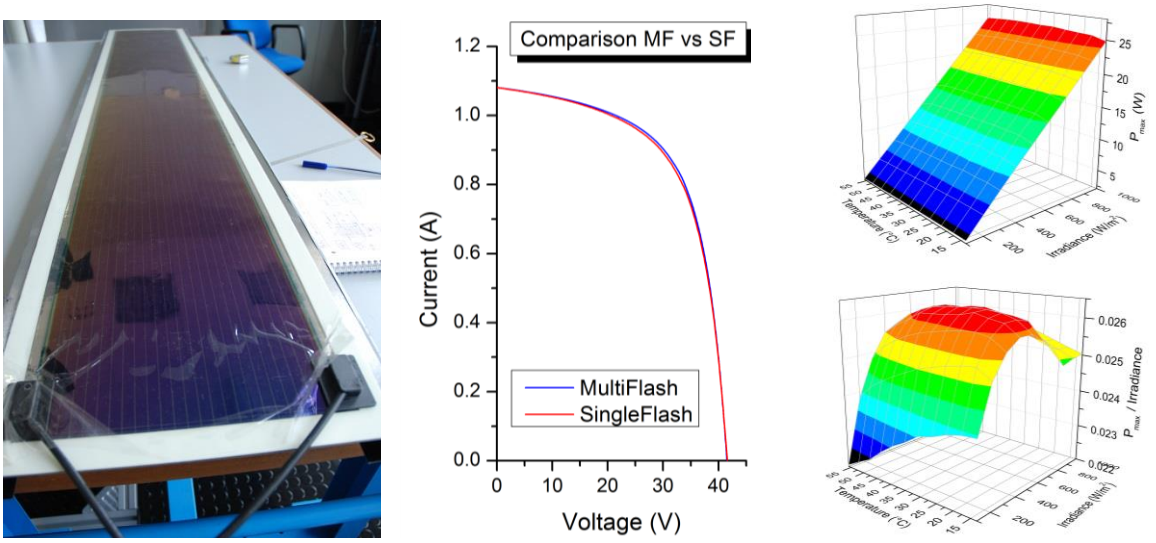

Figure 29: Picture of one large-area module under test, comparison of single flash and multiflash (MF) I-V curves, and plot of the power matrix measurements

7.3.3 Large-area dye-sensitized semi-transparent modules

The main objective of this collaboration was to test our internal protocol for the calibration of innovative PV devices, in particular the ones possessing a long response to a light pulse i.e. dye-sensitized solar cells (DSSC). In this case standard protocols cannot be applied and new procedures need to be adopted. Previous work was performed in our laboratory with small 1x1 cm^2 DSSC. In this case we worked with a large area module of the same technology (Figure 30).

The manufacturer is one company from Switzerland working in the DSSC PV sector. The device under test is a screen-printed DSSC PV large area semi-transparent module with an area of 30x200 cm^2 and 24 cells in series. The measurements performed at ESTI consisted of a study of the time response of the device and subsequent calibration at STC indoor under continuous large area solar simulator. A protocol developed internally for the calibration of emerging PV devices in general and specifically for DSSC was tested in this case. The results have been summarised in a JRC technical report (JRC112321) and discussed with the company in a bilateral meeting.

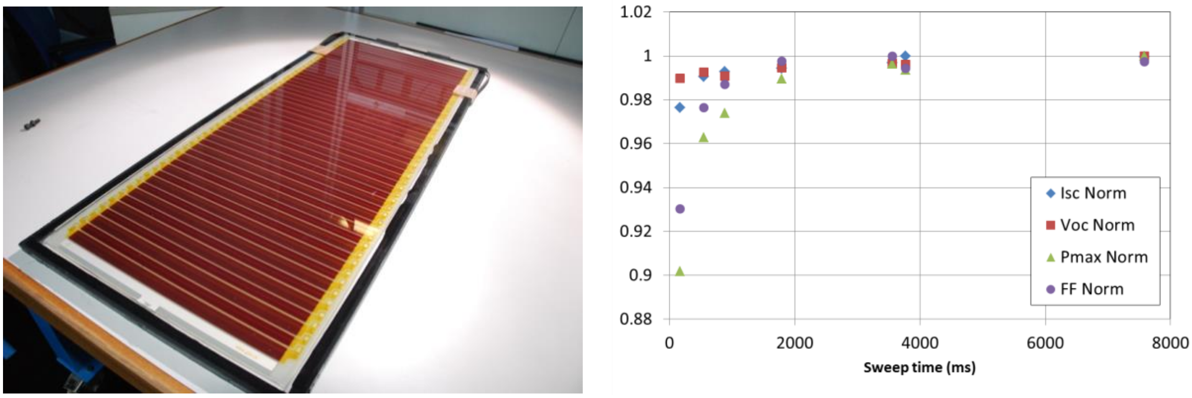

Figure 30: Picture of the large area module under test and analysis of the electrical parameters dependence from the sweep time in I-V curves.

7.3.4 Perovskite solar cells: test before calibration, light soaking and stability

The main objective of this collaboration was to evaluate the contributions affecting the calibration of perovskite solar cells and propose solutions on how to better control them in order to improve the quality of the results, ensure more reliable power measurements and contribute to the development of new measurement protocols (Figure 31).

The manufacturer of the perovskite solar cells under test is one research centre from Netherland working in the perovskite PV sector. The cells were prepared on glass-glass substrate and have an active area cell 1x1 cm^2. The measurements performed at ESTI on these devices consisted of an initial evaluation of the time response under continuous light exposure and the optimization of the parameters for I-V sweep. Subsequently the effect of holding the cell at V_{oc} or I_{sc} for different time before performing the I-V sweep was studied and considerable differences in the I-V curves observed. Finally the short time stability of the performances under continuous illumination and their recovery in the dark were analysed. The results of the measurements of one of these devices have been presented in a conference (SEPV 2018 conference – Stability of emerging photovoltaics from fundamental to application).

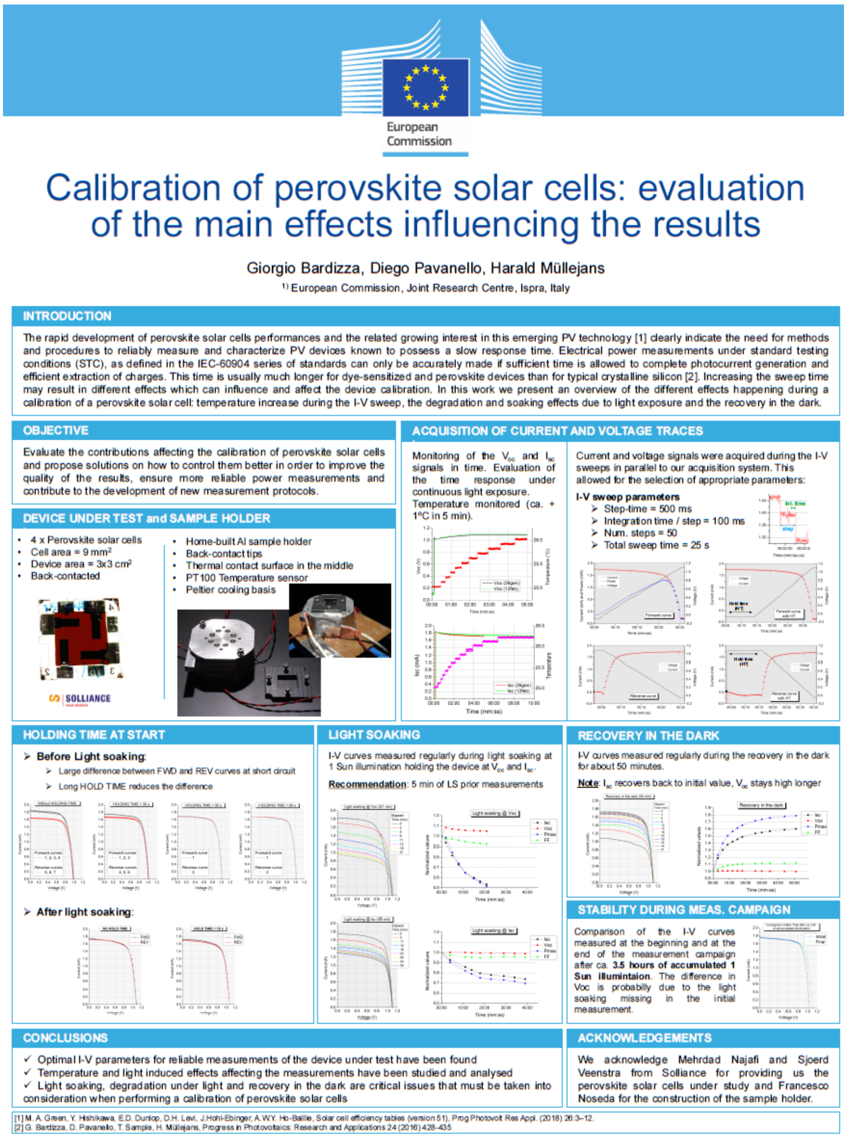

Figure 31: Poster presented at the SEPV 2018 conference (Stability of emerging photovoltaics from fundamental to application).

8 Conclusions

Benchmarking, intercomparisons and proficiency tests have a crucial role to play in maintaining and improving the measurement techniques for solar irradiance and electrical performance of PV devices and to promote transfer knowledge to the European PV research community. Moreover, periodical intercomparisons are part of performance-based quality-control checks for a calibration laboratory as ESTI working according to ISO/IEC 17025 and also highly recommended by the World Meteorological Organization.

Since many years, and confirmed also for 2018, ESTI has played a leading role in intercomparisons for spectroradiometers, pyrheliometers and PV devices with international and European organisations from scientific as well as industrial sectors. ESTI has provided PV device calibration and connection to the PV traceability chain for clients and partners, has validated new PV technologies, has developed and/or improved new measurements methods for existing and emerging PV technologies. All this finds its final practical outcome and broadest out-reach activity in the application of what is developed and/or validated at ESTI into their standardisation in international standards for PV, as discussed in the Science for Policy Report [61].

Overall, the described activities underline the standing of ESTI as a true reference laboratory for the assessment of electrical performance of PV devices.

List of abbreviations and definitions

AIST	National Institute of Advanced Industrial Science and Technology, Japan
AIT	Austrian Institute of Technology, Austria
AM	Air mass
ARC	Anti-Reflective Coating
BIPV	Building Integrated PV
CEA INES	Alternative Energies and Atomic Energy Commission, National Solar Energy Institute, France
CENER	National Renewable Energy Centre, Spain
CIEMAT	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, Spain
CSIR	Council for Scientific and Industrial Research, South Africa
CV	Calibration Value
DSM	Direct Sunlight Method
DSR	Differential Spectral responsivity
DSSC	Dye Sensitized Solar Cell
DTU	Denmark Technical University, Denmark
DUT	Device under Test
EKO	EKO Instruments B.V., The Netherlands
EMPR	European Metrology Research Programme
EMPIR	European Metrology Programme for Innovation and Research
ENEA	Italian National Agency for New Technologies, Energy and Sustainable Economic Development
ESTI	European Solar Test Installation
EURAMET	The European Association of National Metrology Institutes
FDIS	Final Draft International Standard
GSM	Global Sunlight Method
HIT	Heterojunction With Intrinsic Thin Layer
IEC	International Electrotechnical Commission
IEC TC 82	IEC Technical Committee 82

INTA	National Institute of Aerospace Technology, Spain
IPC	International Pyrheliometer Comparison
FhG-ISE	Fraunhofer Institute for Solar Energy Systems, Germany
ISFH	Institute for Solar Energy Research in Hamelin, Germany
ISO	International Organization for Standardisation
ISRC	International Spectroradiometer Comparison
ITRPV	International Technology Roadmap for Photovoltaic
JRC	Joint Research Centre
KCRV	Key Comparison Reference Value
LED	Light Emitting Diode
MJ	Multi-junction (PV device)
NIR	Near Infrared light
NMI	National Metrology Institute
NPC	National Pyrheliometer Comparison
NREL	National Renewable Energy Laboratory, USA
OPV	Organic Photovoltaics
PMOD	Physikalisch-Meteorologisches Observatorium Davos, Switzerland
PERC	Passivated Emitter Rear Cell
PERL	Passivated Emitter Rear Locally-Diffused
PERT	Passivated Emitter Rear Totally-Diffused
PSC	Perovskite Solar Cell
PTB	Physikalisch-Technische Bundesanstalt, Germany
PV	Photovoltaic(s)
RR	Round Robin
RSE	Ricerca sul Sistema Energetico S.p.A., Italy
SERIS	Solar Energy Research Institute of Singapore, Singapore
SI	International System (of units)
SR	Spectral Responsivity

SSM	Solar Simulator Method
STC	Standard Test Conditions
TC	Temperature Coefficient
TÜV	Technischer Überwachungsverein, Germany
UC	Uncertainty
UCY	University of Cyprus, Cyprus
UEX	Universidad de Extremadura, Spain
UV	Ultraviolet light
VIS	Visible light
WPVS	World Photovoltaic Scale
WRC	World Radiation Centre
WRR	World Radiometric Reference
WSG	World Standard Group
WTO	World Trade Organisation

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