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State-of-the-art for assessment of solar energy technologies 2019

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Contact information
Name: Harald Müllejans
Address: European Commission, Joint Research Centre (JRC), Via E. Fermi 2749, Ispra (VA), Italy
Email: JRC-ESTI-SERVICES@ec.europa.eu

EU Science Hub
https://ec.europa.eu/jrc

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Abstract

To realize the EU target of energy transition to a carbon neutral energy system, wide scale deployment of photovoltaic solar energy is required. This report describes the contribution of the European Solar Test Installation to enable this transition.

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Authors

Müllejans, Harald

Zaaiman, Willem

Galleano, Roberto

Pavanello, Diego

Salis, Elena

Sample, Tony

Bardizza, Giorgio

Lopez Garcia, Juan

Kenny, Robert

Shaw, David

Field, Michael

Castellazzi, Luca

Dunlop, Ewan D

Executive summary

Photovoltaics (PV) are expected to make a major contribution to achieving European and global climate change mitigation goals over the coming 30 years. PV is the renewable energy technology with the largest scope for cost reduction and efficiency gains, as well as exploiting the largest resource. The Joint Research Centre (JRC) operates the European Solar Test Installation (ESTI) that develops expertise for state-of-the-art assessment of electrical performance of PV devices based on traditional as well as emerging PV technologies.

Policy context

The Paris Climate Agreement entered into force on 4 November 2016 and aims to keep the maximum global average temperature rise below or close to 1.5 °C. The European Union has set out plans for a new energy strategy based on a more secure, sustainable and low-carbon economy. In December 2018, the EU agreed on a binding, renewable energy target of 32% for 2030, including a review clause by 2023 for an upward revision of the EU level target [EU 2018].

Key conclusions

The PV sector requires accurate and reliable assessment of electrical performance of PV modules. Due to the high-tech character and the innovative aspect, this requires that calibration laboratories, such as ESTI, provide assessment of the performance to be used as reference values by the PV industry. To keep up with the development of the PV sector, this requires the laboratories to improve further the accuracy of PV performance measurement as well as to develop new measurement procedures for emerging PV technologies.

One key aspect is to extend from the traditional measurement of output power of PV modules to a metric related to their energy production when deployed in the field.

Furthermore research and development of measurement methods is urgently needed, accompanying the development of new PV products, be it new concepts (such as bi-facial PV modules) or new PV technologies (such as perovskite solar cells). Often the PV industry can have products in the market faster than the respective measurement technology is developed. This is because the pre-normative research and the following standardisation process requires typically several years, whereas some new technologies such as bi-facial PV modules appear quickly in the market. Indeed, modern crystalline-silicon PV modules are inherently sensitive to light from both sides (i.e. bi-facial). A new PV product can easily be created by only changing the rear side cover of a crystalline-silicon PV module from standard opaque material to transparent glass. In the absence of published international standards for advanced measurement of PV devices, it is very important for both manufacturers and legislators to have full availability of experienced reference laboratories, such as ESTI, which can provide official performance assessment based on their expertise and under an accreditation scheme.

Main findings

The PV industry is characterised by two main aspects:

1. It has to be cost competitive with respect to other electricity generation technologies. This requires the assessment of electrical performance and energy generation with the highest possible accuracy.
2. It is highly innovative. Producing new products such as bi-facial PV modules or new PV technologies such as perovskite solar cells requires either to adapt existing or to develop new measurement techniques to evaluate these new (emerging) PV technologies in a realistic and reliable way in order to make well-founded decision on their feasibility, both technologically and economically.

The European Solar Test Installation (ESTI) of the JRC addresses these issues

1. by developing and implementing measurement procedures to improve the accuracy of the calibration of PV devices. The measurement of the solar irradiance is essential for an accurate measurement of energy production from PV. ESTI has developed and rigorously implemented the world photovoltaic scale (WPVS) approach and thereby improved the accuracy of solar irradiance determination from around 2% in the mid-1990s to currently less than 0.25%, the latter being the best accuracy available anywhere. This led to the improvement of the accuracy of PV modules' power measurement from 2.6% to 1% providing the highest accuracy available from any PV calibration laboratory. This reduction corresponds to a monetary value of €480 million for the annual world-

wide PV production. ESTI is a fully ISO/IEC 17025 accredited calibration laboratory for these measurements and has issued a total of 72 calibration certificates to clients in 2019. ESTI's facilities and expertise are employed as follows:

- To regularly compare electrical performance measurements of PV devices to peer-laboratories around the world, ensuring the international equivalence of calibration and measurement results.
- To generate PV reference material for other laboratories, thus providing a crucial step in the traceability chain for PV from the solar irradiance measurement to the final PV device performance measured in the factory production line.
- To validate independently claims of potential new efficiency record-breaking PV devices. In 2019 there were three such requests and all of the submitted devices had efficiencies outclassing the published records at the time of measurement.

2. by executing pre-normative research on PV measurement technologies and accompanying the standardisation process as active member of international standardisation organisation such as the International Electrotechnical Commission (IEC) and the European Committee for Electrotechnical Standardisation (CENELEC). It achieved this in the following way:
   - ESTI has significantly developed the international standards for PV energy rating [series IEC 61853], which relates advanced power measurements on the PV modules (see above) to estimates of site-specific energy production. Currently, ESTI is one of the very few laboratories accredited as calibration laboratory for the full power matrix measurement [IEC 61853-1].
   - Similarly, ESTI collaborated in the development of the technical specification for the measurement of bi-facial PV modules [IEC TS 60904-1-2 published in January 2019] and became accredited for these measurements at the end of 2019.
   - Adapting existing and developing new measurement procedures for perovskite solar cells, the currently fastest developing new PV technology with frequent announcements of record-breaking efficiencies. This allowed ESTI to provide realistic evaluation of this technology under its accreditation scheme.

Related and future JRC work

The JRC publishes annually

— the PV Status Report, providing comprehensive information on the dynamic PV sector for decision-makers in policy and industry as well as the general public.

— its contribution to international and European standards in the areas: a) power calibration, b) energy rating, c) reliability and lifetime, d) module electrical safety, e) PV products for buildings and f) energy-savings potential for Ecodesign.

JRC conducts Geographic Information System (GIS) based research on current and future PV deployment that can revise the EU PV development trend during the current transition from policy driven markets to competitive ones. PVGIS is freely available.

The impact of PV is being studied as an enabler for net-zero energy buildings and for the electrification of transport.

Quick guide

Photovoltaics, a technology generating electricity directly from sunlight, is currently the most important solar-power technology. PV modules are priced according to their electrical performance, namely power and energy production. The profitability of production and deployment of PV devices depends crucially on the accurate determination of these performance parameters. Therefore, the JRC operates the European Solar Test Installation (ESTI), a European reference laboratory for PV calibration independent from any commercial and national interests. At ESTI the electrical performance of PV devices is validated with high accuracy based on the world photovoltaic scale (WPVS), providing the world-wide best accuracies for both solar irradiance in PV and PV module power measurements. ESTI also performs research to develop and improve accurate measurement techniques for current and future PV technologies.

1 Introduction

1.1 Background

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 and a review clause by 2023 for an upward revision of the EU level target [EU 2018]. The EU's reaffirmation of its commitment to achieving a competitive and climate neutral economy by 2050 [EC 2018] recognises the importance of renewable energy to achieving that aim. The European Green Deal, announced in December 2019 [EC 2019], aims to make Europe the world's first climate-neutral continent by 2050 with implications across the entire energy sector. The commitment to a power sector based largely on renewable sources implies substantial further growth of PV. A primary electricity generation of 50,000 TWh from PV power is envisaged for 2050 [Ram 2019]. This amounts to a 100-fold increase with respect to 2018 [Jäg 2019].

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 (five-fold over the last decade) and efficiency gains. In Europe, PV currently provides already about 5% of the EU's final electricity demand. The sector has been growing rapidly, the world-wide installed capacity increased from around 40 GW in 2010 to more than 600 GW in 2019, with about 130 GW installed in the EU [Jäg 2019]. The global Compound Annual Growth Rate over the last decade was over 40%, thus making PV one of the fastest growing industries at present. 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 [EC 2016].

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 of PV devices based on traditional as well as emerging PV technologies and to assess their lifetime on the basis of many years of expertise in the field [Vir 2019]. 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) and/or in the European Committee for Electrotechnical Standardisation (CENELEC) 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 developing the solutions for the future.

The Ecodesign and Energy Labelling legislative framework has the two purposes:

1. ensuring that more energy-efficient products come to the market (through Ecodesign);
2. encouraging and empowering consumers to buy the most efficient products based on useful information (through energy labelling).

The Ecodesign Working Plan includes studies on energy-savings potentials of PV panels and inverters. In particular, a preparatory study on sustainable product policy instruments for the product group 'solar photovoltaic panels, inverters and systems' was launched in 2017. The study is performed under an administrative arrangement (AA) from DG GROW, with a specific contribution regarding standards also from ESTI staff [for more details see SAM 2020].

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 120 GW in 2019 [Jäg 2019] and a market value only for the PV module components reaching over €30 billion, the methods and standards for the calibration of the power of PV modules and systems are vital for evaluating the economic feasibility of PV. 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 electrical power generated by a PV module is influenced by the intensity and 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, i.e. the distribution of the total irradiance over the wavelengths that constitutes the former. International standards require foremost the PV calibration at standard test conditions (STC) (as defined by [IEC TS 61836]), which for terrestrial applications include a total irradiance of 1000 W/m^2 with a spectral irradiance distribution of the reference spectrum [IEC 60904-3].

One significant transition in the assessment of PV devices is currently underway, namely the transition from rating PV products according to their power output at STC to that of the energy that can be generated at the PV system's installation location. The energy rating is based on internationally agreed climate specific data sets [IEC 61853-4] and a rated energy output for these conditions can be calculated [IEC 61853-3] based on a series of performance measurements at a range of irradiance and device temperatures, which constitutes the PV module's power matrix [IEC 61853-1]. The energy rating is not a prediction of the actual output of PV products at a given site nor a direct prediction of the energy production for future time, but rather a rating of energy output under typical conditions. The latter are in some way conceptually similar to STC, but they are defined in much more detail and with more parameters, which can better represent real conditions encountered by PV modules installed in the field during their lifetime, and additionally for several climate zones [IEC 61853-4].

1.2 JRC work in the field of Photovoltaics

The following four conditions or parameters need to be evaluated in order to determine the economic feasibility of PV systems, that is the cost per produced energy:

1. The power output (or more correctly the energy production) of PV systems. This reports presents a comprehensive summary of the main activities of ESTI in this field.
2. The available solar resource: the JRC developed in the last fifteen years a Geographic Information System (GIS) to estimate the site-specific potential of PV deployment; the PVGIS tool, which now covers almost the entire world, is freely available.
3. The lifetime of the PV modules. The JRC has worked for many years in this field and still takes an active role in crucial research projects [Lop 2019c] and the international standardisation [Sam 2020]. The JRC is also involved in the Ecodesign preparatory study [Sam 2020].
4. The total cost of a PV system, including the prices for PV modules and balance–of-system components as well as financing. The JRC publishes annually the PV status report [Jäg 2019], providing comprehensive information on the PV sector for the interested public as well as for decision-makers in policy and industry. This report includes typical values for PV module and system prices as well as an analysis of the levelised cost of electricity (LCOE).

1.3 European Solar Test Installation (ESTI) at the JRC

ESTI is an ISO/IEC 17025 accredited calibration laboratory. As such, it is also involved in benchmarking, inter-laboratory comparisons (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. 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 independent verification of PV device performance.

Overall, ESTI activities covering all these aspects make it 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 institutes dealing with renewable energies. ESTI is one of only three to five laboratories around the world providing PV measurements at the highest level. ESTI compares regularly to these peers ensuring equivalence of results from these top-level laboratories around the globe.

1.4 Report outline of ESTI activities

The measurement of the electrical parameters is rather straightforward. The difficult part is to determine accurately the irradiance conditions under which the electrical performance is measured, because the measurement results need to be corrected to STC. The correction procedures are well established [IEC 60891], [IEC 60904-7], but in order to apply them the determination of the actual irradiance conditions during the measurement is paramount.

In this report the activities of 2019 are summarised.

- Starting from principles of traceability of PV irradiance measurements, the activities of ESTI in establishing the PV traceability chain at its own laboratory are outlined (section 2).
- In the following all activities are described that ensure the international equivalence of measurement results, including the international inter-laboratory comparison measurements for the major instruments used in the traceability chain, from cavity radiometers and spectroradiometers to PV devices (both cells and modules). These serve to establish the traceability, stability and conformity of ESTI's calibration measurements (section 3).
- Based on these activities and its ISO/IEC 17025 accreditation as calibration laboratory, ESTI provides reference calibrations for other laboratories and industry, whether for proficiency testing or for serving as the primary reference in those laboratories (section 4).
- Another activity concerns the independent validation of PV device performance, when extraordinary device performance is claimed by the device manufacturers, be it world record efficiencies or other performance beyond the usual (section 5).
- In order to prepare for future challenges in PV device performance measurements, pre-normative research is carried out, improving and developing new methods to be applied to existing and emerging PV technologies (section 6).
- The dissemination of the knowledge is described aiming at both the scientific community, to improve measurement and calibration of PV devices world-wide, as well as to the general public, thus raising awareness of PV technology and its potential (section 7).
- Finally, the findings are summarised and concluded (section 8).

Thereby, this annual report:

- describes 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.

2 Solar irradiance measurement for photovoltaics

As for any measurement, the traceability of all measured quantities to international standards is a fundamental requirement. The assessment of electrical performance of PV devices requires the measurement of electrical parameters at well-defined solar irradiance conditions. The accurate and traceable measurement of the latter is the most difficult and critical, while those of the electrical quantities are relatively straightforward. This section describes the basics of traceable solar irradiance measurements and the activities of the European Solar Test Installation (ESTI) in this field, from its participation in the project teams developing international standardisation down to the unique reference measurement standard for PV irradiance measurement, which is the ESTI reference cell set incorporating the World Photovoltaic Scale (WPVS).

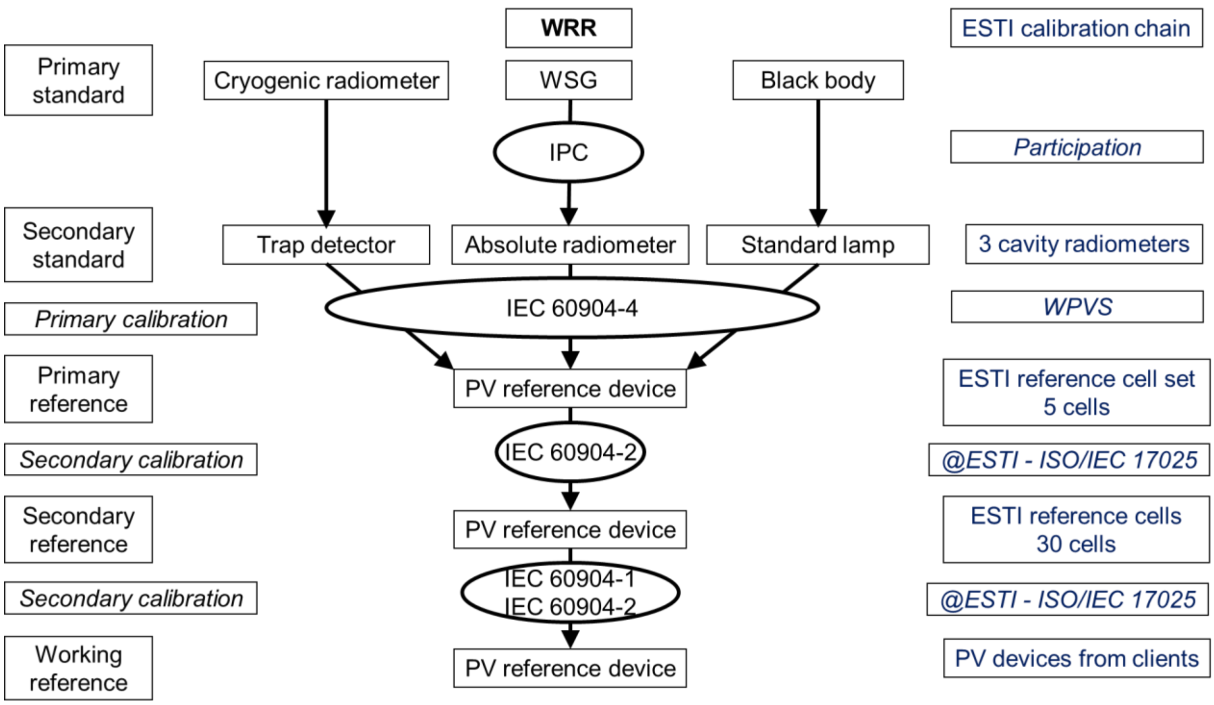
2.1 Traceability standard for PV

The international standard [IEC 60904-4] describes the traceability chain of the solar irradiance measurements for PV. This standard was both originally developed and recently revised under project leadership from the JRC. Its second edition was published in November 2019.

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.

Essentially, the irradiance measurement can be traced either to the World Radiometric Reference (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 (**Figure 1**). The WRR has total irradiance and spectral irradiance similar to the defined PV reference spectrum [IEC 60904-3] 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**.

Figure 1. Schematic diagram of the traceability chain for PV reference devices. WSG is the World Standard Group, WRR is the World Radiometric Reference and IPC is the International Pyrheliometer Comparison.



Source: JRC, 2020.

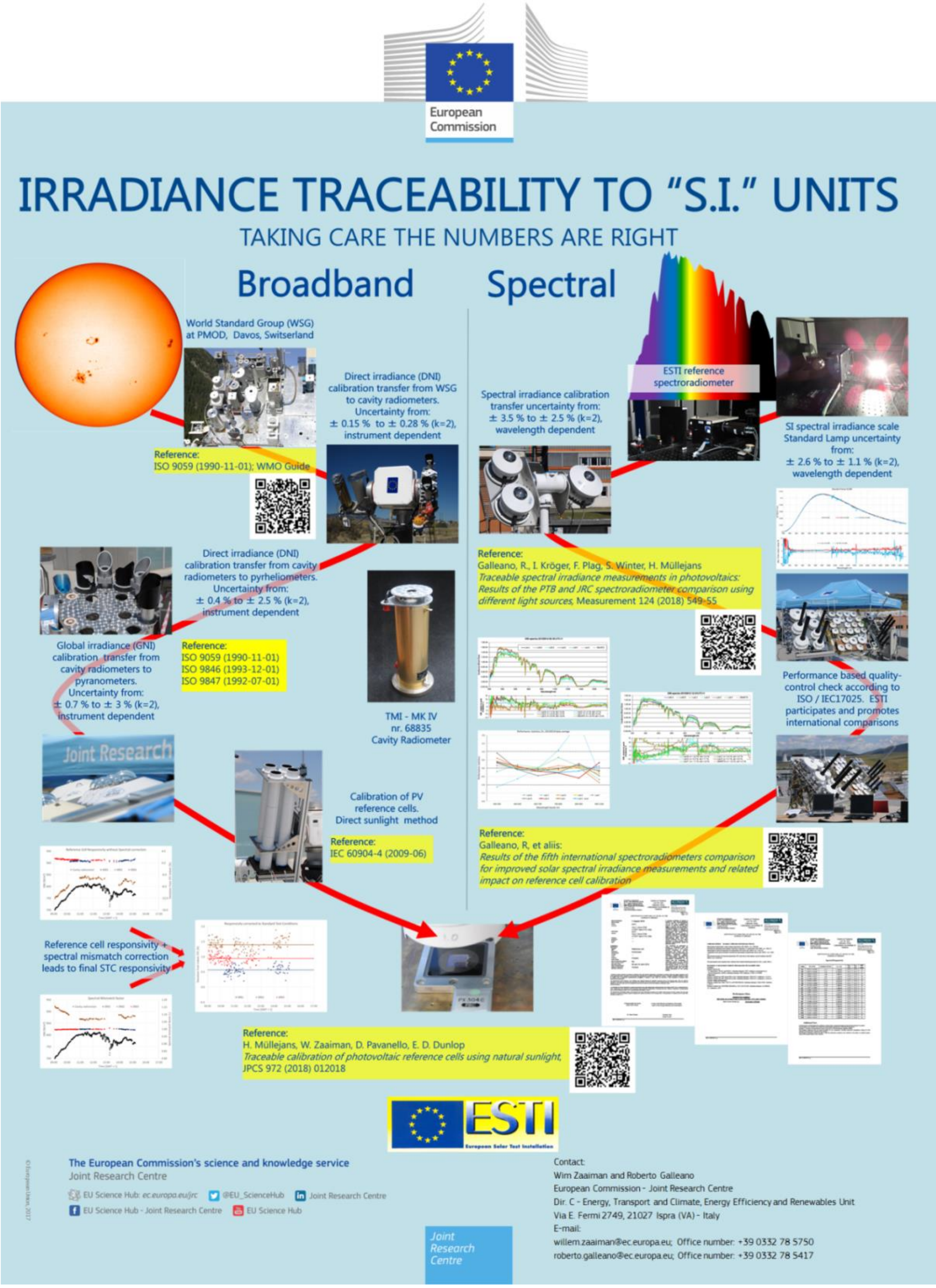
Once the transfer to a PV reference device (typically a solar cell) has been achieved traceably by these methods (i.e. primary calibration), the further transfer (i.e. secondary calibration) to other PV devices can be performed and is governed by separate IEC standards [IEC 60904-2] [IEC 60904-1].

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 (i.e. a calibrated reference), which measures irradiance traceable to international measurement standards. In the case of natural sunlight the international standard for irradiance is represented by the WRR, which is measured with cavity radiometers (often simply named cavities). However, cavity radiometers 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 much 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. 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 (secondary calibrations) 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.

Figure 2: Overview of irradiance traceability chain at ESTI.



Source: JRC, 2018.

2.2 World Radiometric Reference (WRR)

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 during the International Pyrheliometer Comparison (IPC). ESTI holds three such secondary standards and it uses them 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 the 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

As mentioned above, another traceability route for irradiance is to black-body radiation via standard lamps (see **Figure 1**). This method was pioneered at AIST and ESTI has implemented it to have the widest possible range of methods available in-house.

2.4 World Photovoltaic Scale (WPVS)

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 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]), that is only to check that their own results are in agreement with the WPVS (within declared accuracy).

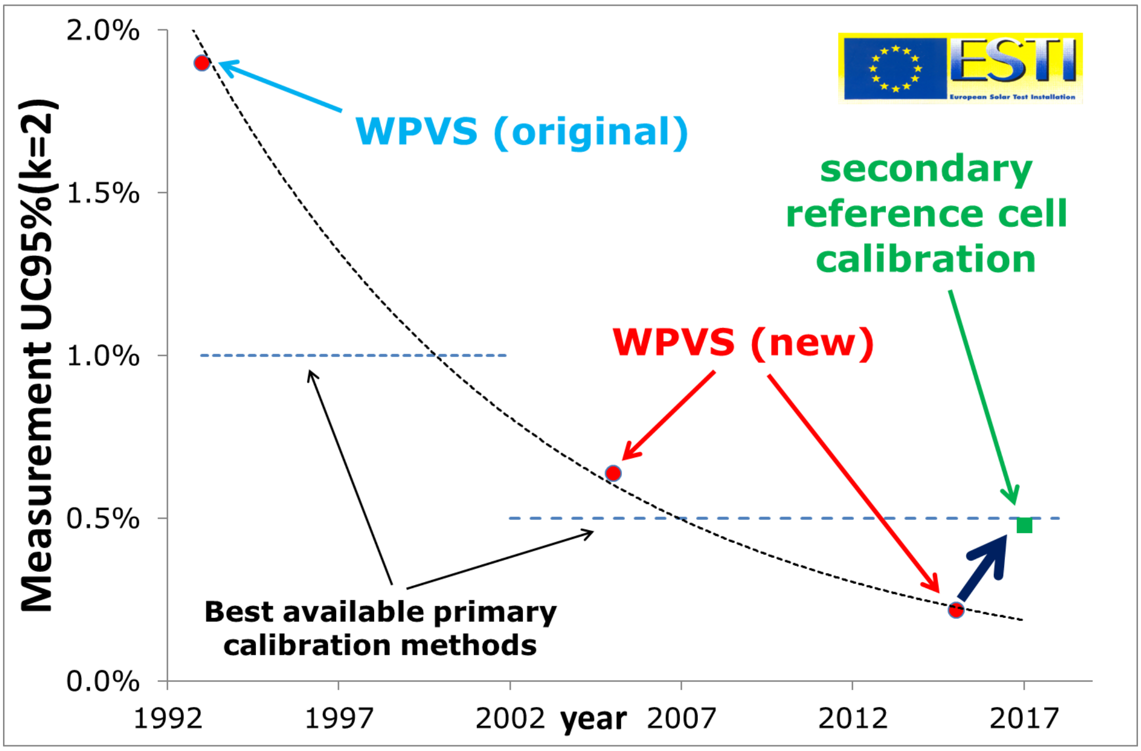
The methods for irradiance calibration of PV devices have been validated and proven to produce results consistent with each other within declared measurement accuracy[1]. However, as is usual practice in international metrology at the highest level, a key comparison reference value (KCRV) can be assigned based on all valid measurements on the same device. In general, the weighted average is used, with the weighting provided by the measurement accuracy of the contributing results. This will provide a value which is more reliable than any individual values, as it contains information from all validated methods, thereby also improving the accuracy of this final average. This concept was the original idea at the basis of the WPVS, implemented in the 1990s as outcome of the Photovoltaic Solar Energy Project (PEP) of the Technology, Growth and Employment Working Group of the G7 summit [Ost 1998]. However, only arithmetic averaging was used at that time. Furthermore, participants other than ESTI chose to maintain their own traceability, comparing to the 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, implementing (in 2008) the weighted average approach, thus reducing the measurement uncertainty (UC) of the original WPVS from 1.9% to 0.25% (that is almost tenfold (**Figure 3**). Now, ESTI is the keeper of the WPVS, which is constituted by the ESTI reference cell set (at present five cells). The accuracy for solar irradiance measurements with these reference cells has now become the highest available world-wide [Mül 2015]. This puts ESTI into the unique position of offering the calibration of PV reference cells by secondary calibration methods with the same accuracy as with the more expensive primary methods (**Figure 3**). The history of the WPVS was summarised and presented in 2019 [Mül 2019b].

The UC reduction of the PV reference cell calibration is not an aim in itself, but has been motivated by an analysis of the several UC components contributing to the overall UC in the electrical performance assessment of PV modules. Back in 1995 the analysis showed (**Figure 4**, left) that the main contribution to overall UC was due to the UC in the calibration of the reference cell (more than 50%). Thanks to the development and improvements of the WPVS described above, the situation is now completely different (**Figure 4**, right), with the contribution of the reference cell calibration being almost negligible. The final outcome of this development process is that overall UC for the measurement of PV module power at ESTI has

[1] In metrology the accuracy of measurements is expressed by the declared measurement uncertainty (UC). A lower UC corresponds to a higher accuracy of a measurement (and vice versa). Therefore the terms "improving accuracy" and "reducing UC" are synonymous.

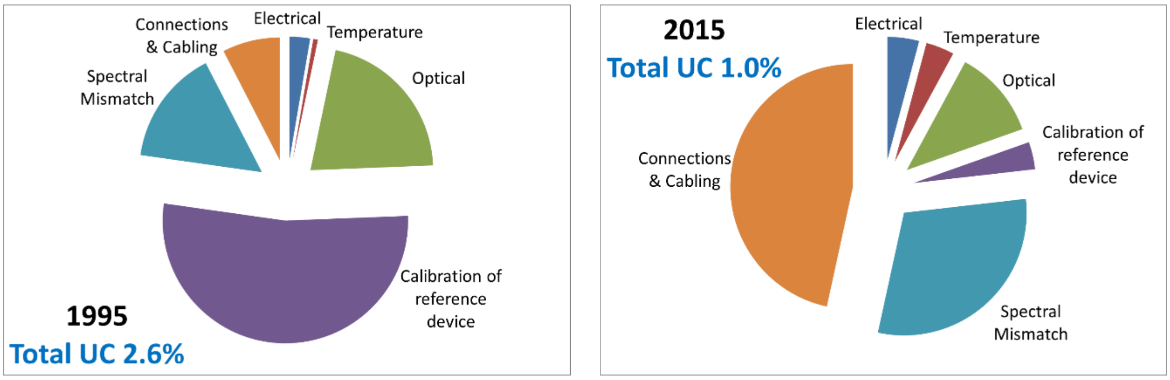
decreased from 2.6 % (1995) to 1.0% (2015), which is the lowest value available world-wide. Considering the annual PV production world-wide, this corresponds to a monetary value of €480 million.

Figure 3: Evolution of uncertainty for solar irradiance measurement through WPVS [Mül 2019b].



Source: JRC, 2019.

Figure 4: Contributions to measurement uncertainty of PV module power then and now [Mül 2019b].



Source: JRC, 2019.

2.5 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 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.

ESTI has used the WPVS ever since its introduction in 1995. 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 provided not only 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 stored under controlled conditions (inside the laboratory, under air, at room temperature (23±1) °C with relative humidity between 40% and 55%). PV devices under these conditions are proven to have very long-term stability (>30 years).

3 International inter-laboratory comparison measurements

ESTI participates in and organises international inter-laboratory comparisons for the measurement of solar irradiance, from broadband measurement with cavity radiometers, over those with spectroradiometers, to the calibration of PV reference cells and modules. The purpose of these measurements is to regularly check the validity of the measurement methods and results of the ESTI laboratory against those of its peers. This is most important to guarantee international equivalence of results from all recognised laboratories. Moreover, the participation in such inter-laboratory comparisons is required for ISO/IEC 17025 accredited laboratories as a factual-based quality-control assessment. ESTI's peer laboratories around the world are the National Renewable Energy Laboratory (NREL) in the USA, the National Institute of Advanced Industrial Science and Technology (AIST) in Japan and in Germany the Physikalisch-Technische Bundesanstalt (PTB) (for reference cell calibration) and the Fraunhofer Institute for Solar Energy Systems (FhG-ISE) (for PV module calibration). The impact of international standardisation and periodic world-wide inter-laboratory comparisons of PV device performance measurements is evident in a reduction over time in the discrepancy between labelled and verified PV module power [Lop 2018].

Two critical aspects of the irradiance measurement influence the power calibration and energy yield [Gra 2019] determination for PV devices. As such, it is important to maintain a high level of comparability to peer laboratories for those measurements based on cavities and spectroradiometers.

The first aspect concerns the measurement of the level of direct normal (beam) solar irradiance (DNI) using broadband radiation 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

- the development and deployment of solar energy conversion systems,
- improving our understanding of the Earth's energy budget for climate change studies and
- 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 of experience with a set of precision instruments.

In PV devices 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 [IEC 60904-3], a spectral mismatch error [IEC 60904-7] is introduced in the DUT performance measurement, as the reference device and the device under test 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 annually organising the International Spectroradiometer Comparison (ISRC) in order to gather and spread knowledge and good practices in this field.

3.1 Comparison of broadband irradiance instruments

In the late 1970s, the World Meteorological Organization (WMO) established the WRR as a conventional international standard for DNI measurement [Frö 1991]. 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. 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.

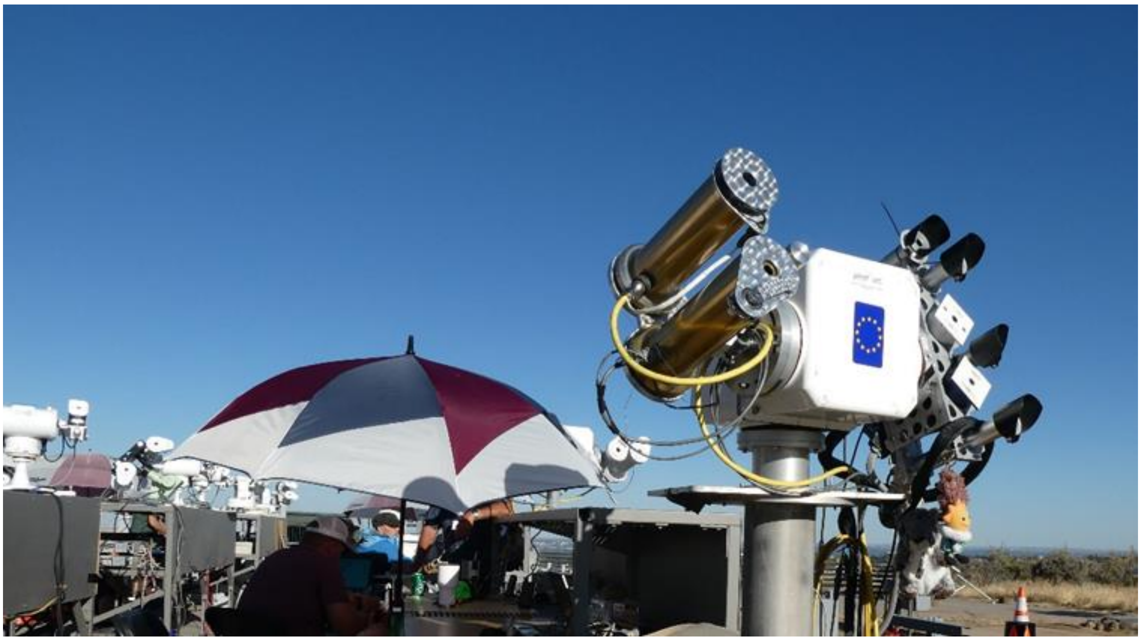
Annually, (except in IPC years) ESTI also participates in the NPC held at the National Renewable Energy Laboratory (NREL), Golden (CO), USA.

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.

3.1.1 National Pyrheliometer Comparison (NPC) 2019

In 2019, ESTI participated to the US NPC organised by NREL (23 Sep – 4 Oct 2019 in Boulder, CO, USA) with its three cavity radiometers (codes: PMO-6 81109, PMO-6 911204 and TMI 68835) [NREL 2019] (**Figure 5**). 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, IPC-XII (2015) [IPC-XII] (**Table 1**). The stability of all three instruments was confirmed by E_n number analysis (Annex 1).

Figure 5. ESTI cavity radiometers (two on right hand side with square white front plate and one of the two gold-coloured instruments on the left hand side) and pyrheliometers (on right hand side with black protection caps) mounted for measurement on a solar tracker (white box with EU flag) during NPC 2019.



Source: JRC, 2019.

Table 1. Comparison of the correction factors calculated with respect to WRR (rows two and three), their difference row four) and the E_n number analysis (row five) showing the stability of the ESTI cavity radiometers in 2019 versus their calibration at IPC-XII.

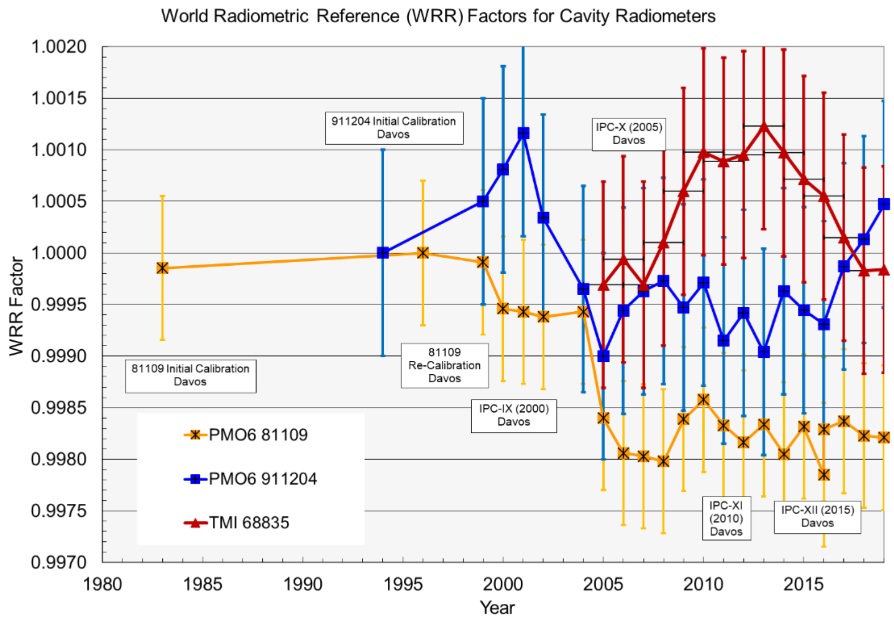
	PMO6 81109	**PMO6 911204**	**TMI 68835**
IPC-XII (2015)	0.998317 ± 0.32%	0.999446 ± 0.41%	1.000714 ± 0.32%
NPC (2019)	0.998210 ± 0.36%	1.000470 ± 0.36%	0.999840 ± 0.36%
Difference	-107 ppm	+1024 ppm	-874 ppm
$\boldsymbol{E_n}$	-0.02	+0.19	-0.18

Source: JRC, 2020.

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 from 2015. The next IPC is planned for autumn 2020.

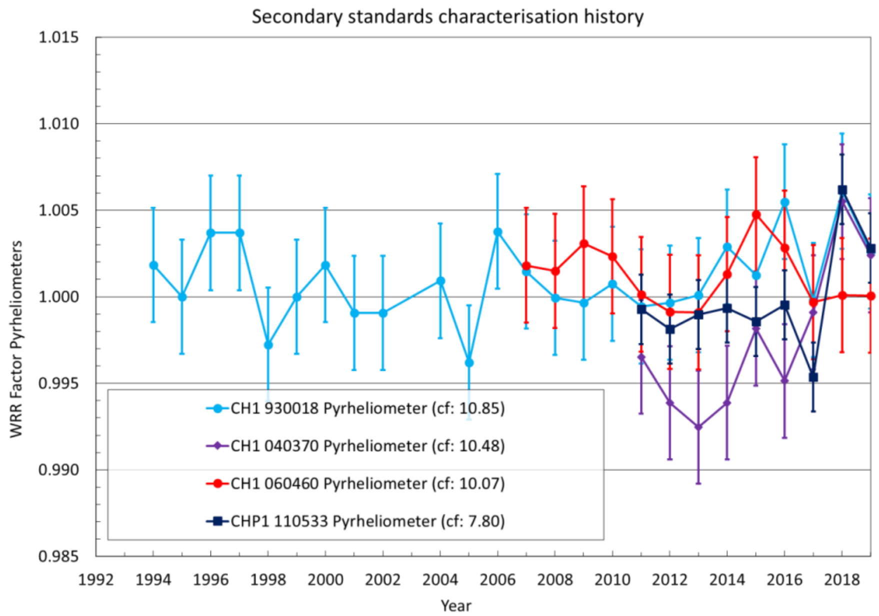
Figure 6 shows the long-term stability of the three ESTI cavity radiometers during international inter-comparisons. The ESTI secondary pyrheliometers were also compared to the NREL reference standards during NPC 2019. The historical trend in the WRR correction factors (for pyrheliometer CH1 930018 this goes back 25 years) is shown in **Figure 7** and the E_n number analysis (not shown) confirms the stability of these instruments. The annual variation of the WRR correction factor for the pyrheliometers is larger than for the cavity radiometers, because the pyrheliometers are simpler instruments.

Figure 6. Long-term stability of ESTI cavity radiometers as determined from international comparisons.



Source: JRC, 2020.

Figure 7. Long-term stability of ESTI pyrheliometers as determined from international comparisons

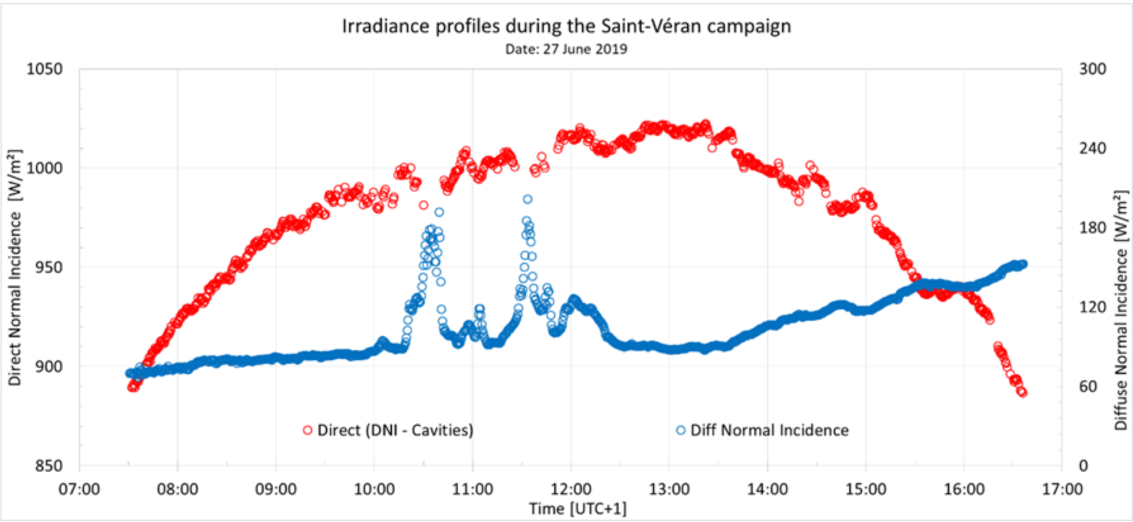


Source: JRC, 2020.

3.1.2 Bi-lateral measurement comparison for direct normal irradiance (PTB-ESTI)

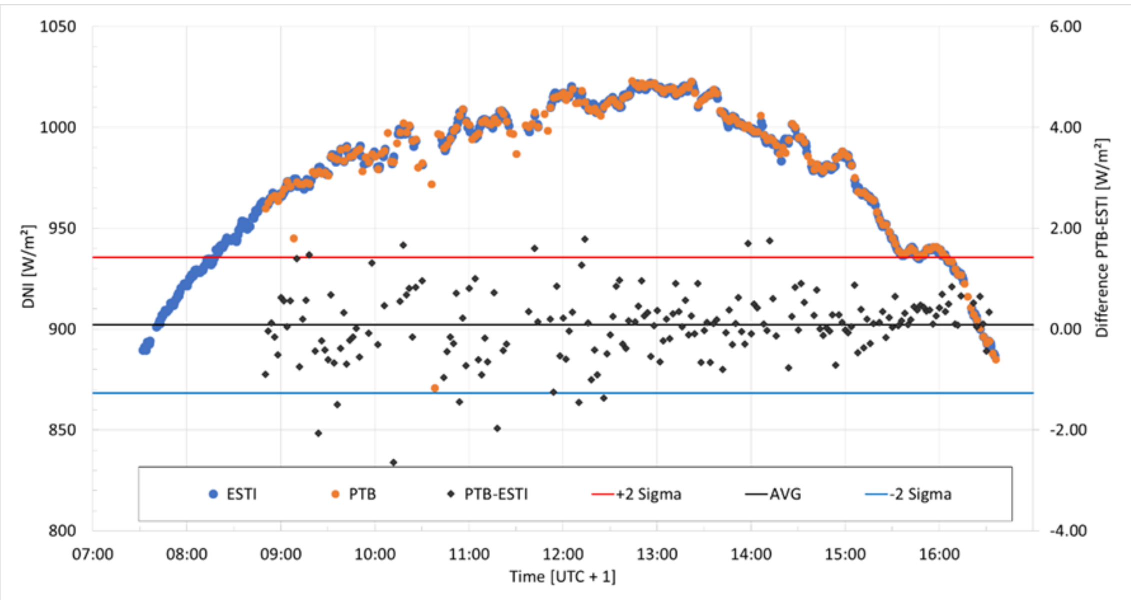
In June 2019 during the ISRC (section 3.2.1) the irradiance measurements of two ESTI cavity radiometers (**Figure 8**) were compared to those from a similar cavity radiometer from PTB, also traceable to WRR. The purpose was to check all instruments for stability and consistency. After data filtering to detect and reject obviously erroneous data points, the average difference between PTB and ESTI DNI measurements is (0.08 ± 1.35) W/m² [k=2] or (0.009 ± 0.136)% [k=2] (**Figure 9**). The very small difference (0.08 W/m²) proves the relative stability of the radiometers to each other (since their calibration at IPC in 2015), including data acquisition, calculation of the direct irradiance and operator related factors. The spread of the differences (±0.136%) is consistent with ESTI's stated uncertainty of ±0.21% [k=2].

Figure 8. Reference direct normal irradiance and diffuse normal incidence as measured by ESTI



Source: JRC, 2020.

Figure 9. Reference irradiance as measured by ESTI and PTB and difference between the reported irradiances



Source: JRC, 2020.

3.2 Spectroradiometer comparisons

There is a growing request for harmonisation of good measurement practices and knowledge transfer in the field of spectrally-resolved solar radiation measurements for solar energy applications (e.g. PV). This is needed to increase the comparability between the various measurements and to make them directly traceable to SI units. Moreover, there is a growing request for spectral irradiance measurements to be comparable, traceable and with low uncertainty in order to improve the quality and the reliability of the more and more requested PV energy-yield estimates. The spectroradiometer inter-laboratory comparison, whose results are summarised below, is thus a good opportunity to raise the awareness on these crucial measurements.

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

— As mentioned above, spectral mismatch correction [IEC 60904-7] represents nowadays the major source of UC in PV device calibration. Accurate measurements of natural or simulated sunlight spectral irradiance are essential in limiting the overall amount of the spectral mismatch, for example in all those cases where the spectral responsivities (SRs) of the device under test (DUT) and the reference device significantly differ from each other due to active material or measurement conditions;

— While PV devices are rated at the reference spectral irradiance [IEC 60904-3], in real terrestrial PV installations both the total and the spectral irradiance can differ significantly from standard test conditions (STC) (see section 1.1). Although it is not feasible to measure in-situ spectral irradiance for every location on Earth, the availability of accurate measurements of spectral irradiance for a significant amount of sites around the globe can improve the confidence of models that transform satellite data for solar resource to usable spectral irradiance data that can be input to models for energy yield estimation;

— Spectral irradiance is one of three parameters for rating solar simulators [IEC 60904-9];

— Comprehensive knowledge of both repeatability and reproducibility of spectral irradiance measurements is important for a correct UC estimate of the PV device performance measurement. This is also mandatory for any ISO/IEC 17025 accredited laboratory.

Nowadays, spectroradiometers with quite different operating principles such as

- single- or double-stage rotating-grating monochromator;
- fixed single-grating polychromator with photodiode array or CCD detectors;
- filter radiometer-based instruments

are routinely used for natural as well as simulated sunlight spectrum measurements.

The spectral composition of natural sunlight depends on and varies with geographic location, season and time of day as well as actual weather conditions. This has an influence on the performance of PV systems depending on the PV technology, as each technology is sensitive to a different wavelength range of the solar spectrum. The assessment of these effects is a challenge in research and requires the knowledge of the spectral irradiance of the natural sunlight. Moreover, thanks to the significant reduction in the reference cell contribution to the overall UC of PV devices calibration (see **Figure 3** in section 2.4), the main contribution to the final UC of a PV module calibration is now due to the spectral mismatch, which is linked to the differences in the spectral responsivities of the device under test and reference device as well as in the spectrum actually used for the calibration in comparison to the reference spectrum tabulated in IEC 60904-3 [IEC 60904-3]. Therefore, the knowledge of the test spectrum with the lowest UC and over an extended wavelength range is becoming crucial for the next improvement in PV calibration. Moreover, the energy rating approach for PV systems requires accurate and long-term in-situ broadband sunlight spectral measurements.

3.2.1 International Spectroradiometer Comparison (ISRC) 2019

As part of its role to disseminate and manage knowledge on PV and related measurements, ESTI has coordinated and provided the scientific guidance to a European inter-laboratory comparison since 2011. The dissemination activity performed by ESTI in the framework of the spectroradiometer inter-laboratory comparisons is fundamental to maintain a reliable and traceable connection of the solar spectral measurement performed in the European PV community to the SI units. Periodic inter-laboratory comparisons of solar radiation measurements are also highly recommended by the World Meteorological Organization (WMO).

The international spectroradiometer comparison (ISRC) is run in various localities in the Mediterranean Basin (usually Italy or Spain), so to ensure the best measurement conditions for natural sunlight. ESTI provides the calibration measurement standard (traceable to SI units and also to the WRR) to the ISRC participants. All other participating instruments are compared against ESTI reference. This aims at improving within the EU the equivalence of the methods used for spectral sunlight resource measurements. Participants to the ISRC are research institutes, universities and commercial partners. During the ISRC campaigns, a series of seminars and discussions is also organised to increase the outreach of best practices and knowledge transfer to a wider scientific/technical audience. So far the scientific output of the ISRCs includes seven conference presentations and five papers published in peer-reviewed journals [Pra 2014] [Gal 2014a] [Gal 2014b] [Bel 2016] [Gal 2016a] [Gal 2016b] [Pra 2018] [Gal 2019]. The good scientific production rate and the increasing participation from European and even non-European partners testify the interest of the PV community in the subject.

The 9th edition of ISRC was held at the Observatoire Saint-Véran, Saint-Véran, France from 24th to 28th June 2019 and included one participant from USA and one from Singapore. **Table 2** summarises the participating institutes and the main characteristics of their instruments. **Figure 10** shows a group photo. The ISRC 2020 is planned to be held in Catania, Italy.

Figure 10. Participants to the 9th ISRC 2019

Source: JRC, 2019.

Table 2. Participants to ISRC 2019 listing the respective spectroradimeter, their wavelength range and the type of irradiance measured (DNI: direct normal irradiance; GNI: global normal irradiance; GHI: global horizontal irradiance)

Institute	Country	Instrument	Wavelength range [nm]	Global / direct
JRC (ESTI)	EU	EKO MS701, MS710, MS712 CAS140CT, CAS140CTS	300–1700 300-1600	DNI / GNI / GHI DNI / GNI
AIT	Austria	NIRQuest 512-1.7	300-1600	GNI
EKO Instruments	The Netherlands	EKO RSB-01S	300-1200	DNI (calculated)
ENEA	Italy	Stellarnet EPP2000 VIS & NIR	300-1700	GNI/DNI
ESA	The Netherlands	Ocean Optics Raysphere 1900	350-1900	DNI
ReRa solutions	The Netherlands	EKO MS711, MS712	300-1700	GNI
Davos Instruments	Switzerland	PSR	320-1025	DNI
PTB	Germany	CAS140CT+CTS	300-2150	DNI
RSE-web	Italy	Spectrafy SolarSIM-D2	300-4000	DNI (modelled)
SERIS	Singapore	AVANTES (3 channels)	250-1700	GNI
SUPSI	Switzerland	EKO MS710,MS712	300-1700	GHI

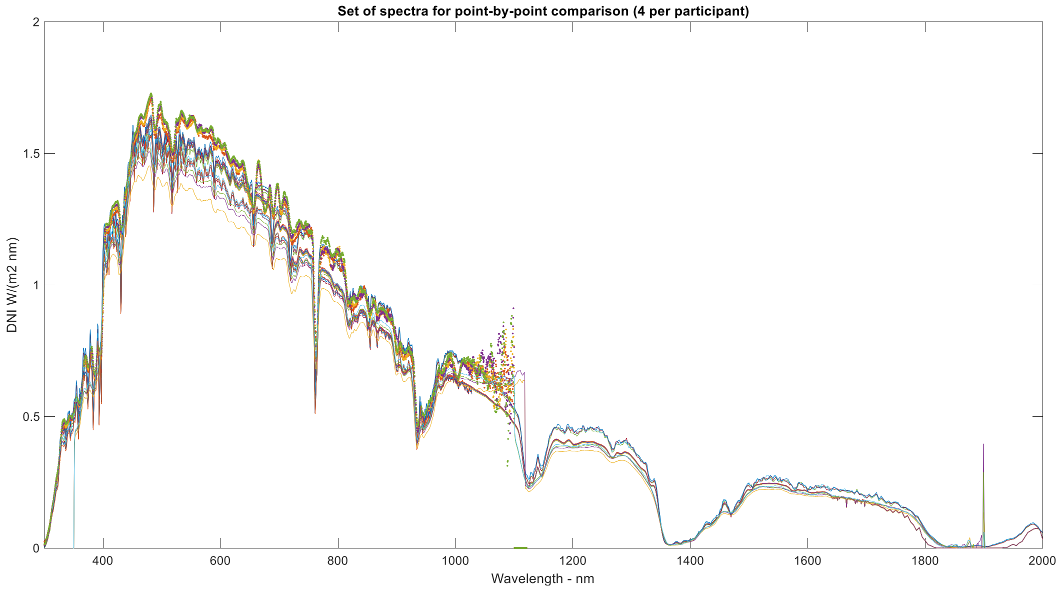
Source: JRC, 2020.

Because of the inevitable differences between the various instruments in measurement time, in bandwidth and in spectral resolution, specific procedures for instruments synchronisation as well as data acquisition and analysis were developed to make the results comparable to each other. Prior to the inter-laboratory comparison, each participant laboratory 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 via a calibrated radiometric standard lamp or externally 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 inter-laboratory comparison between the spectroradiometers, including the reference one from ESTI, the ESTI cavity radiometers were also in use as reference instruments for broadband total irradiance measurement, ensuring the direct link to SI units.

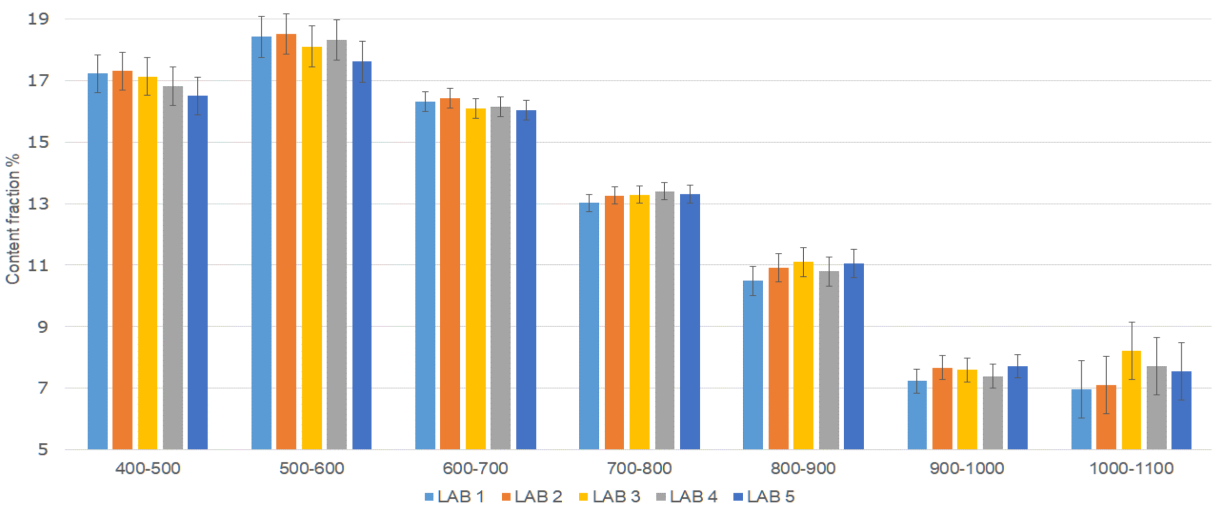
Data from ISRC 2019 are being analysed and circulated to the participants to increase awareness regarding accuracy, stability, repeatability and reproducibility for their respective instruments. The final goal is to publish the comparison results as a scientific paper in a peer-review journal.

Figure 11. Example comparison of selected measured spectra



Source: JRC, 2020.

Figure 12. Example comparison of spectral content in various wavelength bands



Source: JRC, 2020.

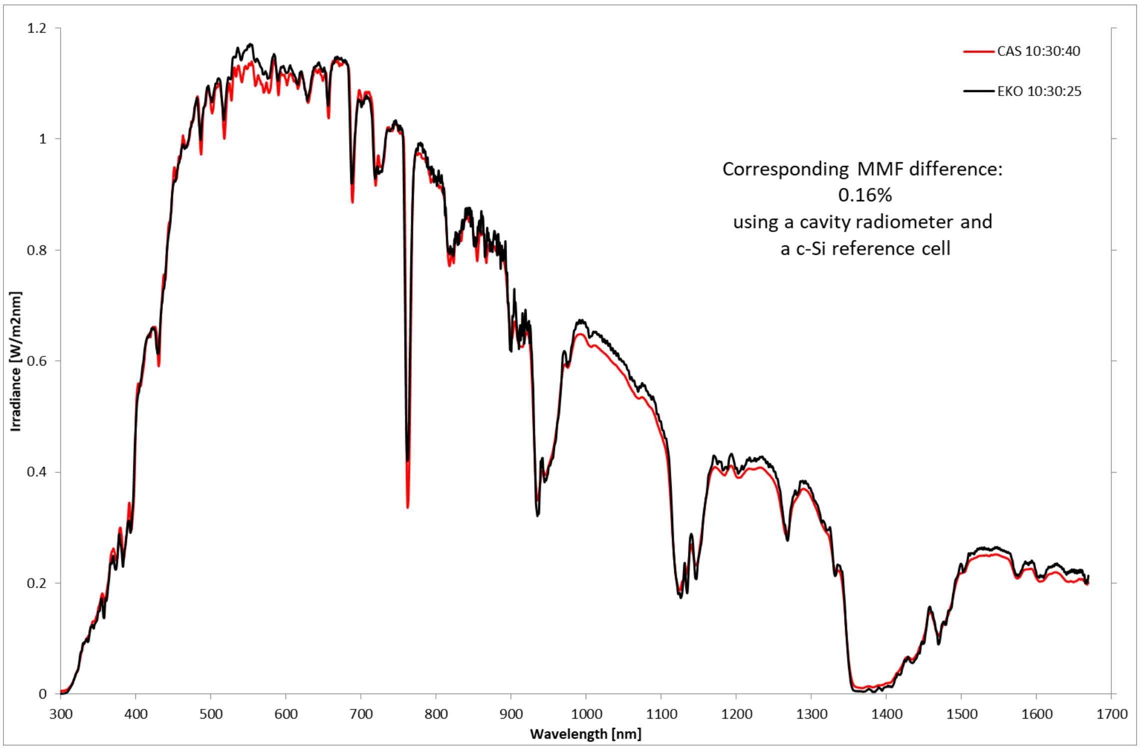
An example of spectra acquired during the ISRC 2019 is shown in **Figure 11**. **Figure 12** shows a detailed analysis of how the irradiance is distributed over a limited selection of wavelength bands. As not all instruments could cover the range from 300 nm to 2500 nm, the range used in the IEC 60904-9 (i.e. 300 nm to 1100 nm) has been adopted for the comparison.

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 (such as arising from instrument calibration, from time drift, from non-linearity, internal stray light or distortion) as outlined previously [Gal 2016b]. This is important in sunlight spectrum measurement applied to PV, where a correct measurement of the (shape of the) incoming sunlight spectral distribution is fundamental. This has direct consequences for the spectral mismatch correction factor [IEC 60904-7] and the analysis of the data from ISRC 2019 will focus on its variation depending on the input of measured spectra.

3.2.2 Internal ESTI comparison of two spectroradiometers

ESTI has several spectroradiometers, each of which has its own characteristics. For example the EKO (set of) instruments, which are weather resistant and permanently mounted outdoors, and the CAS instrument, which is a fast spectroradiometer capable of reliably measuring also the simulated sunlight of pulsed solar simulators (typical pulse length: 10 ms). Both instruments are calibrated (traceable to SI units) via a standard FEL lamp and therefore, from a metrological point of view, they give equivalent results. This equivalence was though validated at ESTI by simultaneously measuring the DNI natural sunlight over one day with both instruments mounted on solar trackers. **Figure 13** shows an example. The analysis of the spectral mismatch correction factor, which (as already discussed above) is the most relevant source of UC in the calibration of PV devices nowadays, showed differences between 0.1% and 0.3% (0.16% in the example of **Figure 13**), which is well within the estimate of its UC of 0.48%. Therefore, it was confirmed that both instruments yield metrological equivalent results.

Figure 13. Spectrum of natural sunlight as measured by EKO, black curve, and CAS, red curve. Corresponding calculated MMF difference is also reported.

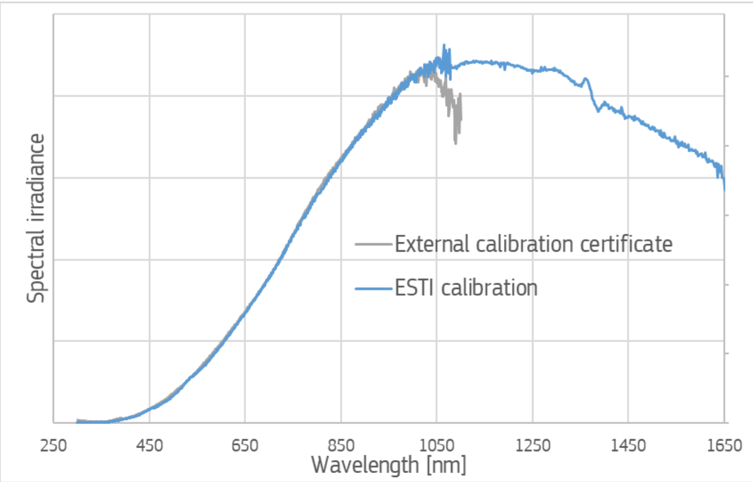


Source: JRC, 2020.

3.2.3 Verification of third-party calibration certificate for standard lamp

The spectroradiometers are usually calibrated against a standard lamp, which is typically calibrated in turn at a NMI. However, once calibrated, they can also be used to measure the light emission and irradiance of other standard lamps in order to verify them. The ESTI CAS was used in 2019 to measure a standard lamp (provided by SERIS) at the ESTI laboratories (**Figure 14**). The external calibration certificate of the lamp covers a wavelength range only up to 1100 nm, whereas the CAS measures up to 1650 nm. Good agreement was found up to 1000 nm, whereas above the calibration certificate deviates even from the expected emission distribution of a typical standard lamp. This is most likely due to the limited possibilities of the instrument used at the original calibration laboratory at the higher edge of the wavelength range. After ESTI informed SERIS of this problem, it is expected that they will take appropriate action to correct their calibration.

Figure 14. ESTI measurement of a standard lamp compared to its calibration certificate.



Source: JRC, 2020.

3.3 Calibration of PV devices

One principal activity of ESTI is to calibrate of PV devices, cells and modules. In the previous sections several comparisons on the instruments used in the PV performance measurements were described, whereas here the attention is on the PV device calibration itself. In the following sections, the specific approach of calibration of PV reference cells at ESTI is first described. Then a summary of the comparisons of calibration results to those of other laboratories is presented for both, PV cells and modules.

3.3.1 Annual calibration of ESTI reference cells

The ESTI laboratory has a set of about 30 PV reference cells used for everyday calibrations and generation of reference materials (section 4). In the annual calibration, all these reference cells are calibrated, either via primary or secondary method, against the primary reference (ESTI reference cell set).

3.3.1.1 Primary calibrations of PV reference cells

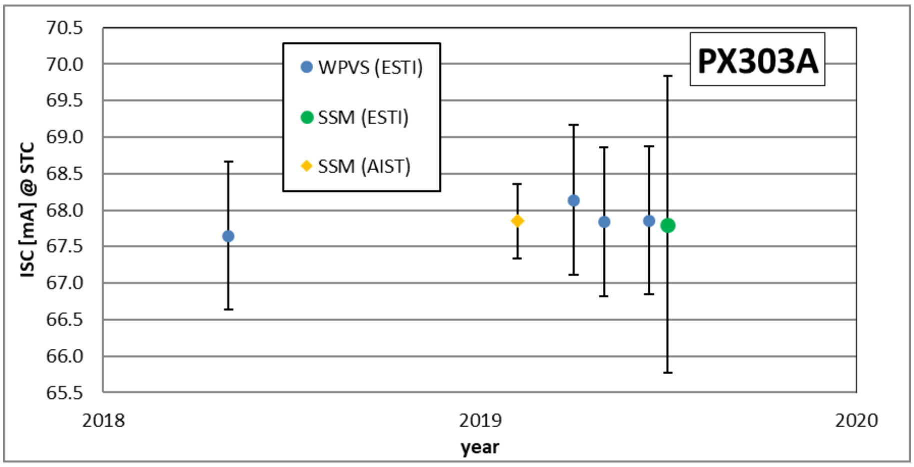
In 2019 a number of ESTI reference cells were calibrated by the primary solar simulator method. The results were used to update the WPVS values for the ESTI reference cell set and for the other cells as an additional cross-comparison with the annual secondary calibration (an example is shown in **Figure 15**). As the WPVS has the higher accuracy, these values are used in the operation of the ESTI laboratory.

3.3.1.2 Stability check of ESTI primary reference

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.

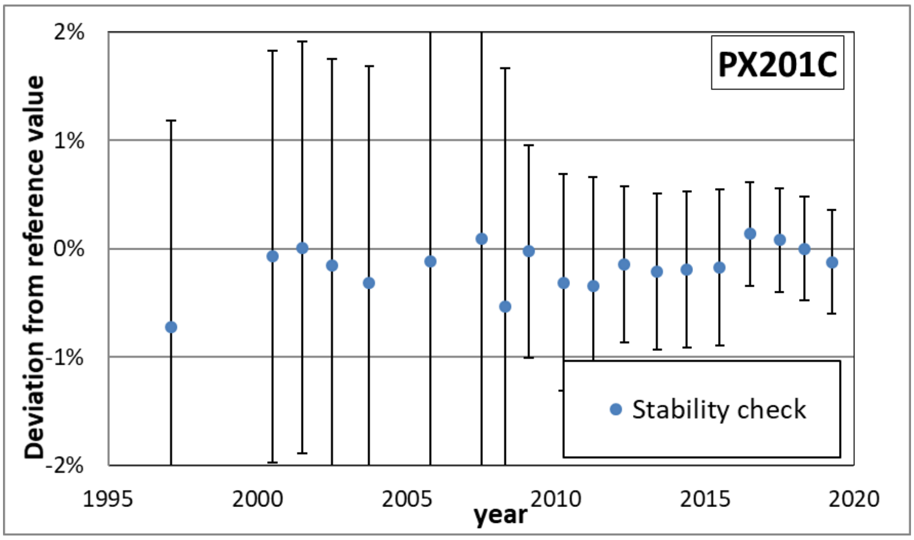
The first step consists in calibrating the five cells of the set against each other. This means taking in turn one of the cells as the reference device and calibrating the other four cells against it. The results are then compared to the last valid calibration value (CV) for each cell. As the set comprises five crystalline-silicon cells of different types, the drift of any member of the set can be detected by this cross comparison. Indeed, only if all cells in the set drifted exactly by the same amount relatively to each other, the drift would pass unnoticed. However, this occurrence is very unlikely. As an example, **Figure 16** shows the results of this stability check for cell PX201C over more than 20 years and with respect to the assigned reference value, which is the WPVS value as explained above. The verification shows that the results are fully consistent within their measurement UC, as the variability of the measured values (blue dots) is much less than the measurement UC shown as error bar for each point.

Figure 15. Example of primary calibration of reference cell PX303A by the solar simulator method at ESTI. The short-circuit current (I_{SC}) output of the cell is measured.



Source: JRC, 2020.

Figure 16. Stability of reference cell PX201C within the ESTI reference cell set.

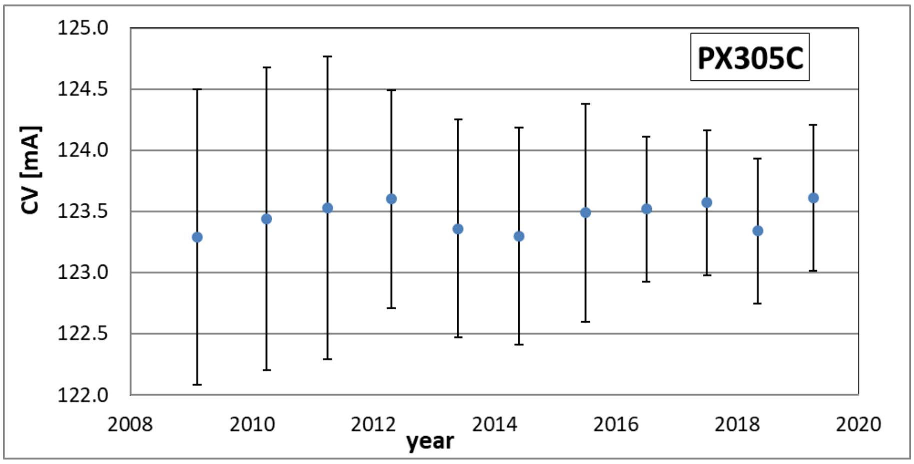


Source: JRC, 2020.

3.3.1.3 Calibration transfer to secondary reference cells

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 CV for the latter. As an example, the yearly calibration of one secondary reference cell (PX305C) is shown in **Figure 17**. Again, the yearly variability is much less than the measurement UC, indicating on the one hand that this reference cell itself is stable over time and on the other hand 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 17. Yearly calibration of reference cell PX305C in use at ESTI for routine measurements (typically for transfer to external reference cells of the ESTI traceability to SI).



Source: JRC, 2020.

3.3.2 Inter-laboratory comparisons with peer and other laboratories

As additional check of the reliability of the calibration results delivered by ESTI, bilateral, star-like and round-robin calibration inter-laboratory comparisons are regularly run with peer laboratories around the world. This includes reference cells as well as full-size PV modules. Such inter-laboratory comparisons are vital to guarantee the world-wide equivalence of PV calibrations, but as already mentioned above, they are also a requirement under the ESTI ISO/IEC 17025 accreditation as calibration laboratory.

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 sequence without going back to the initiator until the very end of the campaign itself. Contrary, in star-like inter-laboratory comparisons, the DUTs are always sent back by each participant to the coordinator, which usually performs intermediate measurements to verify the stability of the PV devices, which might be affected by damage due to handling or shipment or meta-stability issues (typically for thin-film PV technologies).

Sometimes, the expertise level of the participants is varied, ranging from peer laboratories to some with less expertise or even some newly entering the field of PV device measurement. The round-robin or star-like inter-laboratory comparisons between peer laboratories give a broader overview of equivalence in their measurement capabilities, as the effort required to achieve the same with bilateral comparisons would be larger. In the case of participants with different expertise level, the round-robin inter-laboratory comparisons are extremely useful to disseminate good measurement practices and to periodically check the laboratories procedures (even at the reference laboratory).

3.3.2.1 Bilateral comparison with the Japanese calibration laboratory (AIST)

Since several years there has been fruitful collaboration with the Japanese reference laboratory for PV calibration, AIST, by directly comparing the calibration of actual PV devices. AIST is one among the three to five of ESTI peer-laboratories for PV device calibration world-wide. In 2019, four ESTI reference cells were calibrated at AIST and compared to the results of calibration made at ESTI.

Table 3. Comparison of the calibration results of three PV reference cells between ESTI and AIST.

ESTI code	CV (ESTI) [mA]	CV (AIST) [mA]	E_n
PX303A	67.86 ± 1.02	67.85 ± 0.51	-0.01
PX404	103.10 ± 1.55	102.66 ± 0.77	-0.25
PX502A	59.27 ± 0.89	58.43 ± 0.44	-0.85

Source: JRC, 2020.

For three reference cells the agreement was satisfactory (absolute value of E_n larger less than or equal 1) (see **Table 3**, see also **Figure 15**). For the fourth cell, a relatively new reference cell with little calibration history, the comparison flagged an inconsistency (absolute value of E_n larger than 1). Therefore, that reference cell is at present quarantined and under further investigation to find the cause of the discrepancy. The cell was not (because of its recent acquisition) and will not (until the problem is resolved) be used for the calibration of other PV devices.

3.3.2.2 Calibration of high-efficiency cells (coordinator TÜV Rheinland Shanghai)

Modern crystalline-silicon PV cells have not only high efficiency, but also high capacitance. Traditionally the performance of PV devices is measured in the laboratory with pulsed solar simulators, as they are much cheaper and more readily available than steady-state solar simulators. However, the device capacitance poses challenges for measurements with pulsed solar simulators. After the inter-laboratory comparison on high-efficiency PV modules to which ESTI provided also the reference measurement [Mon 2019], further work on high-efficiency single cells was started. The comparison of measurement results is even more challenging when using bare cells, as they are extremely fragile and are likely to be damaged during round-robin measurement campaigns. Besides, the contacting itself is not trivial and sometimes not manageable by every participating laboratory. Therefore, the coordinator TÜV Rheinland, Shanghai, initiated a specific round-robin exercise using encapsulated cells (made specifically for these measurements) in order to compare the measurement methods. ESTI participated in this inter-laboratory comparison as one of the accredited calibration laboratories that will set the reference value, against which all other participants will be evaluated. Eight encapsulated cells of typical high-efficiency technology and size were calibrated and the results submitted to the coordinator. The overall results are expected to be available in 2020.

3.3.2.3 Calibration of full-size PV modules (coordinator FhG-ISE)

In 2019, ESTI performed the measurements on a set of nine full-size modules of various PV technologies, including thin-film PV, for the periodic (at present the third) inter-laboratory comparison with other peer-laboratories, namely AIST, NREL and FhG-ISE. Three modules of different crystalline-silicon technology already included in the previous two inter-laboratory comparisons were kept in the count as reference modules of the overall periodic exercise, in order to easily spot deviations at one laboratory in case of issues with the measurement procedures or setups. The other six modules were provided by the coordinator by purchasing them on the market before the inter-laboratory comparison' start, thus representing some of the most recent products available. The format was similar to the previous round-robin inter-laboratory comparisons [Sal 2017], with specific additional emphasis on the temperature coefficient measurement of the PV modules because this has been scarcely the object of real measurement comparisons up to now. After completion of the inter-laboratory comparison in early 2020, results are expected to be delivered and possibly published in late 2020.

3.3.2.4 Calibration of bi-facial PV modules (coordinator SERIS)

Bi-facial PV modules have entered the market since some years now, but the agreed measurement methods are so recent [IEC TS 60904-1-2 published in January 2019] that international inter-laboratory comparisons are not yet available. Therefore, in 2019, ESTI participated in the "1st International round-robin on bifacial modules", organised by the Solar Energy Research Institute of Singapore (SERIS) with a total of 24 partners. Overall sixteen PV modules were calibrated, of which four were mono-facial and twelve were bi-facial. The results of the mono-facial modules will serve to distinguish possible deviations due to the laboratories traceability chain for the irradiance measurement from deviations due to the actual bi-faciality assessment. The ESTI calibration certificates were submitted to the coordinator and the comparison results are expected to be available in 2020.

3.3.2.5 Calibration of bi-facial PV modules (PV-Enerate project)

Within the EURAMET EMPIR "PV-ENERATE" project, a round-robin inter-laboratory comparison was also started on bi-facial PV modules. The aim of the project is to develop, implement and improve an advanced metric based on energy rating following and further developing the example of the EURAMET EMPR PHOTOCLASS project [Mül 2018b]. A set of two mono-facial and six bi-facial PV modules was calibrated at ESTI. Also in this case, the results of the mono-facial modules will serve to distinguish possible deviations due to the laboratories traceability chain for the irradiance measurement from deviations due to the actual assessment of the bi-faciality. The ESTI calibration certificates were submitted to the coordinator and the results from all six participants are expected to be delivered in 2020.

4 Generation of PV reference material

Based on the calibration chain available at ESTI (section 2), transfer of the traceability chain to downstream PV calibrations is made for clients and partners. Essentially, all laboratories for PV measurements are required to have an unbroken traceability chain to SI units. 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 crucial 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 as calibration laboratory, and thereby providing them with the necessary traceability chain. 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.

ESTI was the first laboratory world-wide to be accredited initially for PV device testing (COFRAC 1-0717 in 1996) and later for PV device calibration (COFRAC 2-1671 in 2004). Subsequently ESTI transferred to the national accreditation body of the member state where ESTI is located (Italy), still as accreditation for PV device calibration (Accredia LAT 225 since 2011) [Acc2019]. The ESTI laboratory remains one with the largest range of calibration 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. This creates the uninterrupted metrological connection of the traceability chain between the testing laboratories or PV manufacturers and the international irradiance standard through ESTI.

Furthermore, the measurement capability of other PV laboratories has to be periodically assessed through proficiency testing. This does not concern the top-level calibration institutes (such as ESTI), as they fulfil this verification requirement by the calibration inter-laboratory comparisons between peer laboratories (see above), but rather all those test laboratories who routinely measure the 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 such as ESTI.

4.1 Accreditation as calibration laboratory

Fundamental to the service as reference material provider is the ISO/IEC 17025:2017 accreditation of the ESTI laboratory as calibration laboratory for electrical performance of PV devices. This ensures to the client that the calibration results provided by ESTI guarantee the unbroken traceability chain with a documented uncertainty evaluation. It is to be noted that the accreditation as calibration laboratory is distinct from that as testing laboratory, although both are covered by the same international standard [ISO/IEC 17025:2017]. The accreditation as calibration laboratory is more complex, requires a higher level of measurement uncertainty evaluation and is more rigid, thereby giving more reliability and confidence to the results provided. Accreditation entails the existence of an ISO/IEC 17025 compliant quality system and periodic external audits by the accreditation body, which in the case of ESTI is ACCREDIA. Typically, a four-year cycle is applied, where after the initial granting of an accreditation there will be two surveillance audits during the four-year period (2019-2023). At the end of this period, a new (more extensive) audit will be performed for re-accreditation, essentially as if the laboratory were applying for it for the first time. In 2019, ESTI underwent such a re-accreditation audit successfully [Acc 2019]. In particular, in July 2019 ESTI has been audited by ACCREDIA according to the new version of the standard ISO/IEC 17025:2017 for the re-accreditation and extension of the scope of accreditation to include “bifacial photovoltaic” devices. The new version of the standard introduced the “risk-based thinking”, enabling some reduction in perspective requirements and their replacement by performance-based requirements and giving greater flexibility to laboratories in the requirements for processes, procedures, documented information and organizational responsibilities.

Over the years, ESTI has constantly extended its scope of accreditation, which describes the type of the test devices, the parameters that can be measured together with their range, the methods used and the best measurement uncertainty attainable. ESTI has a wide scope for PV device types ranging from single solar cells to full-size PV modules. The electrical performance can be measured including the spectral responsivity and the resulting spectral mismatch correction as well as the temperature coefficients of the devices. For reference cells both primary and secondary methods are accredited. Furthermore, ESTI has been granted the *flexible scope* of accreditation for most of its procedures. This is based on the long-term experience gained by the laboratory and the high level expertise of its staff. It allows ESTI to adapt its measurement procedures, for example to accommodate new editions of international standards, without first passing an audit. The flexible scope allows ESTI to issue calibration certificates with the logo of the accreditation body also for those measurements. Therefore the flexible scope is essential for ESTI to be able to react promptly to measurement request from its clients, in particular in relation to new PV technologies.

The transition in defining the price paradigm of PV modules and cells from €/(watt-peak) to €/(produced kWh), that is the price per produced energy, requires the power matrix as crucial input for the calculations of energy rating. Therefore, in the last years ESTI has implemented the measurement facilities and procedures to be able to measure the full matrix. One essential prerequisite for such a measurement, though, is the ability to traceably measure the irradiance to which the DUT is exposed over a range of one order of magnitude. It is important to know whether the output of the reference device is proportional (i.e. linear) to the incident irradiance or not (i.e. non-linear). Two different methods (one primary and one secondary) were implemented at ESTI to check the reference devices for their linearity.

In 2019, the scope of ESTI accreditation was significantly extended and became effective in December 2019 (16/12/2019) (**Figure 18**). All of these are the first time that a laboratory has been accredited for the following tests as calibration laboratory:

- Power matrix: The measurement of electrical performance of PV devices (cells and modules) at non-STC was extended as to cover the entire power matrix [IEC 61853-1] (see also elsewhere in this report).
- Linearity: As a prerequisite for traceable measurement at irradiance levels different from the STC, linearity testing, with both primary and secondary methods, was accredited, in order to check the proportionality of the output of reference cells with respect to the incident irradiance level. The accredited secondary method covers as well the measurement of linearity for PV (reference) modules.
- Bi-facial PV modules: The measurement of bi-facial PV devices according to IEC TS 60904-1-2 was accredited.

In summary, ESTI is now accredited essentially for the full range of IEC measurement standards for PV devices [IEC 60891, IEC 60904 series, IEC 61853-1].

Figure 18: Accreditation certificate of the ESTI laboratory as a calibration laboratory.

ACCREDIA
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Membro degli Accordi di Mutuo Riconoscimento EA, IAF e ILAC
Signatory of EA, IAF and ILAC Mutual Recognition Agreements

ilac-MRA

CERTIFICATO DI ACCREDITAMENTO
Accreditation Certificate

ACCREDITAMENTO N. / *ACCREDITATION N.* **225T** REV. **02**

EMESSO DA / *ISSUED BY* **DIPARTIMENTO LABORATORI DI TARATURA**

SI DICHIARA CHE / *WE DECLARE THAT*
EUROPEAN COMMISSION
DG JRC – Joint Research Centre
Dir. C – Energy, Transport and Climate
Energy Efficiency and Renewables Unit
ESTI - European Solar Test Installation
SEDE PRINCIPALE/HEADQUARTER
▪ Via E. Fermi, 2749, TP 450 21027 ISPRA (VA) - Italia

MD-17-DT Rev. 02

È CONFORME AI REQUISITI DELLA NORMA: UNI CEI EN ISO/IEC 17025:2018 - Requisiti generali per la competenza dei laboratori di prova e taratura

MEETS THE REQUIREMENTS OF THE STANDARD: ISO/IEC 17025:2017 - General requirements for the competence of testing and calibration laboratories

QUALE **Laboratorio di taratura (LAT)**

AS ***Calibration laboratory (LAT)***

Data di 1ª emissione *1st issue date* **30-09-2011**	Data di Modifica *Modification date* **16-12-2019**	Data di Scadenza *Expiry date* **29-09-2023**
Ing. Rosalba Mugno Il Direttore di Dipartimento *The Department Director*	Dott. Filippo Trifiletti Il Direttore Generale *The General Director*	Ing. Giuseppe Rossi Il Presidente *The President*

L'accreditamento attesta che il Laboratorio ha la competenza per operare quale Centro di taratura ACCREDIA per le grandezze, i campi e le incertezze di misura riportati nella tabella allegata al presente certificato di accreditamento. Il presente certificato non è da ritenersi valido se non accompagnato dalla tabella allegata e può essere sospeso o revocato in qualsiasi momento nel caso di inadempienza accertata da parte di ACCREDIA. La validità dell'accreditamento può essere verificata sul sito WEB (www.accredia.it) o richiesta direttamente al Dipartimento di competenza. Questo Laboratorio è accreditato in accordo alla norma internazionale ISO/IEC 17025. L'accreditamento dimostra che il laboratorio possiede competenza tecnica per lo scopo definito. I requisiti del sistema di gestione riportati nella norma ISO/IEC 17025 sono scritti in un linguaggio attinente all'attività di laboratorio e sono generalmente in accordo con i principi della norma ISO 9001 (si veda il comunicato congiunto ISO-ILAC-IAF dell'Aprile 2017).

Accreditation attests that the Laboratory has the competence to operate as calibration Centre of ACCREDIA, for the physical quantities, the range and uncertainty of measurement reported in the table attached to the present accreditation certificate. The present certificate is valid only if associated to the annexed schedule, and can be suspended or withdrawn at any time in the event of nonfulfillment as ascertained by ACCREDIA. The in force status of the accreditation may be checked in the WEB site (www.accredia.it) or on direct request to relevant Department. This laboratory is accredited in accordance with the recognised International Standard ISO/IEC 17025. This accreditation demonstrates technical competence for the defined scope. The management system requirements in ISO/IEC 17025 are written in language relevant to laboratory operations and generally operate in accordance with the principles of ISO 9001 (refer joint ISO-ILAC-IAF Communiqué dated April 2017).

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ACCREDIA

Sede operativa: Strada delle Cacce, 91|10135 Torino - Italy|Tel. +39 011 328461|Fax +039 011 3284630
Sede legale: Via Guglielmo Saliceto, 7/9|00161 Roma - Italy|Tel. +39 06 8440991|Fax +39 06 8841199
info@accredia.it|www.accredia.it|Partita IVA - Codice Fiscale 10566361001

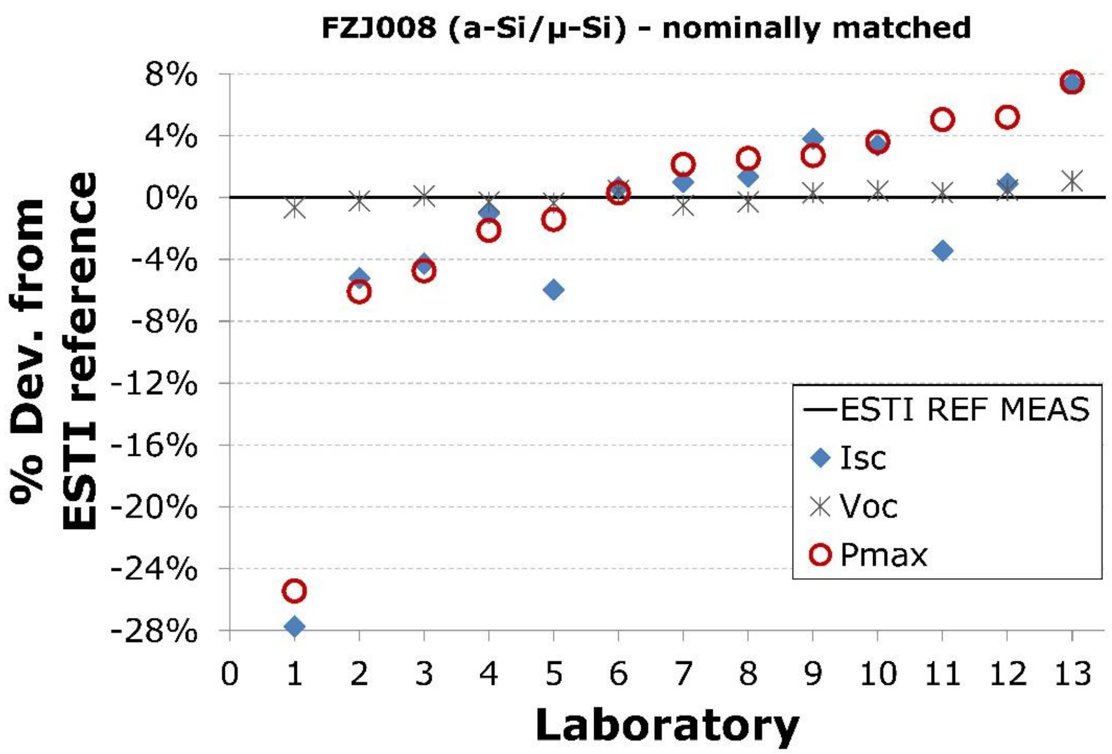
Source: Accredia, 2019.

4.2 Reference measurements for proficiency testing

Monolithic multi-junction (MJ) PV devices are formed by the superposition of two or more photoactive layers electrically connected in series. Such devices have long been used in space but were also developed for terrestrial applications. Their market share has reduced over the last five years as they were not cost competitive with respect to crystalline silicon, the main PV technology. More recently there has been renewed interest as it is now possible to manufacturer MJ PV modules using emerging PV technologies in particular perovskite solar cells.

MJ devices require a more complex measurement procedure (as opposed to the more common single-junction PV devices), which is not readily or fully available at laboratories. Therefore, between 2016 and 2017 a proficiency testing campaign was carried out with ESTI serving as the reference laboratory, against which all other participants were evaluated. ESTI stabilised and calibrated the devices, and then they were circulated to 13 other laboratories before returning to ESTI for verification of the final performance. ESTI also performed the overall data analysis of the proficiency test, as the reference measurements were not made available to participants until their deviations from the reference was communicated at the end of the project (December 2017). A presentation of preliminary and partial results has been published at the EU PVSEC 2019 [Lau 2019], showing the deviation of all participating laboratories against the reference value as determined by ESTI, such as in **Figure 19**. The results have then been evaluated in more detail, including a qualitative comparison of the spectral responsivity as submitted by some participants, and will be published in a peer-reviewed paper currently under preparation.

Figure 19. Percentage deviation from the reference value as measured by ESTI for the parameters short-circuit current (I_{SC}), open-circuit voltage (V_{OC}) and maximum power (P_{max}) for the tandem cell FZJ008, which was nominally currentmatched.



Source: JRC, 2020.

4.3 Reference devices for clients

In 2019, ESTI calibrated a number of reference devices for clients (**Table 4**). A short description of each case is given in the following sub-sections.

Table 4. Overview of ESTI calibration certificates issued in 2019 to clients and partners under its ISO/IEC 17025 accreditation as calibration laboratory.

Client	ESTI job code	Number of calibration certificates issued
CENER (Spain)	DC-19-UW DC-19-VG	4 7
CSIR Energy Centre (South Africa)	DC-19-UM	1
c-Si module manufacturer	DC-19-VK	3
EURAC Research (Italy)	DC-19-VF	6
Loughborough University (UK)	DC-19-VJ	5
Politecnico di Milano (Italy)	DC-19-UY	1
PV Lab (Germany)	DC-19-VH	5
SERIS (Singapore)	DC-19-VM	4
Total		**36**

Source: JRC, 2020.

4.3.1 CENER (ES)

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 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 to CENER and, through it, to its clients. This is in the framework of international harmonisation of PV device calibration and their traceability.

4.3.2 CSIR Energy Centre (South Africa)

ESTI is collaborating with the PV testing facility of the Energy Centre of the Council for Scientific and Industrial Research (CSIR). The Energy Centre PV facility 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.

4.3.3 c-Si PV module manufacturer

ESTI provided calibration certificates to a major c-Si PV module manufacturer, which will use this calibrated PV modules as golden modules to measure their production.

4.3.4 EURAC research (IT)

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.

4.3.5 Loughborough University (UK)

ESTI is collaborating with the Applied Photovoltaic Research Laboratory of the University of Loughborough, UK, 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.

4.3.6 SERIS (Singapore)

ESTI is collaborating with the Solar Energy Research Institute of Singapore (SERIS) in the area of PV device assessment as well as new and improved measurement methods. ESTI provides SERIS with traceable calibration of their PV reference solar devices. This is in the framework of international harmonisation of PV device calibration and their traceability.

4.3.7 Politecnico di Milano (IT)

ESTI provides the Politecnico di Milano with calibration of their reference PV solar devices, which are used in the field of solar energy for PV technology development. This work is in support of European Regions and in the framework of international harmonisation of PV device calibration and their traceability.

4.3.8 PV Lab (DE)

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.

5 Validation and verification of PV device performance

PV technology is still rapidly improving. Claims of new world record or other extraordinary PV device performance are announced several times per year, both for the more established technologies such as crystalline silicon and for new emerging technologies such as perovskite solar cells (PSC). The claims are usually made by the manufacturers of the new devices. However, they might not have the equipment or the expertise to measure the PV device performance accurately and traceably. Therefore, it is important that such claims are verified by independent calibration laboratories, which are not only independent of commercial or national interest, but also have the required expertise in measurement technology. ESTI is one of the few laboratories in the world recognised as fully capable of independently verifying and validating claims of exceptional performance of PV devices, based on its experience and measurement capability.

5.1 Co-authorship of world record PV efficiency tables

For many years, ESTI has co-authored the world record efficiency tables published twice a year in Progress in Photovoltaics [Gre 2019a] [Gre 2019b]. Results for inclusion in the tables are submitted to the board of authors, which consists of representatives of the four peer-laboratories for measurement of PV devices, namely AIST, ESTI, NREL and ISE-FhG. The authors critically review the submitted results, based on their high-level technical expertise and long-term experience. Based on the high profile of the board of authors, these publications are highly regarded in the field of PV and cited very frequently.

5.2 Polycrystalline silicon

Improvements are still made for PV modules based on traditional crystalline silicon technology. ESTI verified that a polycrystalline silicon PV module had a higher efficiency at the time of measurement compared to the published world record efficiency.

5.3 Perovskite solar cells (PSC)

Perovskite solar cells (PSC) is a new emerging PV technology, which has been introduced as recently as 2009, but since then it made enormous progress in its efficiency. However how to accurately determine the electrical characteristics of these devices remains a big challenge (section 6.3.3). A PSC manufacturer requested ESTI to calibrate potential world-record perovskite mini-modules and to certify the performances. A new protocol to measure such devices was developed and validated at ESTI for this purpose. A total of three devices were certified to have efficiencies higher than the published record value at the time of measurement.

6 Pre-normative research

ESTI deals with methods applicable to all PV devices as well as with some 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. This requires recognised independent assessment, which can only be provided and developed based on long-term experience and expertise.

The ESTI laboratory performs 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.

The activities on the measurement methods described here span from the actual development of new methods and their validation up 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 ESTI accreditation scheme. If the measurand (for example the voltage) is already included in the accreditation scheme, this procedure allows the temporary inclusion of the validated methods under the flexible scope, which ESTI has gained under its ISO/IEC 17025 accreditation, with the possibility to issue accredited calibration certificates. The method is included successively in the published list of accredited methods once the accreditation body has approved it.

6.1 Temperature coefficients of PV devices

Temperature coefficient measurements were compared with peer laboratories as such comparisons have historically been sparse in the PV community and even when reported they had shown significant inconsistencies. ESTI extended its facilities and improved its measurement procedures for determination of temperature coefficients. In the following specific inter-laboratory comparison consistency of the results (that is agreement within declared measurement uncertainties) between all participants was found for the temperature coefficient of the short-circuit current and for several devices of different size and PV technology [Sal 2019]. This is significant improvement over previously published results. Work is already in progress at ESTI to extend the same methodology to peer-laboratories inter-comparison on the temperature coefficients of open-circuit voltage and maximum power for a range of full-size PV module technologies.

6.2 Linearity of PV reference devices

The concept of linearity of a PV device is related to the proportionality of the PV device short-circuit current to the incident irradiance. 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 PV modules power matrix [IEC 61853-1] at irradiances between 100 W/m^2 and 1100 W/m^2. In this case, any deviation of the short-circuit current of the reference device from the pure proportionality to the incident irradiance will directly contribute to a measurement uncertainty. However, in practise the linearity has been neglected in the past, partly because it was not well-defined and partly because the proposed measurement procedures were not suitable for its assessment.

6.2.1 Project leader for PV linearity standard

All linear dependence evaluations, including the linearity of PV devices as proportionality to irradiance, are defined and assessed in the so called PV linearity standard [IEC 60904-10]. 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 a proportionality function, 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 by the standard 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. The two-lamp method uses the flux addition principle to determine linearity. The device under test is exposed to the optical flux from a first source, then from a second source and also from both sources together. By comparing the respective output signals of the device under test, its linearity can be determined. ESTI developed a data analysis method such that the information on linearity is aggregated over the entire range of irradiances of interest and can be compared to other methods [Bli 2019]. The current version of the IEC 60904-10 standard is insufficient. The measurement methods in the standard as well as the data analysis have to be improved as evident from the research performed by ESTI. The standard is therefore currently under revision and the (technical) project leadership has been assigned to ESTI.

6.2.2 N-lamp method

The two-lamp method is 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, which means that it does not require any reference device[2] nor a priori knowledge about the DUT. However, even after the data analysis developed for it at ESTI, it does not provide detailed data on linearity with a convenient step over the whole range of interest. Therefore, ESTI developed the scheme towards the "N-lamp method", which is ideally and naturally suited to determine the non-linearity of PV devices and is unique in the field of PV [Mül 2019a]. The improvement provided by this method 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, ideally matched to the power matrix measurements [IEC 61853-1]. This method provides quantitative information about linearity with improved accuracy such that it can be used to quantitatively correct measurements for the effects of non-linearity.

6.3 Measurement and calibration of bi-facial PV

ESTI is a partner in the EURAMET-founded EMPIR project "PV-ENERATE" [PV-ENERATE], which investigates the metrology aspects of performance measurements for bi-facial PV modules (see also section 3.3.2.5). The ESTI contributions to the project are described in the following subsections.

6.3.1 International Technical Specification for measurement of bi-facial PV devices

ESTI was member of the project team within IEC to develop the technical specification for measurement of bi-facial PV devices, which was published in January 2019 [IEC TS 60904-1-2]. During the year, ESTI implemented it into its laboratory practices and was successfully accredited on this by the end of 2019.

6.3.2 Dedicated solar simulator for measurement of bi-facial PV modules

ESTI is already accredited for the calibration of bi-facial PV modules using the equivalent irradiance method, which essentially illuminates the PV module from the front side only with the combined irradiance level to which both front and rear module surfaces would be exposed in normal installation. In this context, the influence of stray-light rear-side illumination was studied [Lop 2019a] [Lop 2019b]. To further increase the ESTI facilities and validate the alternative test method, where the bi-facial modules are actually illuminated with a high irradiance from the front side and a lower irradiance from the rear side, a solar simulator based on light emitting diodes (LEDs) is being constructed for providing this rear-side illumination. The prototype LED simulator developed at ESTI [Sha 2018] has demonstrated very good performance, enabling illumination of the rear side of a bifacial module at variable irradiances to above 300 W/m^2. When combined with a commercial pulsed solar simulator for the characterisation of a bi-facial mini-module, double-side illumination produced results similar to those obtained with the solar simulator using equivalent irradiance and single-side illumination (<1% difference). The non-uniformity below 5% means it meets the requirements of IEC TS 60904-1-2 [IEC TS 60904-1-2] for use with bi-facial modules. Its spectral difference to the reference spectrum [IEC 60904-3] can be compensated by a mismatch correction, or by using the effective irradiance method. The uniformity of the LED solar simulator can also be readily adjusted, by changing the geometry or by varying the powering of individual LEDs, which could enable the performance of bi-facial modules to be evaluated over the full range of outdoor conditions when the required non-uniformity conditions can be achieved. The modular simulator design means that extension of the area to allow measurement of full-size bi-facial PV modules is straightforward and currently under construction.

[2] Normally in PV the light intensity from the lamps has to be measured by a reference device. However, here the lamps are used as generic light sources and the output of the device under test is compared for illumination by different sets of lamps.

6.3.3 Outdoor installation of bi-facial PV modules

The performance of bi-facial PV modules will depend in a complex manner not only on their orientation towards the sun but also on the surroundings, in particular the ground surface and nearby objects, as they contribute to the rear-side irradiance [Ozk 2019]. This cannot be easily simulated inside the laboratory where solar simulators are used for the performance measurements. Therefore, ESTI installed a number of bi-facial PV modules outdoors, ranging from single modules (**Figure 20**) to small arrays (**Figure 21**). Particular attention was given to the design of the environment (covering the surrounding ground surface with white gravel) and the orientation towards the sun, featuring traditional tilted south facing and vertical east-west facing. The latter is a possibility to shift the power-output daily profile of PV from single-peak around lunchtime to double-peak in the morning and evening, providing a better match to typical power load demands of consumers, especially prosumers.

Figure 20. ESTI outdoor test field installation of single bi-facial modules.

Source: JRC, 2019.

Figure 21. ESTI outdoor test field installation of bi-facial modules arrays.

Source: JRC, 2019.

6.4 Emerging PV technologies

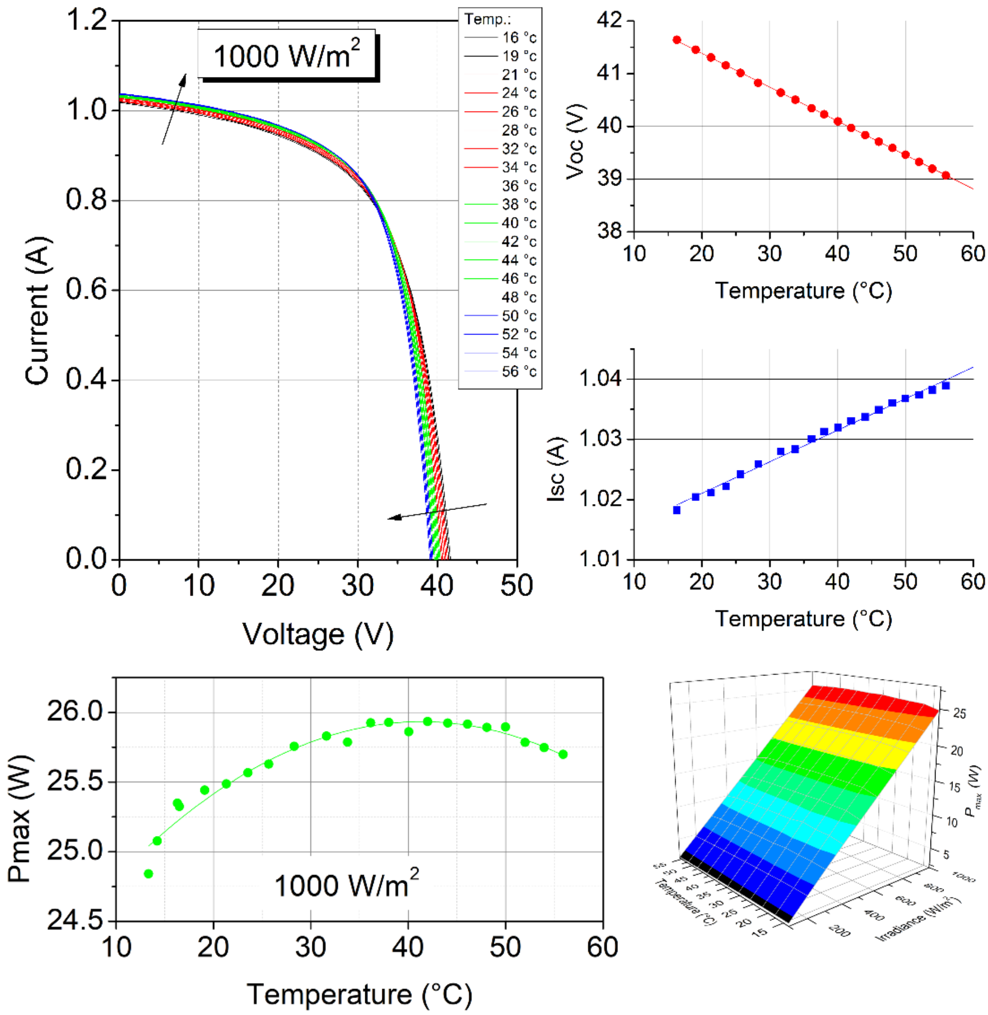
6.4.1 International Technical Report on measurement of emerging PV technologies

ESTI participated in an international group of experts working on an IEC document containing guidelines for assessing emerging PV technologies. The aim was to reach broad consensus with other internationally accredited laboratories on measuring the efficiencies of these devices, thus defining best-practice methods for the measurements of emerging PV devices. The IEC technical report "Measurement protocols for photovoltaic devices based on organic, dye-sensitized or perovskite materials" was published in July 2019 [IEC TR 63228]. It is envisaged that the document will develop into an IEC Technical Specification and then an IEC standard in due course.

6.4.2 Organic PV (OPV)

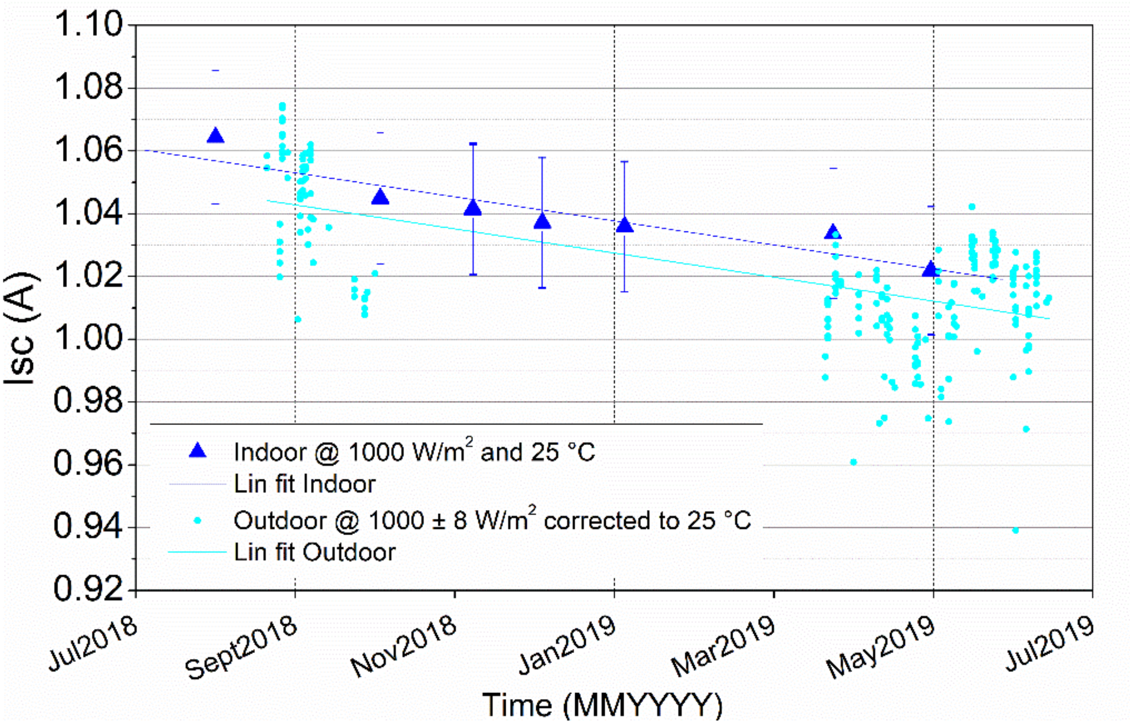
A large-area organic PV module was first characterised indoor at different temperature-irradiance combinations (**Figure 22**), then mounted outdoors in July 2018 and connected to a maximum-power tracking system for medium-term monitoring of its electrical performance. Periodically, the module has been taken indoors for electrical performance measurements and then re-mounted outdoors. One aspect of this work is to study the medium-term degradation (**Figure 23**), which is the main limiting factor for the massive introduction of OPV technology in the market. An account of the work was given at the EU PVSEC 2019 and will soon be published [Bar 2020].

Figure 22. Current-voltage (I-V) curves of OPV module measured indoors under simulated sunlight at 1000 W/m² and increasing temperature from about 15 °C to about 55 °C, and resulting temperature coefficients and power matrix.



Source: JRC, 2019.

Figure 23. Evolution of the OPV module short-circuit current (I_{SC}) during one-year exposure to natural sunlight. Data extracted from outdoor monitoring and from the periodical measurements at solar simulator show consistently a reduction of about 4% over the first year.



Source: JRC, 2019.

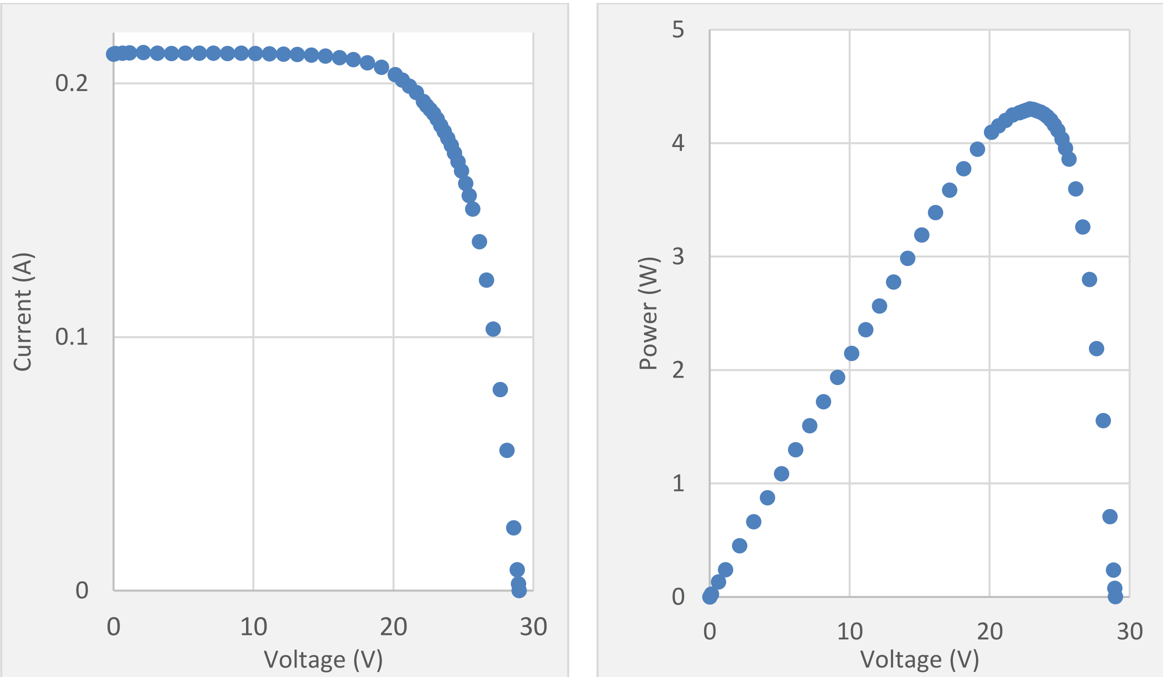
6.4.3 Perovskite solar cells (PSC)

Perovskite solar cells (PSC) have not only potential issues with their stability [Khe 2020], but also a slow response time of the order of several seconds up to minutes to changes in the voltage that is externally applied during the performance measurements. While this is not a problem for deployment in the field, where the conditions under natural sunlight are also slowly changing, it poses challenges for performance measurements under both natural and simulated sunlight, as usually the PV devices are exposed to a wide range of varying bias conditions to obtain the current-voltage characteristics. These traditional measurement routines will invariably give misleading results for PSC technology. Therefore, a new measurement protocol to measure such devices was developed at ESTI and validated. With this the measurements of the innovative perovskite-based PV devices were performed.

The new protocol is based on a manual voltage scan around the conditions of maximum-power point, which is the most relevant as it is the condition at which the modules will be held when installed in the field. Data acquisition at each bias-voltage condition is made when the current has stabilised. Further measurement at other voltages, including short-circuit current and open-circuit voltage points, are then made to construct full current-voltage and power-voltage curves (**Figure 24**), which are still the standard points to report PV electrical performance. It is also checked that the same maximum power is obtained after these intermediate measurements, giving additional information about the device stability.

This pre-normative research will also feed into the further development of the IEC documents concerning measurement of emerging PV technologies (see section 6.4.1). ESTI also discusses measurement protocols with their peer laboratories, in particular AIST, NREL and ISE-FhG.

Figure 24. Current-voltage and power-voltage curves of a PSC device: All measured points were acquired after stabilisation according to the newly developed measurement protocol.



Source: JRC, 2020.

7 Dissemination of knowledge

ESTI is committed to disseminate its knowledge as widely as possible. The technical expertise is regularly published in peer-reviewed publications and presented at international conferences. Furthermore, there are outreach activities to the general public.

7.1 Scientific dissemination

7.1.1 Peer-reviewed scientific publications

In 2019 a total of nine peer-reviewed publications were published with ESTI authorship (**Table 5**). They are cited in the relevant sections of this report together with the description of the respective work.

Table 5. Overview of peer-reviewed publications with ESTI authorship published in 2019.

Journal	Impact factor	Number of publications	References
Progress in Photovoltaics Research and Applications	7.776	4	[Gre 2019a] [Gre 2019b] [Mon 2019] [Vir 2019]
Solar Energy	4.674	3	[Bli 2019] [Lop 2019a] [Sal 2019]
Measurement Science and Technology	1.861	1	[Mül 2019a]
AIP Conference Proceedings	0.38	1	[Ozk 2019]

Source: JRC, 2020.

7.1.2 European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC)

The EU PVSEC Conference is the world's largest PV conference, reflecting Europe's R&D strength in this area and its pioneering role in large-scale deployment. Since 1996 the conference receives (in-kind) support from the JRC, which provides the overall coordinator for the scientific programme (technical programme chair).

The first of these conferences was organised and established by the European Commission in 1981 (Stresa, Italy), when a large "European PV Pilot Programme" was launched. The conference took place every 18 months until 2004, and since then annually. This conference covers all aspects of PV, from basic research, innovation and deployment to architecture and policies. A particular emphasis is given, through the exhibition, for a tight partnership between academia, research institutions and industry. Given the strong and continued growth rate, the innovation cycle is very short. The industry of manufacturing equipment plays a key role, as they find immediately research results to be transferred into commercial products.

The JRC provides the scientific programme coordination of the conference since 1996. This includes chairing a scientific committee of about 200 international high-level scientists and industry experts from all over the world, which review the submissions received after a public call for papers. The committee typically receives more than 1000 papers, and selects them for plenary, oral or poster presentations, while rejecting around 10% of submissions. The fine-tuning and invitation process is coordinated by the JRC. While ensuring a balanced geographical coverage, span of scientific/technical issues and industry relevance in the conference programme can be demanding, the conference has been very successful every year to date. In 2019, over 2000 registered participants attended the 36th edition held in Marseille, France. The JRC also provided the chair of the international scientific advisory committee and several members of the scientific committee.

The JRC contributed with the following items to the 36th EU PVSEC 2019:

- A booth in the exhibition giving information to the participants about the work of the JRC in the field of PV, but also more in general about the JRC, the European Commission and the European Union.
- ESTI staff members were (co-)authors of two plenary, three oral and four visual presentations. One of the two plenary presentation entitled 'From sunlight to power: The history of achieving a globally harmonised

approach to PV measurement' was selected as a keynote presentation. It presented in detail the history, development and implementation of the WPVS at ESTI [see also section 2.4].

— The JRC organised a parallel event on 'Standardisation of the Protocols for Emerging PV Technologies' to discuss the development of common measurement guidelines for a reliable characterisation of emerging PV technologies. The specific needs and benefits for material research laboratories, testing laboratories and industrial project partners were addressed. At the workshop four invited speakers presented their experience in the field and the JRC presented the new IEC TR 63228 entitled 'Measurement protocols for photovoltaic devices based on organic, dye-sensitised or perovskite materials'.

7.2 Outreach activities for the general public

7.2.1 ARTEFACTS exhibition

The ARTEFACTS exhibition is a cooperation between the Museum für Naturkunde Berlin, the JRC and the American photographer J Henry Fair [ARTEFACTS]. In times of "alternative facts" and "fake news", ARTEFACTS openly and reflectively discusses issues of environmental relevance with politics, science and society. ARTEFACTS bridges ART and FACT. ESTI contributed to the part of the exhibition concerning PV.

7.2.2 Make your own solar cell

A dedicated hands-on activity has been developed by ESTI staff for the public, in particular pupils. The objective of the activity is to involve the public by creating an innovative solar cell with simple materials like blueberry juice, graphite from a pencil and iodine. At the end of the activity, the solar cells are measured and used to power a calculator.

The activity was performed at four distinct events in 2019 (TedX 2019, Meet me Tonight 2019, Science for Europe 2019 and JRC School Days 2019 (**Figure 25**)) and approximately 300 people were involved in total. The activity has been a great success and very positive feedback was received from all participants.

Figure 25. Students measuring the solar cells made with blueberry juice.

Source: JRC, 2019.

8 Conclusions

The two main driving forces behind the work described in this of this report are:

- The PV industry based on the predominant PV technology, which is crystalline silicon, is cost competitive with other energy generation technologies. As a consequence, the assessment of electrical performance of and energy generation from PV modules is required with the highest possible accuracy, which is available at ESTI.
- The PV industry and research community are highly innovative, regularly introducing new products, such as bi-facial PV modules or emerging PV technologies based on new materials, such as perovskite solar cells. This requires the capability to adapt existing or to develop new measurement techniques to evaluate these new products in a realistic and reliable way, thus giving support to industry as well funding and financing institutions for their decision on the feasibility of PV projects, both technologically and economically.

The European Solar Test Installation (ESTI) of the JRC addresses these issues:

- Developing and implementing measurement procedures to improve the accuracy of the calibration of PV devices. The measurement of the solar irradiance is essential for an accurate measurement of energy production from PV. ESTI has developed and rigorously implemented the world photovoltaic scale (WPVS) approach and thereby improved the accuracy of solar irradiance determination from around 2% in the mid-1990s to currently less than 0.25%, the latter being the best accuracy available anywhere. This led to the improvement of the accuracy of PV modules' power measurement from 2.6% to 1% providing the highest accuracy available from any PV calibration laboratory. This reduction corresponds to a monetary value of €480 million for the annual world-wide PV production. ESTI is a fully ISO/IEC 17025 accredited calibration laboratory for these measurements and has issued a total of 72 calibration certificates to clients in 2019. ESTI's facilities and expertise are employed as follows:
  - To regularly compare electrical performance measurements of PV devices to peer-laboratories around the world, ensuring the international equivalence of calibration and measurement results.
  - To generate PV reference material for other laboratories, thus providing a crucial step in the traceability chain for PV from the solar irradiance measurement to the final PV device performance measured in the factory production line.
  - To validate independently claims of potential new efficiency record-breaking PV devices. In 2019 there were three such requests and all of the submitted devices had efficiencies outclassing the published records at the time of measurement.
- Executing pre-normative research on PV measurement technologies and accompanying the standardisation process as active member of international standardisation organisation such as the International Electrotechnical Commission (IEC) and the European Committee for Electrotechnical Standardisation (CENELEC) [Sam 2020]. It achieved this in the following way:
  - ESTI has led the development of the international standards for PV energy rating [series IEC 61853], which relates advanced power measurements on the PV modules (see above) to estimates of site-specific energy production. Currently, ESTI is one of the very few laboratories accredited as calibration laboratory for the full power matrix measurement [IEC 61853-1].
  - Similarly, ESTI participated in the project team for the development of the technical specification for the measurement of bi-facial PV modules [IEC TS 60904-1-2 published in January 2019] and became accredited for these measurements at the end of 2019.
  - Adapting existing and developing new measurement procedures for perovskite solar cells, the currently fastest developing new PV technology with frequent announcements of record-breaking efficiencies. This allowed ESTI to provide realistic evaluation of this technology under its accreditation scheme.

The PV sector requires accurate and reliable assessment of electrical performance of PV modules. Due to the high-tech character and the innovative aspect, this requires that calibration laboratories, such as ESTI, provide assessment of the performance to be used as reference values by the PV industry. To keep up with the development of the PV sector, this requires further improvement of the accuracy of PV performance measurement as well as development of new measurement procedures for emerging PV technologies.

One key aspect is to extend from the traditional measurement of output power of PV modules to a metric related to their energy production when deployed in the field.

Furthermore research and development of measurement methods is urgently needed, accompanying the development of new PV products, be it new concepts (such as bi-facial PV modules) or new PV technologies (such as perovskite solar cells). Often the PV industry can have products in the market faster than the respective measurement technology is developed. This is because the pre-normative research and the following standardisation process requires typically several years, whereas some new technologies such as bi-facial PV modules appear quickly in the market. Indeed, modern crystalline-silicon PV modules are inherently sensitive to light from both sides (i.e. bi-facial). A new PV product can easily be created by only changing the rear side cover of a crystalline-silicon PV module from standard opaque material to transparent glass. In the absence of published international standards for advanced measurement of PV devices, it is very important for both manufacturers and legislators to have full availability of experienced reference laboratories, such as ESTI, which by applying their knowledge and experience can react to these changes and perform pre-normative research which accompanies these industrial developments in real time until the standards bodies can react..

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List of abbreviations and definitions

AIST	National Institute of Advanced Industrial Science and Technology, Japan
AIT	Austrian Institute of Technology, Austria
AM	Air mass
BIPV	Building Integrated PV
CEA INES	Alternative Energies and Atomic Energy Commission, National Solar Energy Institute, France
CENELEC	European Committee for Electrotechnical Standardisation
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
DNI	Direct normal irradiance
DSM	Direct Sunlight Method
DSR	Differential spectral responsivity
DSSC	Dye Sensitised Solar Cell
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
EU	European Union
EURAMET	The European Association of National Metrology Institutes
FDIS	Final Draft International Standard
FhG-ISE	Fraunhofer Institute for Solar Energy Systems, Germany
GHI	Global horizontal irradiance
GNI	Global normal irradiance
GSM	Global Sunlight Method
IEC	International Electrotechnical Commission
IEC TC 82	IEC Technical Committee 82 (Solar photovoltaic energy systems)
IEC TR	IEC Technical Report
IEC TS	IEC Technical Specification
INTA	National Institute of Aerospace Technology, Spain
IPC	International Pyrheliometer Comparison
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
LCOE	levelised cost of electricity
LED	Light Emitting Diode
MJ	Multi-junction (PV device)
ms	millisecond
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
PSC	Perovskite Solar Cell
PTB	Physikalisch-Technische Bundesanstalt, Germany
PV	Photovoltaic(s)
R&D	Research and development
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
TWh	Terra Watt hours
UC	Uncertainty
UCY	University of Cyprus, Cyprus
UEX	Universidad de Extremadura, Spain
UV	Ultraviolet light
VIS	Visible light
W	Watt
Wh	Watt hours
W_p	Watt peak (as measured at STC)
WPVS	World Photovoltaic Scale
WRC	World Radiation Centre
WRR	World Radiometric Reference
WSG	World Standard Group
WTO	World Trade Organisation

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Annex: Metrological comparison of measurement results

The comparison of measurement and calibration results in metrology is done using the concept of E_n number [ISO/IEC 17043] [ISO 13528]. When two independent measurements are performed, such as by two institutions or by the same institution but applying two different methods), each result is quoted 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 and is working also on transferring this acquired knowledge of UC calculation to other PV laboratories.

The E_n number analysis of two measurements is made with the following equation:

$$E_n = \frac{X_A - X_B}{\sqrt{(U_{95,A})^2 + (U_{95,B})^2}} \qquad (1)$$

with

X_A is the result from one laboratory (or one method)

X_B is the known reference value or the result reported by another laboratory or method

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

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

The rationale behind this is that the expression

$$U_{95,diff} = \sqrt{(U_{95,A})^2 + (U_{95,B})^2} \qquad (2)$$

is the combined uncertainty of the difference in measurement results

$$diff = X_A - X_B \qquad (3)$$

Their ratio, the E_n number, represents a metric that measures the distance between the two measured values in terms of their uncertainties which they both have compared to the true (unknowable) absolute value of the quantity under measurement.

It is evident from the above equation that, when the difference according to eq. (3) is zero, the E_n number equals also zero whatever the uncertainty of the measurements. However, the results of two measurements are never exactly the same, and the agreement of the two results is measured by the E_n number according to eq. (1). Consistency of the two results within declared measurement uncertainties is achieved if the E_n number belongs to the interval [-1 ; 1]. If this is not the case then at least one measurement result or its declared uncertainty are inconsistent. In this case the results are flagged and further in-depth investigation follows to determine the cause of the discrepancy. This might not be trivial, as the cause may range from simple mistakes to fundamental problems in the measurement method.

This E_n number approach has been applied at ESTI and in measurement comparisons with ESTI partners for several years. For laboratories in the field of PV measurement that participate in inter-laboratory comparisons and apply a quality system or have an ISO/IEC 17025 accreditation, the E_n number approach is increasingly accepted as the most suitable assessment method of the results.

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