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

Summary of the European Solar Test Installation's contribution to the energy transition in 2020 and 2021

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Contents

Abstract

The European Green Deal set out key actions in the promotion and deployment of renewable energies in order to realize the EU target of energy transition to a carbon neutral energy system. Photovoltaic solar energy is one of the key technology renewable energy sources to enable this transition. The European Commission's JRC with its *PV Energy project* and the dedicated *European Solar Test Installation* Laboratories has been working to support the development and deployment of innovative, dependable and reliable photovoltaic solar energy solutions. This report presents the contribution of the European Solar Test Installation to enable this transition. The document describes the activities carried out in support of innovation concerning new materials from universities and research centres, dissemination activities of best practice for measurement and testing to peer laboratories in the international community and the application of the knowledge generated to improve international standards for characterising and assessing photovoltaic technologies. In addition, we report how the expert knowledge of the JRC is contributing with our partner DG's to develop appropriate transition methods as part of the regulation for Ecodesign and Energy Labelling for PV modules, inverters and systems.

Foreword

This report is an update of the previous version [Mül 2019]. In principle an annual update is foreseen, however, due to the particular circumstances (Covid pandemic) the present report exceptionally covers two years, namely 2020 and 2021.

Acknowledgements

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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), which develops expertise for state-of-the-art assessment of electrical performance of PV devices based on traditional as well as emerging PV technologies. This report summarise the contributions actions and collaborations of the JRC's PV Energy project.: including actions in disseminating best practice in calibration and measurement of photovoltaic materials, the development of new methods to correctly characterise innovative PV materials, the contribution to turning these new methods into European and international standards and the development of technical methods for the inclusion in EcoDesign and Energy labelling regulations for the European market.

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 electrical 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 bifacial 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 subsequent standardisation process typically requires several years, whereas some new technologies such as bifacial PV modules appear quickly in the market. Indeed, modern crystalline-silicon PV modules are inherently sensitive to light from both sides (i.e. bifacial). 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 the availability of experienced reference laboratories, such as ESTI, which can provide official performance assessment based on their expertise and performed 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 bifacial 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 accuracy is implemented in and available through the ESTI reference cell set, a unique set of five primary PV reference cell held at ESTI. Through this the accuracy of PV modules' power measurement improved from 2.6% to 1% providing the highest accuracy available from any PV calibration laboratory. This reduction corresponds to a monetary value of approximately €500 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 64 calibration certificates to clients in 2020/2021. 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 2020/2021 one request was received for a device which had an efficiency 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 electrical performance assessment.
   - 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 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 1 TW in 2021, with about 130 GW installed in the EU in 2019 [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 2022].

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 200 GW in 2021 [ITR 2022] and a market value only for the PV module components reaching over €50 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, which 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 over 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, and 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 2022]. The JRC is also involved in the Ecodesign preparatory study [Sam 2022].
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 monitors the PV sector for decision-makers in policy and industry.

1.3 European Solar Test Installation (ESTI) at the JRC

ESTI is an ISO/IEC 17025 accredited calibration laboratory for the electrical performance of PV devices. 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 are 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 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 generally 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 and reported at 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 2020 and 2021 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).
- The technical expertise is directly used as input to EU policies (section 8).
- Finally, the findings are summarised and concluded (section 9).

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

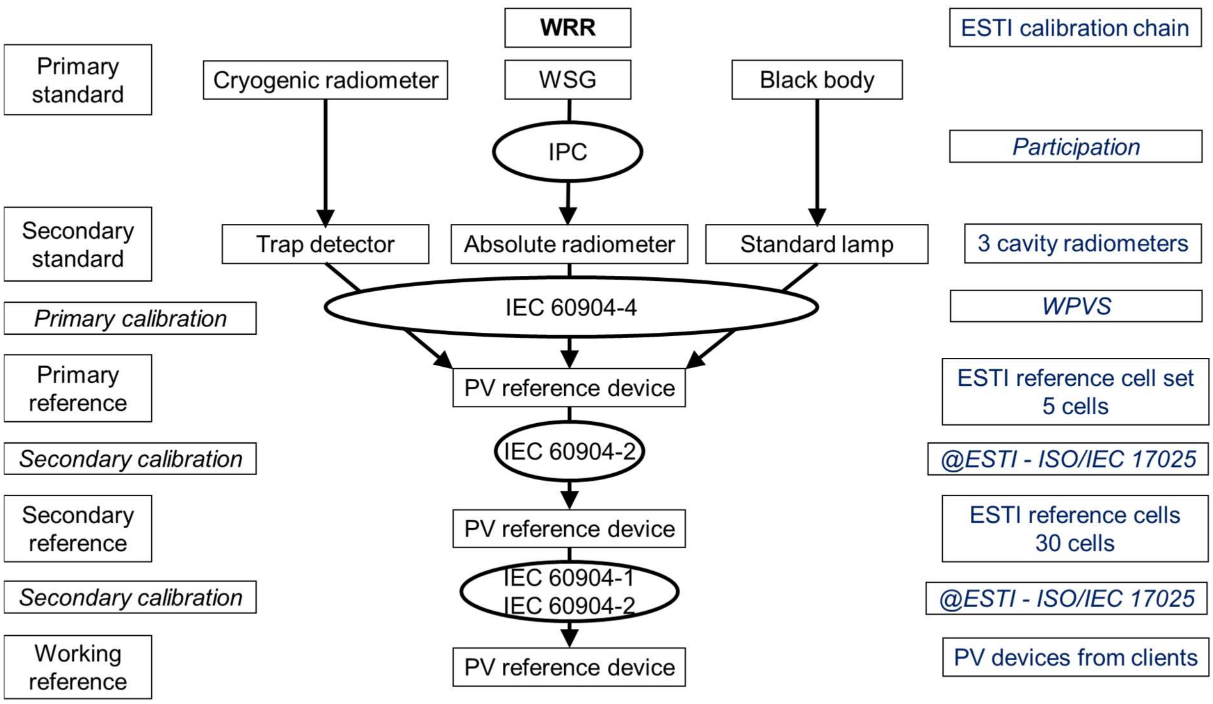
As for any measurement, the traceability of all measured quantities to international standards is a fundamental requirement. The assessment of electrical performance of PV devices requires the measurement of electrical parameters at well-defined solar irradiance conditions. The accurate and traceable 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) [Mül 2019].

2.1 Traceability for PV

A full account has been given previously [Mül 2019]. In summary, the irradiance measurement at ESTI can be traced to the World Radiometric Reference (WRR), which is a conventional detector-based measurement standard for direct natural sunlight (**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. Once the transfer to a PV reference device (typically a solar cell) has been achieved traceably by a primary calibration method, 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].

The calibration of PV devices against cavity radiometers requires special measurement procedures and skills. These 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 was performed in 2021 (section 3.1).

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, 2021.

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.

2.3 World Photovoltaic Scale (WPVS)

ESTI implemented the world photovoltaic scale (WPVS) in 1995 as the WPVS is the best reference, providing the highest level of reliability of solar irradiance measurements for PV. 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 [Mül 2019b].

Essentially ESTI is the keeper of the WPVS, which is embodied in the ESTI reference cell set.

2.4 ESTI reference cell set

As mentioned above the WPVS is currently represented by the ESTI reference cell set. This set of five PV reference cells is kept and maintained by ESTI, At least once every year the stability of the set is verified. Furthermore additional primary calibration results are added to the historic record of these cells.

2.4.1 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. The stability of the five cells in the set has been confirmed in 2020 and 2021. This is achieved by using each of the five cells as a reference cell in turn and calibrating the four other cells against it. The calibrations values thus obtained are then compared against the established calibration value of these five cells and the deviations evaluated by E_n number analysis (**Table 1**). The calibration values obtained are consistent within declared measurement uncertainty as long as E_n values are between -1 and 1. Therefore in both years, 2020 and 2021, the five cells were verified and found to be stable. This justifies to use the long term average of all primary calibration results for these cells to assign their calibration value (section 2.4.2).

Table 1. Cross-calibration table of ESTI reference cell set showing stability of all five cells.

En		against reference					2020
		PX102C	PX201C	LCIE 930417-	PX301C	PX304C	average
DUT	PX102C	NA	0.54	-0.29	-0.02	0.30	0.13
	PX201C	-0.28	NA	-0.66	-0.39	-0.04	-0.34
	LCIE 930417-	0.36	0.84	NA	0.26	0.59	0.51
	PX301C	0.16	0.65	-0.23	NA	0.40	0.24
	PX304C	-0.05	0.43	-0.40	-0.14	NA	-0.04

En		against reference					2021
		PX102C	PX201C	LCIE 930417-	PX301C	PX304C	average
DUT	PX102C	NA	0.26	-0.10	-0.12	0.46	0.13
	PX201C	-0.13	NA	-0.26	-0.28	0.14	-0.13
	LCIE 930417-	0.12	0.37	NA	-0.03	0.39	0.21
	PX301C	0.11	0.36	-0.02	NA	0.38	0.21
	PX304C	-0.22	0.03	-0.35	-0.36	NA	-0.22

Source: JRC, 2021.

2.4.2 Primary calibrations of PV reference cells

In 2020 and 2021 all five cells of the ESTI reference cell set were calibrated three times by primary calibration methods at ESTI. The solar simulator method was performed in both years, 2020 and 2021. Additionally the direct sunlight method was performed in 2020 and final results became available at the beginning of 2022. All three results were used to update the WPVS calibration values for the ESTI reference cell set (**Table 2**).

Table 2. Assignment of calibration values to ESTI reference cell set: Latest additions of primary calibration results (2020 - 2022) (right most columns) and updated calibration values including their uncertainties (columns in light blue) for the five reference cells (left most column) constituting the ESTI reference cell set. The weighted average are calculated considering all available historic primary calibration results for these cells, however, the results from 2019 and before are omitted here. The five cells with their assigned calibration values constitute the WPVS.

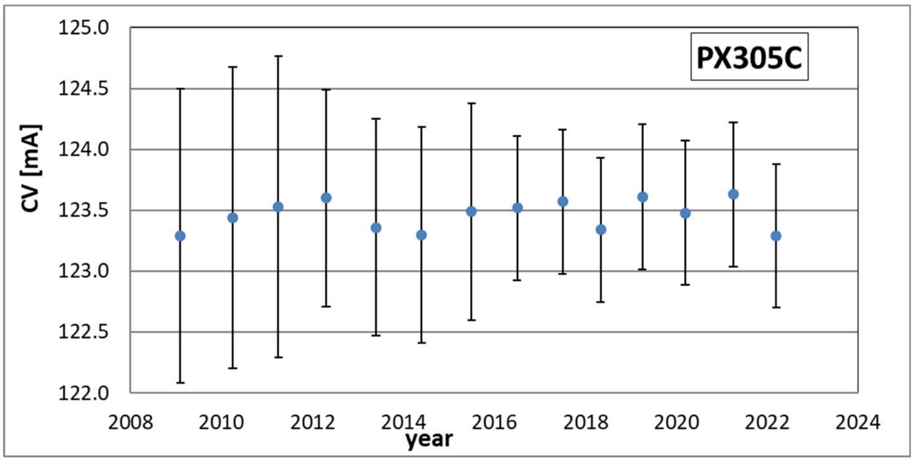
IEC 60904-3 ed.4.0 (2019-02) WRR shifted to SI							
Year		**AVE-RAGE [mA]**	**UC (k=2) [mA]**	**UC (k=2)**	2020.2	2021.2	2022.1
Month					Mar	Mar	Jan
Laboratory					ESTI	ESTI	ESTI
Method					SSM	SSM	DSM
PX102C	[mA]	**116.91**	**0.30**	0.25%	117.11	116.40	116.80
PX201C	[mA]	**123.78**	**0.26**	0.21%	123.75	123.10	123.8
PX301C	[mA]	**125.39**	**0.25**	0.20%	125.64	124.9	125.5
PX304C	[mA]	**124.31**	**0.28**	0.22%	124.40	123.5	125.0
930417-2	[mA]	**123.92**	**0.27**	0.22%	124.31	123.40	124.1

Source: JRC, 2021.

2.4.3 Annual calibration of other 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). 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, and this has been performed also in both 2020 and 2021. As an example the recent calibrations together with the long term history are shown for one cell (**Figure 2**).

Figure 2. Annual calibration of ESTI reference cell PX305C including long term device calibration history. The vertical error bars show the uncertainties of the calibration values (blue dots). The yearly variations are an indication of measurement reproducibility.



Source: JRC, 2021.

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 25 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 DUT 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 together with 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 IPC-XIII

The 13th edition of the International Pyrheliometers Comparison (IPC-XIII) was held at the Physikalisch-Meteorologisches Observatorium Davos, World Radiation Center (PMOD-WRC) from 27th of September to 15th of October 2021. The event is repeated every five years (this cycle was exceptionally of six years due to Covid restrictions in 2020), on a mandate of the World Meteorological Organisation (WMO) to establish solar irradiance measurement traceability of cavities and pyrheliometers to the World Standard Group (WSG), which is the world top-level reference for solar irradiance measurements. ESTI participated with all its instruments for direct solar irradiance measurements, namely the three cavity radiometers (PMO6-811109, PMO6-911204 and TMI68835) as well as eleven pyrheliometers (CH1-040370, CH1-060460, CH1-930018, CHP1-

110533, MS56-12036, MS56-12039, MS57-1702504, NIP-21451E6, NIP-23927E6, NIP-25738E6, NIP-26626E6).

During the three weeks sufficient measurements were taken in order to verify the stability of the instruments and assign new calibration factors to them. The data analysis is ongoing and the final report is expected to be published by PMOD in 2022. Preliminary results disseminated to participants (not for public distribution) indicate that all the ESTI instruments are stable considering their historical calibration values, thus guaranteeing continuity for the ESTI irradiance traceability chain.

Figure 3. Top: Overview of the measurement field of the IPX-XIII in Davos, Switzerland, in October 2021. Participants came from 36 Institutions representing 24 countries. Bottom left: Overview of the set-up with the ESTI instruments in the front and the WSG at the back right. Bottom right: Close-up of ESTI instruments.

Source: JRC, 2021.

3.2 Spectroradiometer comparison

3.2.1 International Spectroradiometer Comparison (ISRC)

The International Spectroradiometer Comparisons (ISRC) traditionally organised by the JRC every year [Pav 2020] [Mül 2019] had to be cancelled due to the COVID pandemic in both 2020 and 2021, but will be resumed in 2022.

3.2.2 Bilateral RSE

During the week 5-9 July 2021 scientists of the European Solar Installation (ESTI) laboratory and of the Italian Research Institute RSE (www.rse-web.it) performed a bilateral interlaboratory comparison on solar irradiance measurements. Both the total irradiance and the solar spectrum were measured simultaneously by a set of pyranometers, pyrheliometers, reference cells and spectroradiometers.

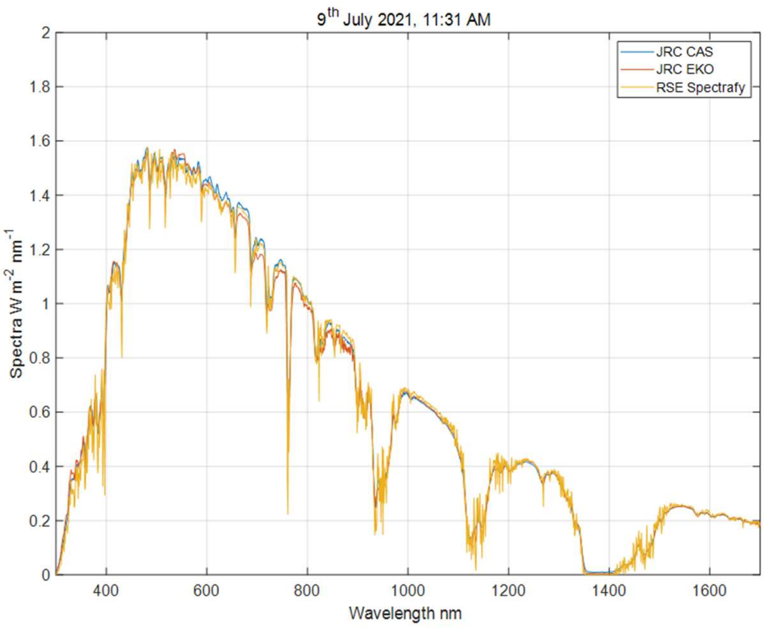
Measuring spectrally resolved solar irradiance is becoming crucial in the PV field, in order to understand correctly the performance of last generation PV devices, both for terrestrial and space applications: organic, dye-sensitized, perovskites, multi-junction devices, whose performance is strongly dependent on solar spectral distribution.

Increasing demand in accuracy and precision for solar cell calibration is an ever more demanding task. The aim is to arrive at uncertainties in the same order of magnitude of reference absolute radiometers. ESTI's primary cavities are directly traceable to the World Radiometric Reference in Davos (CH) and served as reference for the comparison.

At a technical level, the interlaboratory comparison was of interest because the participating instruments were of different types: ESTI made use of a three-detectors CCD spectroradiometer (EKO MS701-710-712) and a dual CCD detector (CAS140 system), while RSE brought an hybrid instrument that measures the spectral content in six bands and then makes use of a mathematical model to reconstruct the entire spectrum.

During the five days, only one provided clear sky conditions, other three had short term variability of the irradiance profile, and one was cloudy all day. The total number of acquired spectra was 8444. As an example, the following picture shows a triplet acquired by the three different systems within 5 seconds time difference.

Figure 4. Comparison of solar spectra measured with two JRC ESTI spectroradiometers and one RSE spectroradiometer on 9th July 2021.



Source: JRC, 2021.

3.3 Inter-laboratory comparisons with peer and other laboratories

This section contains a summary of the comparisons of PV calibration results to those of other laboratories for both, PV cells and PV modules.

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 ISO/IEC 17025 accreditation of ESTI 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).

3.3.1 PTB (DE)

Two reference cells were provide by PTB for calibration. They were calibrated at ESTI with two primary methods, namely under natural sunlight by the Direct sunlight method (DSM) and on a solar simulator (SSM) as well as by secondary calibration against the WPVS. The results were provided to PTB who will compare them with their own calibration and those of NREL (USA) and AIST (Japan). The aim is to check and provide international comparability of PV device calibration results. This exercise can also be understood as an informal comparison similar to the WPVS concept.

3.3.2 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 set the reference value, against which other participants will be evaluated.

The comparison of measurement results for four types of encapsulated high efficiency (HE) c-Si solar cells measured by ten laboratories based in Asia, Europe and North America utilizing a wide range of voltage sweeping methods, which include well-established procedures that represent good industry practice, as well as recently introduced ones that have not been verified yet. A proficiency test was employed to examine the consistency of results and their corresponding uncertainties. The results of all participant laboratories generally remained well within [−1; 1], thus indicating consistency between the measured values and the reference values within stated measurement uncertainties. A preliminary analysis revealed that differences remained within ±1.15% in P_{MAX} and within ±0.35% in V_{OC} for all participants and methods applied, for a given I_{SC}. Essentially this work forms the basis to validate all applied methods and their stated measurement uncertainties [Mon 2021]. A more detailed analysis should be published in 2022.

3.3.3 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 start of the inter-laboratory comparison', 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 compared in 2022 and possibly published later.

3.3.4 Calibration of bifacial PV modules (PV-Enerate project)

Within the EURAMET EMPIR "PV-ENERATE" project, a round-robin inter-laboratory comparison was also started on bifacial 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 monofacial and six bifacial PV modules was calibrated at ESTI. Also in this case, the results of the monofacial 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 bifaciality. 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, via secondary measurement laboratories.

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 LAT225 since 2011) [Acc 2022]. 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), one of which was successfully passed in autumn 2020 and the other is scheduled for spring 2022.

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.

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

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 all 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 have been published at the EU PVSEC 2019 [Lau 2019], showing the deviation of all participating laboratories against the reference value as determined by ESTI. The results have then been evaluated in more detail, including a qualitative comparison of the spectral responsivity as submitted by some participants, and have been published in a peer-reviewed paper [Sal 2020]. Recommendations were made to improve testing of MJ PV which are expected to improve the consistency of future results.

4.3 Reference devices for clients

In 2020 and 2021, ESTI calibrated a number of reference devices for clients (**Table 3**). A short description of each case is given in the following sub-sections.

Table 3. Overview of ESTI calibration certificates issued in 2020 and 2021 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-20-VS DC-20-VX DC-21-WQ DC-21-WW	4 7 4 7
CSIR Energy Centre (South Africa)	DC-19-UM DC-21-WI DC-21-WR	4 2 1
ENEA (Italy)	DC-20-VP	2
EURAC Research (Italy)	DC-20-VU DC-21-WG DC-21-WS	3 3 4
Loughborough University (UK)	DC-20-VY DC-21-WX	4 4
DTU (Denmark)	DC-20-VV	3
PV Lab (Germany)	DC-20-WE DC-21-WY	2 3
University of Cyprus (Cyprus)	DC-2--VW	3
AIT (Austria)	DC-21-WF	2
CIRE (Germany)	DC-21-WP	2
Total		**64**

Source: JRC, 2021.

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 (ZA)

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 ENEA (IT)

ESTI provided PV reference cell calibration to ENEA and thereby the traceability chain for irradiance measurements. This is in the framework of international harmonisation of PV device calibration and their traceability.

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 (GB)

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 DTU (DK)

ESTI provided PV reference cell calibration to DTU and thereby the traceability chain for irradiance measurements. This is in the framework of international harmonisation of PV device calibration and their traceability.

4.3.7 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.

4.3.8 University of Cyprus (CY)

ESTI provided PV reference cell calibration to the University of Cyprus and thereby the traceability chain for irradiance measurements. This is in the framework of international harmonisation of PV device calibration and their traceability.

4.3.9 AIT (AT)

ESTI provided PV reference cell calibration to the Austrian Institute of technology (AIT) and thereby the traceability chain for irradiance measurements. This is in the framework of international harmonisation of PV device calibration and their traceability.

4.3.10 CIRE (DE)

ESTI provided PV reference cell calibration to the Cologne Institute for Renewable Energy (CIRE) and thereby the traceability chain for irradiance measurements. 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.

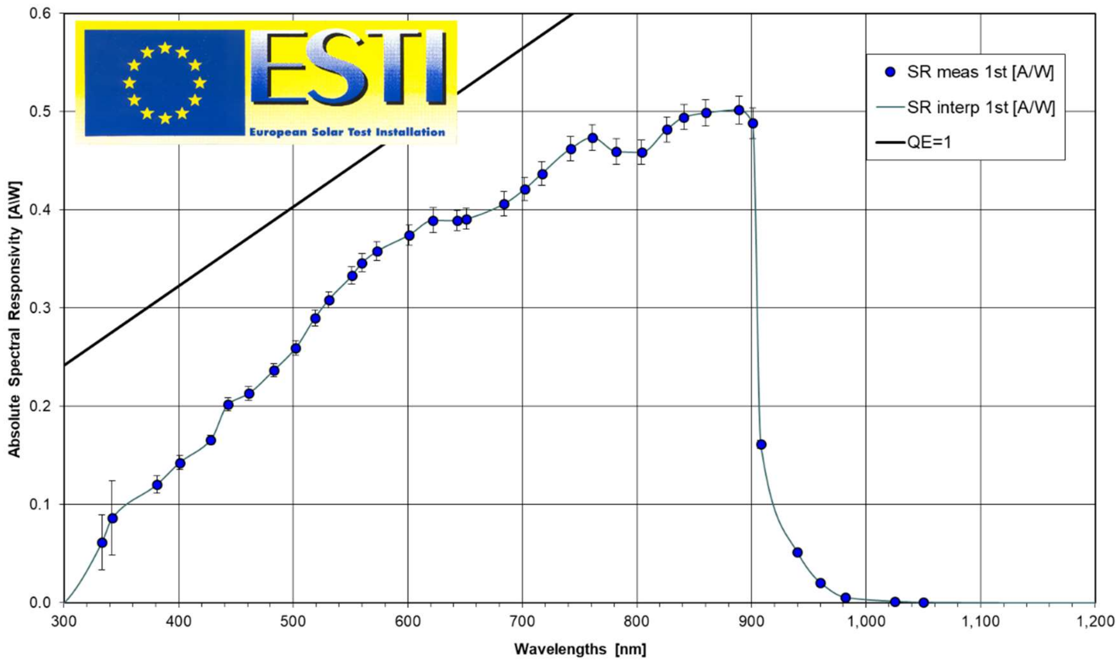
5.1 Co-authorship of world record PV efficiency tables

For many years, ESTI has co-authored the world record efficiency tables published twice a year in Progress in Photovoltaics [Gre 2020a] [Gre 2020b] [Gre 2021a] [Gre 2021b] [Gre 2022a]. 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 Organic photovoltaic device (OPV)

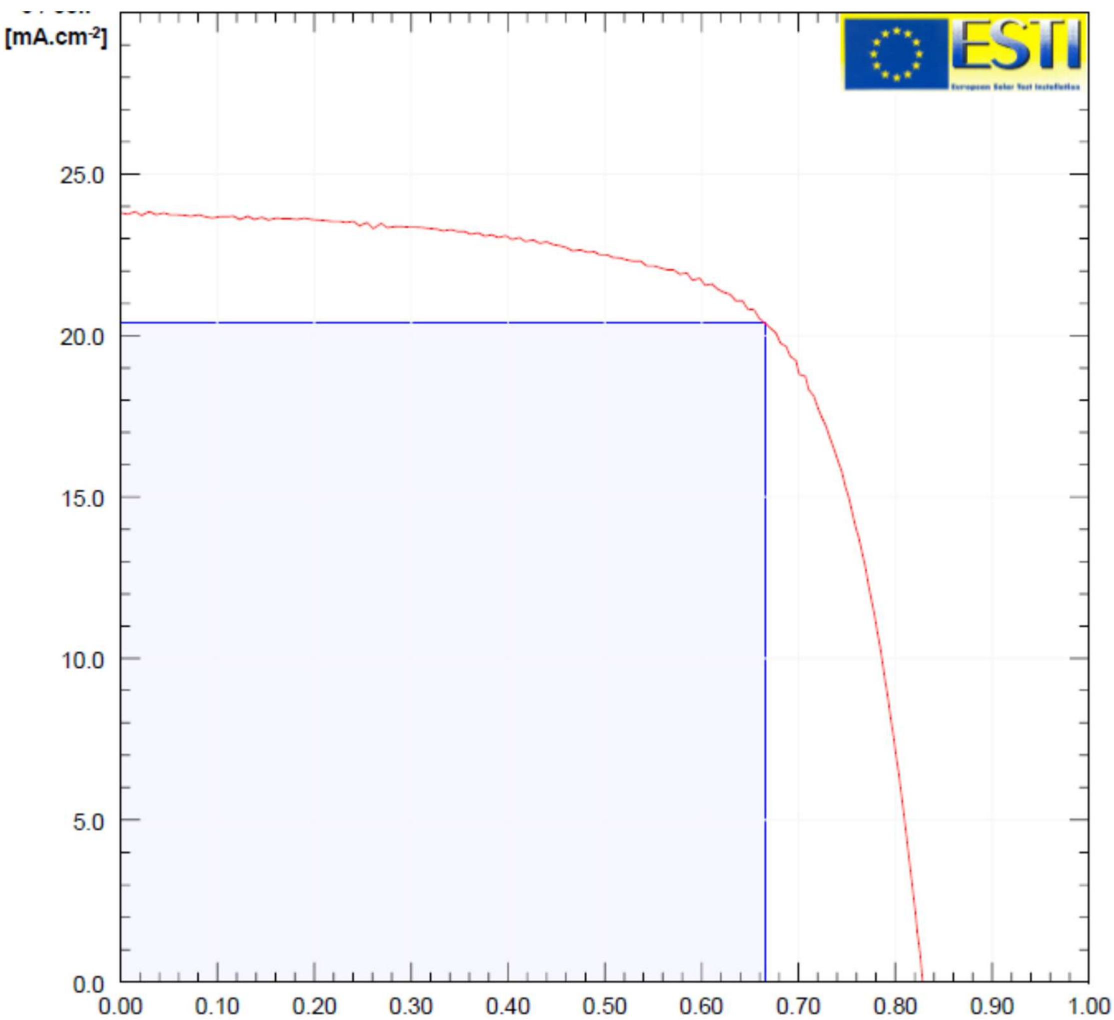
Organic photovoltaics (OPV) is one of the new emerging PV technologies. An OPV mini-module from WAYS/Nanobit/NCU with 16 cells connected in series and a total designated illumination area of 66.62 cm^2 was certified at ESTI to have an efficiency of (13.57±0.32)%, which constitutes a new world-record efficiency for this type of device and was duly included in the respective table [Gre 2021b]. Details of the device characteristics are shown below (**Figure 5** and **Figure 6**).

Figure 5. Spectral responsivity of world record efficiency OPV mini-module.



Source: JRC, 2021.

Figure 6. Current-voltage characteristics of world record efficiency OPV mini-module.



Source: JRC, 2021.

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 Contributions to international standards

The contributions to international and European standards is presented in a separate report [Sa 2022]. Below only the most relevant in the context of the present report are mentioned as well as some pre-normative research.

6.1.1 Project leader for fundamental PV measurement standard

The most fundamental characterisation of the electrical performance of PV devices is based on current-voltage characterisation. The respective international standard IEC 60904-1 was revised under the (technical) project leadership of ESTI and the new version (ed. 3) published in September 2020.

6.1.2 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 previous version (ed. 2) of IEC 60904-10 standard was insufficient. The standard was therefore revised under the (technical) project leadership of ESTI and the new version (ed. 3) published in September 2020.

6.1.3 Improvements in spectroradiometer calibration

The calibration of PV devices relies on reporting the electrical performance at a reference spectral irradiance defined in IEC 60904-3. This necessitates the measurement of the spectral irradiance present under natural or simulated sunlight with a spectroradiometer. In order to improve these measurements the following new procedure for spectroradiometer calibration was devised.

In 2021 ESTI has revised the procedure for the internal calibration of all its spectroradiometers. The fleet of instruments includes an EKO system (composed by three detectors), a CAS system (composed by two detectors) and an OL750 instrument. The calibration of a spectroradiometer is a sequence of operations aiming to calculate a function to convert the counted number of incident photons for each specific wavelength to the spectral quantity in SI units. Until this year, this was possible only for the OL750 instrument, while the others could be only verified using the factory calibration function.

After having developed a software upgrade and improved the internal measurement procedure, now all the spectroradiometers can be fully calibrated using a FEL Standard Lamp (calibrated at NPL or PTB) as a reference light source.

This improvement is of particular importance since it allows not only to detect anomalies and drifts of the instruments but also to correct these undesirable effects by calculating the new coefficients for the units conversion.

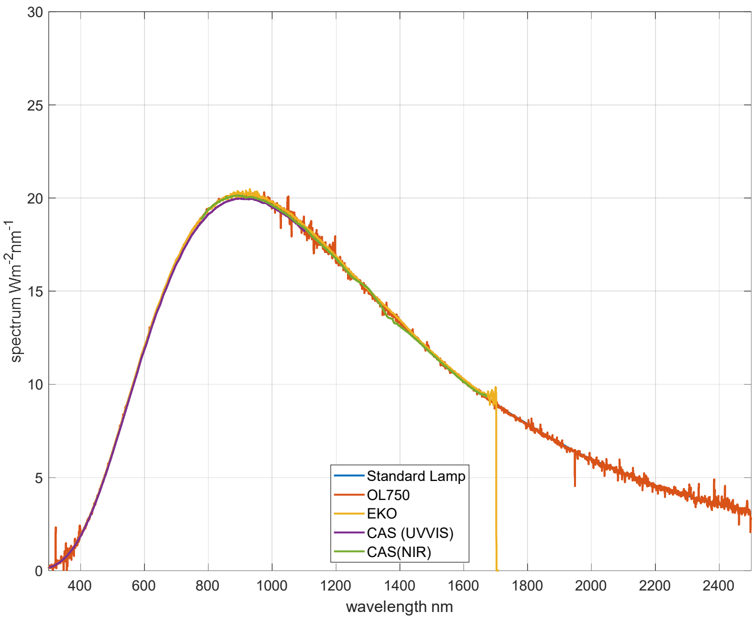
As an example (**Figure 7**), the spectrum of the Standard Lamp Oriel 7-1596 is plotted against the outcomes of the spectroradiometers before and after their calibrations in summer 2021.

Moreover, the uncertainty calculation methodology has been improved by adding a statistical component, assuring that at every wavelength the consistency criterion

$$|E_N(x)| \leq 1 \; \forall x$$

is fulfilled (according to the definition in ISO 17043 standard). The amendment of the uncertainty calculation for the spectrum measurement was deemed necessary having seen the outcomes of the latest interlaboratory comparison in Saint-Veran in 2019.

Figure 7. Example of comparison between known spectral irradiance of standard lamp and the same quantity measured with the spectroradiometers during calibration of the instruments.



Source: JRC, 2021.

6.2 Measurement and calibration of bifacial PV

ESTI was a partner in the EURAMET-funded EMPIR project "PV-ENERATE" [PV-ENERATE]. This project which completed in the latter half of 2020 investigated the metrology aspects of performance measurements for bifacial PV modules (see also section 3.3.2.5). The ESTI contributions to the project are described in the following subsections.

6.2.1 International Technical Specification for measurement of bifacial PV devices

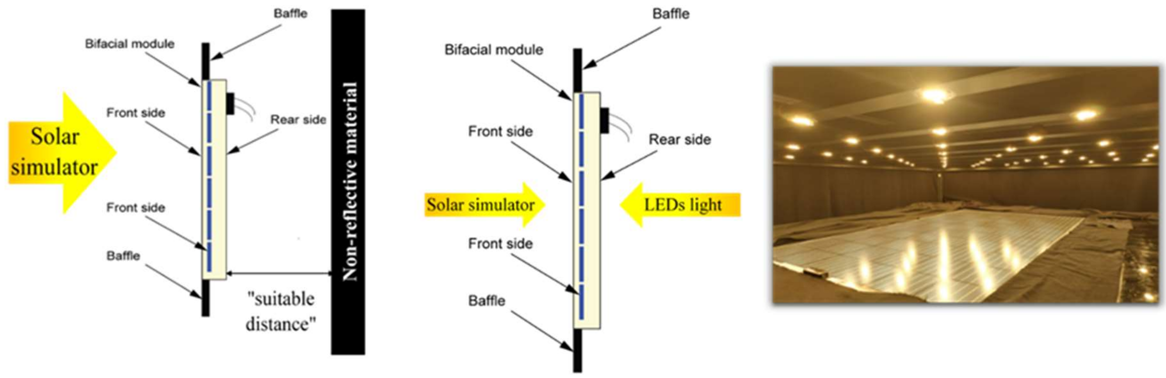
ESTI was member of the project team within IEC to develop the technical specification for measurement of bifacial PV devices, which was published in January 2019 [IEC TS 60904-1-2]. ESTI has implemented it into its laboratory practices and was successfully accredited for this at the end of 2019. In parallel, ESTI has also continued work on evaluating the standard and has produced a report which details a number of proposed improvements to the standard which could be made in a future revision [Lop 2020]. A project for the revision of the IEC TS 60904-1-2 has been launched by the IEC TC82 WG2 at the end of 2021, and ESTI staff are members of the project team.

6.2.2 Indoor measurements of bifacial PV modules

Bifacial crystalline silicon PV devices have become a very competitive and promising technology in comparison with the conventional monofacial modules. This PV technology is receiving growing interest on the market and it is expected to increase rapidly in the near future. The International Technology Roadmap for Photovoltaic (ITRPV) indicated that in 2021 bifacial cells account for about 50% of the total world PV cell market and predicted that by 2032, this share will increase to 85% [ITR 2022]. For bifacial PV modules, the market share for 2021 stands at just under 30% and is predicted to increase to over 60% by 2032 [ITR 2022]; the remaining bifacial cells are incorporated into monofacial modules. The reliable electrical characterization of the performance of the bifacial modules still presents challenges, but is key to the successful market penetration.

The publication of the technical specification IEC TS 60904-1-2 (TS) for the measurement of current-voltage, characteristics of bifacial PV devices standardised various methods used to measure and label a bifacial PV modules. The single-side illumination approach based on the equivalent irradiance method using a pulsed solar simulator is the most widely used for bifacial PV module indoor testing (**Figure 8**, left). Recently, ESTI, has been accredited, for the first time worldwide, for I-V measurements of bifacial PV modules applying the single-side illumination approach according to IEC TS 60904-1-2. However, this approach does not reproduce the real conditions experienced with both front and rear illumination. For this reason, the application of simultaneous double-side illumination approach (**Figure 8**, centre) for the characterization of full-sized commercial silicon bifacial modules is tested [Lyu 2021] as a continuation of previous work on a small-scale prototype [Sha 2018]. The aim of this work is to extend the study towards the development and validation of methods for the characterization of bifacial PV devices under the IEC TS 60904-1-2 requirements as a possible low-cost approach for further industrial implementation. The testing procedure is performed by using a prototype system based on Light Emitting Diode (LED) rear light coupled to a large-area long-pulse solar simulator that illuminates the front side of the device (**Figure 8**, right) developed at ESTI. The applied methodology uses an accredited reference value (ISO/IEC 17025) obtained by single-side illumination of the same test device. The measurements from the single-side illumination are applied as a reference for the double-side illumination method. The long-pulse simulator irradiance (front illumination of the module) is adjusted to obtain the same short circuit current at STC with single-side illumination (i.e. with the LEDs turned off). In the case of double-side illumination, by adjusting the applied voltage, and hence intensity control of the LEDs, an effective irradiance is generated such that the short circuit current matches that obtained using the single-side approach at the desired equivalent irradiances.

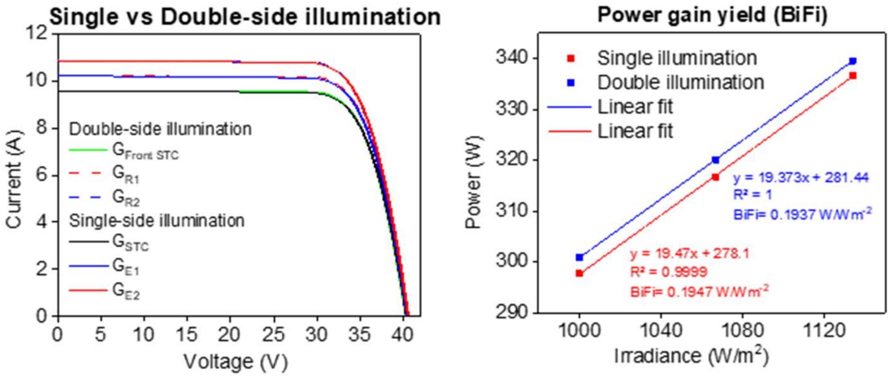
Figure 8. Representation of single-side illumination approach based on equivalent irradiance method (left) and a double-sided illumination method using two light sources (centre); Picture of applied illumination system composed by LED bias light on the rear side and long-pulsed solar simulator on the front side (right).



Source: JRC, 2021.

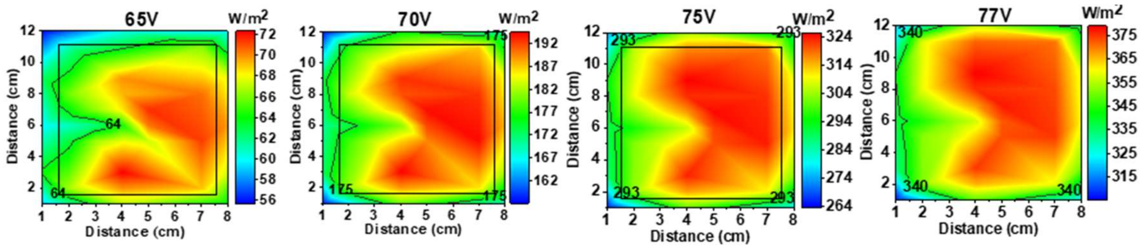
The results obtained have demonstrated good performance in comparison with the single-side measurements based on a commercial Class AAA simulator using validated standard methodology [Lop 2017]. The electrical performance demonstrates practically identical current-voltage (I-V) curves (**Figure 9**) and similar key parameters (deviation less than ±1%), which validates the method for characterization of bifacial devices according to IEC TS 60904-1-2. Slightly higher P_{max}, BiFi and FF are measured and are mostly associated with inherent characteristics of the long-pulse solar simulator used for the front illumination.

Figure 9. Electrical parameters of a bifacial PV module: Comparison of I-V curves of single and double-side illumination approaches (left); Linear fitting of BiFi power gain yield for both approaches (right).



Source: JRC, 2021.

Figure 10. Spatial irradiance distribution maps of the rear side of the module, placed on the test plane at ~51cm of the LED and for different LED power supply voltages. The square represents the standard 60-cells module size (axis x=200cm; y=130cm)



Source: JRC, 2021.

The prototype system based on LED light has demonstrated good performance, enabling illumination of the rear side of a bifacial module at variable light levels up to ~350 W/m^2 by adjusting of supplied voltages from 65V to 78V. The rear-side non-uniformity (NU) varies with applied voltage and distance between LEDs and the device, which would result in a classification of the system in Class B (>200 W/m^2) or Class C (<100 W/m^2) according to the IEC 60904-9. The spatial distribution maps of the rear irradiance made by the LED on the test plane at 51cm distance and for different voltages are depicted in Figure 10. The best rear-irradiance distribution is achieved at higher applied voltages as 75 V and 77 V (~300-380W/m^2) displaying better uniformity and the lowest NU values measured (3.4%). Overall, the suitability of the proposed method in IEC TS 60904-1-2 for the characterisation of bifacial PV devices was experimentally tested and the developed system configuration would be a convenient and low-cost approach for further industrial implementation.

6.2.3 Outdoor installation of bifacial PV modules

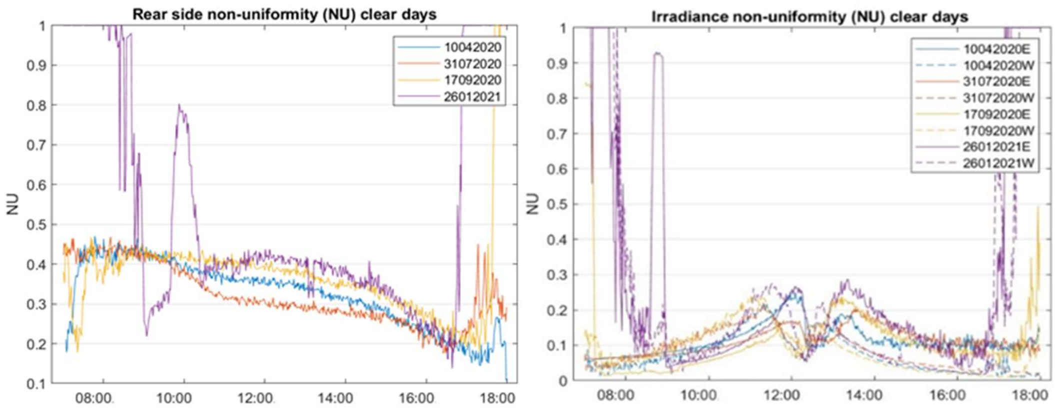
In order to promote the bifacial technology, field performance data under real working conditions for different locations, technologies and mounting configurations are compiled and analysed to contribute to modelling and the long-term energy yield assessment and forecasting [Bon 2018, Del 2017]. One way to increase the energy yield of the PV modules is to capture the rear side illumination. When it comes to energy rating, an extension of the IEC 61853 standard series is proposed for bifacial modules, aiming to help end-users evaluate and select appropriate bifacial modules with the relevant mounting configuration and climatic profile appropriate to their intended use [Gra 2020]. For this purpose, commercially available bifacial crystalline silicon PV modules were installed in the outdoor test field at the European Solar Test Installation (ESTI) in Ispra (Italy) (**Figure 11**). Two arrays of bifacial modules with nominal power of 2.94 kWp each are mounted in different configurations: tilted plane facing the equator South oriented fixed open rack (**Figure 11** left, tilt angle of 30°) and vertically mounted in East/West-facing array (**Figure 11** right).

Figure 11. ESTI outdoor test field installation of bifacial racks: South-oriented tilted equator facing bifacial solar tracking systems (left) and fixed- vertical bifacial PV module array East-West oriented (right).

Source: JRC, 2021.

The vertical configuration brings, a priori, interesting advantages compared to conventional technologies installed in a tilted plane facing the equator as harvesting the solar radiation available when the sun is low at sunrise (East) and sunset (West), with the draw-back of only utilizing diffuse radiation at solar noon. This configuration also takes advantage of higher electricity value derived from the production at off-peak times with regard to the available global solar radiation but better aligned with the average household's electricity consumption daily profile [Lop 2020b]. In addition, the vertical configuration also benefits from reduced soiling losses and cleaning cost [Bha 2019], alternative or shared land use such as agriculture [Hil 2017], use as sound barriers in highways and integration in building facades [Sor 2016]. However, modelling a bifacial cell is by far more complicated than a monofacial one as the irradiance distribution at the rear side of a tilted rack is always non-uniform, and for a vertical rack maybe non-uniform on both sides. The rear-side irradiance behaviour and energy yield performance of both bifacial PV test arrays in a moderate subtropical climate are performed for a 12 months period as an extension of previous work [Ozk 2019, Gra 2019]. The results are compared with a similar monofacial c-Si array equator oriented fixed rack used as a reference [Cal 2021].

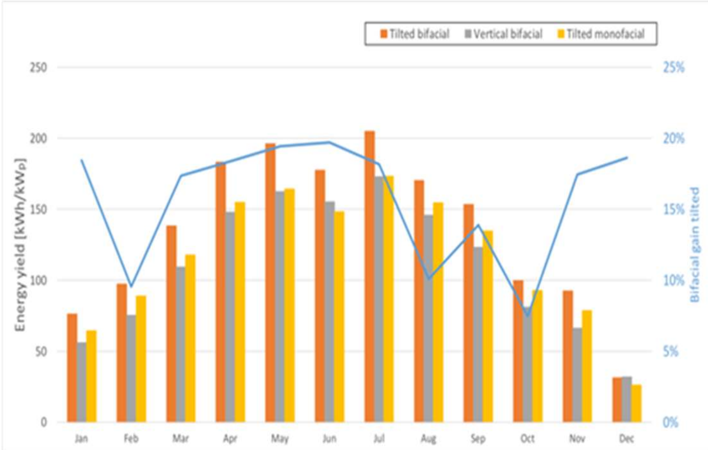
Figure 12. Non-uniformity of the rear-side irradiance in different seasons on selected clear days: tilted system on clear days (left) and East/ West vertical system (right).



Source: JRC, 2021.

One of the challenges for estimating the bifacial module performances is to calculate the solar irradiation impinging on the rear-side in real-life conditions over long time periods. The results reveal that for the tilted system, the non-uniformity rear-irradiance distribution (NU) has the lowest daily average values in summer and the highest in winter (**Figure 12** left). Overall, the highest NU is observed in early morning hours (before 7 a.m.) and later hours in the afternoon (after 7 p.m.) for all seasons, even though the absolute values of irradiance at these moments of the day are very low, consequently the total energy yield of these periods represent a low fraction of the daily yield. The NU irradiance distribution of the vertical array (calculated for both sides, East and West) shows seasonal behaviour (**Figure 12** right): for the East side, the average values of NU are lower for fall and higher for winter, while the West side present lower, but similar values for all seasons. The maximum NU values happen around noon in the winter day. Nevertheless, the NU values for this configuration are relatively low in comparison to the tilted system.

Figure 13. Yearly energy yield for tilted and vertical bifacial systems in comparison to a tilted monofacial and bifacial gain of tilted system (blue line).



Source: JRC, 2021.

The direct current (DC) energy yield analysis (**Figure 13**) finds 15.8% energy output gain over the year for the tilted bifacial array in comparison with the tilted monofacial rack. The vertical array has a lower energy yield around most of the year. The bifacial modules installed in both configurations have as a disadvantage a low bifaciality coefficient (about 67%), which causes the performance of the system to be poor during the afternoon hours. In average, the yield of this system is 5% lower than the reference tilted rack over the year and this difference is less pronounced during the summer months of the year, which are responsible for a great share of the annual energy production. Previous work in the same location with a single module of the same bifaciality as the ones used in this work has shown a bifacial gain of around 25% [Gra 2019]. This demonstrates that systems composed of multiple modules have additional effects – such as the rear-side non-uniformity, which cause a significant reduction on the effective bifacial gain. Moreover, the results of this work will be useful for on-going work focusing on extension of IEC 61853 energy rating standard series for bifacial modules.

6.2.4 Energy Rating of PV modules

6.2.4.1 Extension of energy rating to bifacial modules.

ESTI has contributed to work towards extending the energy rating standard series IEC 61853 to bifacial modules. A similar approach to the existing standard is proposed, with an additional configuration defined (vertical with E/W orientation). New hourly irradiance datasets are calculated for the rear side of the tilted configuration and for the East and West sides of the vertical configuration. A modified calculation algorithm is proposed to calculate the instantaneous power output taking into account both sides of the module. A report entitled 'Extension of energy rating to bifacial modules – proposals from the PV-Enerate project' has been published [Gra 2020].

6.2.4.2 Energy Rating - implementing and evaluating IEC 61853

ESTI has continued work that helped lead to the publication of the four parts of IEC 61853 series on energy rating. During 2020 this work has been in two specific areas:

- Implementation of IEC 61853-3.
  This part 3 contains the algorithms used to calculate the energy rating of a PV module using module performance data measured according to parts 1 and 2, and the hourly climatic datasets of part 4. The implementation of this algorithm is not trivial due to some ambiguities in the text. Together with partners from the PV-Enerate project, JRC has contributed to an understanding of the best way to reliably and repeatedly perform these calculations, and has produced a reference dataset for use by other groups to test their implementation [Vog 2020].
- Evaluation of the discrimination capability of the energy rating method applied to c-Si PV modules.
  Measurement of the performance matrices of a number of different c-Si modules of recent production has been made in accordance with IEC 61853-1. Calculation of the energy rating has been performed in

accordance with IEC 61853-3 and has revealed differences significantly above the expected uncertainty, indicating that the standard can discriminate between commercially available c-Si modules.

6.3 Emerging PV technologies

Emerging PV technologies are rapidly evolving and considerable research effort has addressed alternative approaches to increase their efficiency, now reaching promising values. A reliable technology assessment and a correct evaluation of their potential when compared with currently available marketable PV technologies require performance measurements of the PV modules not only at standard test conditions (STC), but also at real operating conditions (IEC 61853-1).

A study is to provide an insight into the behaviour of organic photovoltaic (OPV) full-size modules, allowing for subsequent energy rating studies and energy performance evaluation at different locations and climate conditions according to the IEC 61853 series was performed [Bar 2020c].

A generic measurement protocol for the assessment of the electrical performance of perovskite solar cells (PSC) has been published based on the development done at ESTI [Bar 2021a].

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. Workshops for experts are also (co-)organised by the JRC.

7.1 Scientific dissemination

7.1.1 Peer-reviewed scientific publications

In 2020 and 2021 a total of 14 peer-reviewed publications were published with ESTI authorship (Table 4). They are cited in the relevant sections of this report together with the description of the respective work.

Table 4. Overview of peer-reviewed publications with ESTI authorship published in 2020 and 2021.

Journal	Impact factor	Number of publications	References
Progress in Photovoltaics Research and Applications	7.953	8	[Gre 2020a] [Gre 2020b] [Gre 2021a] [Gre 2021b] [Gre 2022a] [Bar 2020b]] [Pav 2020] [Sal 2020]
Solar Energy	5.742	2	[Bar 2020a] [Bla 2020]]
Journal Physics Energy	5.967	1	[Bar 2021a]
Solar Energy Materials and Solar Cells	7.267	1	[Bea 2020]
Nature Energy	60.858	1	[Khe 2020]
Solar RRL	8.582	1	[Pol 2021]

Source: JRC, 2021.

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 JRC also chairs the International Scientific Advisory Committee. 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, who review the submissions received after a public call for papers. The committee typically receives around 1000 papers, and selects them for plenary, oral or poster presentations, while rejecting around 10% of submissions. 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.

7.1.2.1 EUPVSEC 2020

In September 2020, over 1500 registered participants from 65 countries attended the 37th edition held online due to the coronavirus epidemic. The JRC also contributed with several members of the scientific committee.

The JRC made a number of contributions to the technical programme. ESTI staff members were (co-)authors of seven oral and three visual presentations. Another JRC group co-authored one oral presentation. JRC staff also chaired five oral sessions.

7.1.2.2 EUPVSEC 2021

In September 2021, over 1300 registered participants from 62 countries attended the 38th edition held online for the second time due to the coronavirus epidemic. The JRC also contributed with several members of the scientific committee.

The JRC made a number of contributions to the technical programme. ESTI staff members were (co-)authors of one plenary, nine oral and two visual presentations. One of the visual presentations won a best poster award. Another JRC group co-authored one plenary presentation. JRC staff also chaired several oral sessions. A member of ESTI staff took part in one of the topical panel discussions 'Managing Performance and Sustainability at the TW scale'.

7.1.3 ESA workshop

The workshop "Advanced PV Measurements and Reliability" was organised jointly by the European Solar Test Installation (ESTI) of the European Commission's Joint Research Centre (JRC) and by the European Space Technology and Research Centre (ESTEC) of the European Space Agency (ESA). This workshop was one of the collaborative initiatives falling under the administrative agreement signed in 2013 between JRC and ESA.

The workshop on "Advanced PV Measurements and Reliability" was held online on 11th and 12th of November 2020, with more than 50 participants from both space and terrestrial PV communities and a balanced representation between them. Participants were from PV calibration and testing laboratories, national metrological institutes, university, public and private research centres, as well as manufacturing companies of PV cells, instrumentation and services. The areas covered by the workshop were the reliability of PV cells and ensembles, the standardisation for PV and the state-of-the-art best practices in the characterisation and calibration of PV cells, assemblies and modules. Good practices as well as present and foreseeable future challenges were reported and discussed from which conclusions and recommendations on future collaborations and activities were drawn [Sal 2021].

8 Contribution to EU policies

The work of ESTI is directly contributing to EU policies as described in detail recently [Pol 2021]. The following is a brief summary, for details the reader is referred to [Pol 2021] and references therein.

8.1 Introduction

Photovoltaic (PV) is a key technological sector. The European Union (EU) cumulative installed capacity of 138 GWDC in 2020 and is projected to grow significantly by 2030 (to some 440 GWDC) and expand further in the long term. A future annual market of the 20 GW translates to approximately 50 million photovoltaic modules. Residential, commercial and industrial rooftop installations are expected to continue to represent a sizable part of the market. A share of 20% could amount to 6 GW per year, or about 1,200,000 systems. It is therefore of primary importance to ensure that newly installed PV products in the EU are environmentally-friendly and do not create future burdens on Europe's environment. In particular, the energy yield of PV systems can potentially be improved through a combination of better design to take into account site-specific conditions, best installation practices and by reducing losses thanks to selecting and coupling the most appropriate equipment with adequate cabling and maintenance. A 2019 preparatory study on the environmental impacts – and related policy approaches at EU level – of PV modules, inverters and systems carried out by the European Commission Joint Research Centre concluded, inter alia, that improvements in the energy yield and long-term performance of PV modules, inverters and systems could be ensured by mandatory legal instruments, in particular via the synergic application of implementing measures in the framework of the Ecodesign Directive and labelling schemes in the framework of the Energy Labelling Regulation.

Implementing measures (i.e. Regulations) in the framework of the Ecodesign directive and the Energy Labelling Regulation typically foresee the use of harmonised standards, adopted by recognised European Standardisation Organisations (CEN or CENELEC), for the testing and calculation methods necessary for the compliance assessment. However, when harmonised standards are not available, other already existing standards or methods may be considered, when proved that they are suitable to the extent of assessing the compliance of products with the applicable requirements (Ecodesign or energy labelling). An extensive review of available standards for the characterization of the performance of PV modules and PV systems identified important aspects that are not yet the subject of a published standard for the implementation of EU legislation to PV products. At present, parameters such as the expected energy yield delivered by a PV system over its lifetime or the lifetime itself of PV modules or systems are neither defined nor modelled in any standard. Therefore, transitional methods are needed to define these and other concepts necessary to implement Ecodesign and energy labelling schemes on PV products. An additional aspect is the increasing deployment of bifacial photovoltaic modules which are not yet fully considered in the existing standardization framework. To deal with this significant and growing market segment within the Ecodesign and energy labelling framework, additional transitional methods are required.

The aim of this work is twofold; firstly, to devise in detail the policy approach related to the energy labelling, and secondly to contribute to the knowledge base by proposing a methodology and calculation procedure in support of potential energy labelling schemes for both PV modules and PV systems (installations). The estimated annual and lifetime yields per unit area for PV modules and systems respectively are used as a parameter for classification from A to G in the proposed energy labelling scheme. How to 'translate' the methodology into an actual energy labelling scheme, i.e. for use in EU policy implementing measures and the conceptual challenges of proposing an energy label for energy generating products, i.e. PV modules and systems are investigated.

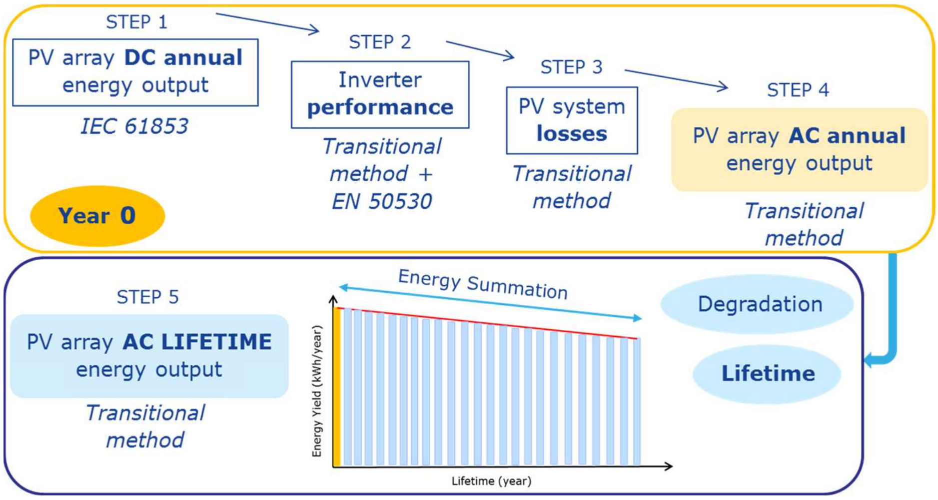
8.1.1 Estimation of PV module and PV system performance

Concepts such as the degradation of PV modules, lifetime of PV systems or the expected long-term performance of PV systems and their components (such as inverters) under real working conditions are still the subject of debate and scientific investigation. No European or international standard that defines or models these parameters exist. Nonetheless, they are fundamental for the implementation of the policy tools.

Therefore, as part of the preparatory study mentioned in previous sections, various methods were analysed and compared in order to propose a methodology to define these concepts. In addition to a procedure to define the degradation rate of PV modules, or the lifetime of PV systems, in the preparatory study several methods were developed to model the effect on performance of the main components of a PV system such as the inverter and how to deal with system losses. For example, four different methods were evaluated to model the long-term performance of PV inverters. Each represents a compromise between accuracy and the limitations of the information typically made available by manufacturers.

The concatenation of the selected models representing each component of the PV system results in a methodology to model and quantify the lifetime performance of PV systems (**Figure 14**). The proposed methodology estimates the AC energy yield delivered by a PV system over its lifetime under real working conditions, taking into account the efficiency and performance of the various components, as well as the effect of various losses and the annual degradation rate.

Figure 14. Diagram of the complete methodology to estimate the lifetime AC energy yield from a PV system



Source: JRC, 2021.

The electrical performance of PV modules can be estimated following the IEC 61853 series, which defines a methodology to estimate DC energy yield of the PV device over one year under real working conditions (no degradation applied). These are defined by six different climatic reference datasets which describe the most representative worldwide climatic conditions. Three of these reference climates are relevant for Europe: subtropical arid, temperate coastal and temperate continental.

While the first step of the complete methodology to estimate the AC lifetime energy yield from PV system is based on the IEC 61853 series, the other steps in the calculation process rely on transitional methods defined in the preparatory study. Notwithstanding, due to the fact that IEC 61853 standard's scope only covers monofacial PV devices, a transitional method was developed as well to extend the IEC 61853 methodology to bifacial devices and estimate the DC energy yield from this type of PV module, based on recent research in the EU-funded PV-ENERATE project.

The complete methodology to estimate the lifetime AC energy yield from PV systems is divided into two parts (**Figure 14**). The first part results in the estimation of the AC energy yield of the PV system for the first year of installation, taking into consideration the performance of the PV array, inverter and the effect of various losses derived from the installation and configuration of the PV system. The second part of the methodology accounts for the lifetime performance of the PV system taking into consideration the degradation of the PV system. The AC lifetime energy yield is estimated assuming a linear degradation rate over a lifetime of 30 years.

8.2 Building an energy label for PV modules and systems

8.2.1 How to define the 'energy efficiency' of energy generating products

In general terms, 'energy efficiency', when related to energy conversion processes, represents the conversion efficiency, i.e. the ratio of generated end-use energy in proportion to the primary energy. When related to energy consuming products, the energy efficiency can be regarded as the ratio between the product performance, provided that it is possible to quantify it, and the energy used to obtain it (for instance, the light emitted by a light bulb for a given amount of energy). In line with this rationale, the definition of 'energy efficiency' within the Energy Labelling Regulation is 'the ratio of output of performance, service, goods or energy to input of energy'. So far, this approach has been successfully applied to a wide range of energy using products from both the business-to-consumer and the business-to-business sectors, such as washing machines, dishwashers, household, commercial and professional refrigerators, ventilation units, etc.

Despite the relevance of energy labels for energy using products, the Energy Labelling Regulation clearly extends to all energy-related products. Article 2(1) of that Regulation defines such energy-related products as any 'good or system with an impact on energy consumption during use.' Both PV systems and modules fit within this definition. When defining the 'energy efficiency' of PV modules and systems, a change of perspective is needed, as we are dealing with energy generating products, rather than energy consuming ones. In line with the concept outlined at the beginning of this section, the 'energy efficiency' of energy generating products can be conceptually conceived as the ratio of generated end use energy (which can be also considered as a proxy of the module/system performance) in proportion to the primary energy:

- the energy label for PV modules could be based on the module energy efficiency index, which can be considered conceptually as a ratio between the electricity generated by the module over the course of the year under realistic operation conditions for each reference climate, normalized per unit area (module).
- the energy label for PV systems, i.e. installations, could be based on the conceptual ratio between the electricity generated by the installation throughout its (expected) lifetime for the relevant reference climate, normalized per unit area (system).

8.2.2 Proposed energy labels for PV modules and systems: energy labelling classes and label design

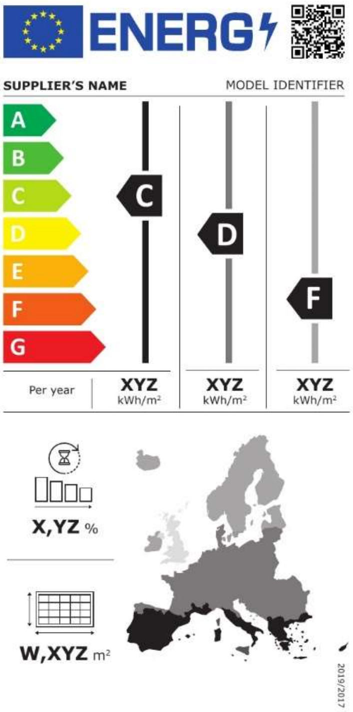
A preliminary definition of the energy label classification for small PV systems based on the PV system Energy Efficiency Index (EEI_S) for the three reference climates relevant for Europe, subtropical arid, temperate coastal and temperate continental.

While the preliminary energy label classification for PV modules, based on the module Energy Efficiency Index (EEI_M) for the three reference climates relevant for Europe.

Figure 15 shows how the label for PV modules could actually look like, based on the methodology presented. The label in printed form would be provided by suppliers at the point of sale (including at trade fairs) and displayed in such a way as to be clearly visible. The label would be also displayed in any technical promotional material concerning a specific model of PV module, including on the Internet.

In the upper half, the label would present the module energy efficiency class, defined based on the Module Energy Efficiency Index value, $EEI_{M,}$ as well as the EEI_M value itself (i.e. the yearly energy generated by the PV module per module area), under 'subtropical arid', 'temperate coastal' and 'temperate continental' reference climate conditions. It would be necessary to show the values related to all the three climatic areas, as it would not be possible for the suppliers to know in advance the actual place of installation.

Figure 15. The proposed draft energy label for PV modules.



Source: JRC, 2021.

In the lower half, the label would display the reference EU map, giving a visual representation of the geographical distribution of the three reference climatic areas. In the left lower side, two more informative elements would be present, i.e. the lifetime performance degradation rate (represented with an icon featuring some histograms of decreasing height below an hourglass) and the PV module area.

9 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 bifacial 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

- 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 accuracy is implemented in and available through the ESTI reference cell set, a unique set of five primary PV reference cell held at ESTI. Through this the accuracy of PV modules' power measurement improved from 2.6% to 1% providing the highest accuracy available from any PV calibration laboratory. This reduction corresponds to a monetary value of approximately €500 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 64 calibration certificates to clients in 2020/2021. 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 2020/2021 one request was received for a device which had an efficiency outclassing the published records at the time of measurement.
- 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 electrical performance assessment.
    - 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 bifacial 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 bifacial PV modules appear quickly in the market. Indeed, modern crystalline-silicon PV modules are inherently sensitive to light from both sides (i.e. bifacial). 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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[PV-ENERATE] PV ENERATE

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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
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
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
ESA	European Space Agency
ESTEC	European Space Technology and Research Centre
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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