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Summary of the European Solar Test Installation's contribution to the energy transition from 2022 to 2025

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Contents

Abstract

The European Union (EU) has an urgent need to achieve the ambitious climate-neutrality targets by 2050, emphasizing the acceleration of clean energy transitions towards decarbonization and sustainable economic growth. The European Commission's Joint Research Centre (JRC), through its Photovoltaic (PV) Energy project and the European Solar Test Installation (ESTI) laboratory, plays a pivotal role in underpinning the development and deployment of next-generation PV technologies that align with the EU's industrial strategy (NZIA), circular economy principles, and global leadership in clean energy innovation. Through its role as an accredited calibration laboratory and its commitment to knowledge dissemination, ESTI not only enhances the quality and innovation of solar technologies but also empowers the EU to meet its sustainability goals.

This report presents an overview of the ESTI activities at the JRC over the period 2022–2025. ESTI provides reference measurements, calibration services and scientific support in the field of solar irradiance and photovoltaic device performance, ensuring traceability to international standards and worldwide comparability of results. The report covers the maintenance and development of the solar irradiance traceability chain, participation in international inter-laboratory comparisons, generation of PV reference materials and accredited calibration services. It also describes pre-normative research activities addressing measurement challenges associated with emerging PV technologies and bifacial energy rating. It covers contributions to international standardization and support to EU energy and sustainable climate policies. Through these activities, ESTI continues to play a key role in supporting reliable PV performance assessment and evidence-based policymaking.

Foreword

This report is an update of the previous version [1]. Periodical update is foreseen, exceptionally this version covers four years, namely from 2022 to 2025.

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Executive summary

Photovoltaics are a major contributor to achieving the European and global climate change mitigation goals both today and in the coming years. Photovoltaics are the renewable energy technology with the largest scope for cost reduction and efficiency gains. The European Solar Test Installation at the Joint Research Centre develops expertise for state-of-the-art assessment of electrical performance of photovoltaic devices based on traditional and emerging technologies. ESTI provides independent scientific support that underpin European energy, climate and industrial policies. The report highlights ESTI's role in performing pre-normative research resulting in new international standards, supporting innovation and contributing to the implementation of EU legislation. ESTI's work strengthens transparency, regulatory effectiveness and confidence in the performance of photovoltaic technologies deployed across the European Union.

Policy context

Solar energy is a cornerstone of the European Union's decarbonisation strategy and a key enabler of the climate goals (European Green Deal, 2019-2024 and Clean Industrial Deal, 2025), Fit for 55 package, REPowerEU plan, Net Zero Industry Act (NZIA) as well as Solar Photovoltaic being identified as a strategic technology for European re-industrialization. Achieving the EU's targets for climate neutrality and energy security requires rapid deployment of photovoltaic technologies alongside robust regulatory frameworks that ensure product quality, performance transparency and consumer trust.

In this context, accurate, traceable and internationally harmonised measurements of PV device performance are essential. The JRC, through ESTI, provides independent scientific and technical support to sustainable and competitive PV policies by developing and validating measurement methods, contributing to international standards and verifying high-impact performance claims.

ESTI's work directly supports the implementation and revision of EU legislation, including the Ecodesign Directive and Energy Labelling Regulation and future initiatives on sustainable and circular economy of PV products. It also strengthens Europe's position in global standardization and ensures that European industry and authorities operate on a level playing field with international partners.

Key conclusions

Solar photovoltaic has become the most competitive source of electricity in EU. Therefore, the PV sector requires accurate and reliable assessment of electrical performance of PV devices. 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, such as bifacial PV modules, vehicle integrated PV-VIPV or Building Integrated PV-BIPV or new PV technologies like perovskite solar cells

or tandem. Often the PV industry can have products in the market faster than the respective measurement mythologies are developed. This is because the pre-normative research and the subsequent standardization process typically require several years, whereas commercialization of new technologies appear rapidly in the market. In the absence of published international standards for measurement of PV devices, it is especially 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. Hereafter, key conclusion are listed:

- ESTI remains a world-leading reference laboratory for solar irradiance and PV device performance measurements, ensuring traceability to international standards and global equivalence of results.
- The World Photovoltaic Scale, embodied in the ESTI reference cell set, continues to provide the highest level of accuracy for PV irradiance measurements worldwide.
- Continuous participation in international inter-laboratory comparisons confirms the stability, reliability and scientific credibility of ESTI's measurement infrastructure.
- Results from IPC-XIV and ISRC confirm the long-term stability and international consistency of ESTI's cavity radiometers and spectroradiometric measurements.
- Laboratory intercomparisons related to innovative materials like perovskite devices have been crucial for the development of measurement protocols and their further standardization worldwide.
- Pre-normative research at ESTI effectively addresses measurement challenges posed by new and emerging PV technologies, supporting their reliable market uptake. New and improved measurement methodologies have been developed and confirmed for perovskite and tandem solar cells, bifacial devices, vehicle-integrated photovoltaics, and energy rating of PV modules.
- ESTI's contributions to IEC standards and technical specifications have a direct and lasting impact on global PV measurement practices.
- Through accredited calibration services and independent verification of record efficiencies, ESTI strengthens transparency, trust and competitiveness in the PV sector. ESTI issued a growing number of ISO/IEC 17025 accredited calibration certificates, reflecting increased global demand for traceable PV reference materials.
- ESTI provides technical expertise for policy initiatives, ensuring that scientific evidence was translated into practical and policy-relevant outputs.

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. Upcoming version is PVGIS v.6.

The impact of PV is being studied as an enabler for Net-Zero Energy Buildings and for the electrification of transport. On-going activities of the introduction of PV devices into Ecodesign and Energy labelling scheme and Waste Electrical and Electronic Equipment (WEEE) Directive (2012/19/EU) open the possibility to close the circular economy of these devices and offer high quality and sustainable product on the market.

Quick guide

Photovoltaics, a technology generating electricity directly from sunlight, is currently the most important electrical power technology. PV modules are priced according to their electrical performance, namely power and/or 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 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 and module power measurements. ESTI also performs research to develop and improve accurate measurement techniques for current and future PV technologies.

This report documents ESTI’s core activities over the period 2022–2025, structured around traceable measurement infrastructure, international cooperation, pre-normative research, standardization, policy support and knowledge dissemination. It highlights how ESTI’s technical work translates into tangible benefits for EU policies, industry competitiveness and the global transition towards sustainable energy systems.

1. Introduction

1.1 Background

The European Union's energy policy aims to ensure a secure, affordable, sustainable and resilient energy system for European citizens, while strengthening Europe's strategic autonomy and global leadership in clean energy. These objectives are central to the implementation of the European Green Deal [2], Clean Industrial Deal [3], Fit for 55 package [4], REPowerEU Plan [5], which together accelerate the decarbonization of the energy system, reduce dependence on fossil fuel imports, and reinforce energy security.

Within this framework, the EU has substantially raised its climate and energy ambitions. The revised 2030 Climate and Energy Framework, notably through the recast Renewable Energy Directive (RED III), commits the EU to at least 42.5% renewable energy by 2030, with an aspiration to reach 45% [6]. These measures highlight the EU's objective of achieving climate neutrality by 2050, as established by the European Climate Law [7], while fostering industrial competitiveness and innovation in Net-zero technologies [8].

Renewable electricity generation is a cornerstone of this transition, with solar photovoltaics playing a leading role due to their scalability, rapid deployment potential and affordable costs. The EU policy framework, including the EU Solar Energy Strategy [9], foresees a power system increasingly dominated by renewables, supported by grid flexibility, digitalization, storage and sector integration, making PV one of the most critical technologies for achieving climate neutrality and energy security.

In this context, reliable, traceable and harmonized measurement methods, together with robust international standards, are essential. They ensure market transparency, support fair competition, reduce investment risks and facilitate the uptake of innovative PV solutions, in line with EU objectives for sustainability, circularity and product performance [10].

The Joint Research Centre supports EU energy and industrial policy by conducting pre-normative research and actively contributing to European and international standardization activities. The European Solar Test Installation serves as an independent European reference laboratory for the validation of electrical performance and reliability of PV devices, covering both established and emerging technologies [11], [1]. Through long-standing expertise in PV, ESTI contributes to ensuring the quality, reliability and comparability of PV products placed on the EU market. ESTI develops accurate, traceable and reliable measurement techniques, which frequently feed into standards developed within the International Electrotechnical Commission (IEC) and European Committee for Electrotechnical Standardization (CENELEC). In line with EU priorities, ESTI also collaborates closely with policymakers, industry and the research community to monitor technological progress and support evidence-based policymaking.

The Ecodesign and Energy Labelling legislative framework [12] [13] and Waste Electrical and Electronic Equipment (WEEE) Directive [14] support these objectives by:

- ensuring that only energy-efficient and sustainable products are placed on the EU market (Ecodesign Directive).
- empowering consumers and professional users through transparent and comparable information (Energy Labelling Regulation).

— establishes rules under which manufacturers are financially and operationally responsible for the production and the end-of-life management of their products included PV modules within its scope (Ecodesign Directive).

— promotes efficient recycling and circularity for PV by managing the PV waste and finding markets for recovered materials (WEEE Directive).

Under the Ecodesign Working Plan [12], studies have been conducted to assess the energy performance and sustainability potential of PV panels and inverters. A preparatory study on sustainable product policy instruments for solar photovoltaic panels, inverters and systems was carried out for the European Commission, with technical input from ESTI, particularly on performance measurements and standards systems [15].

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 [16], 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 [17].

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 [18] and a rated energy output for these conditions can be calculated IEC 61853-3 [19] 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 [20]. 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 like 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 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. 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 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 specialized 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.

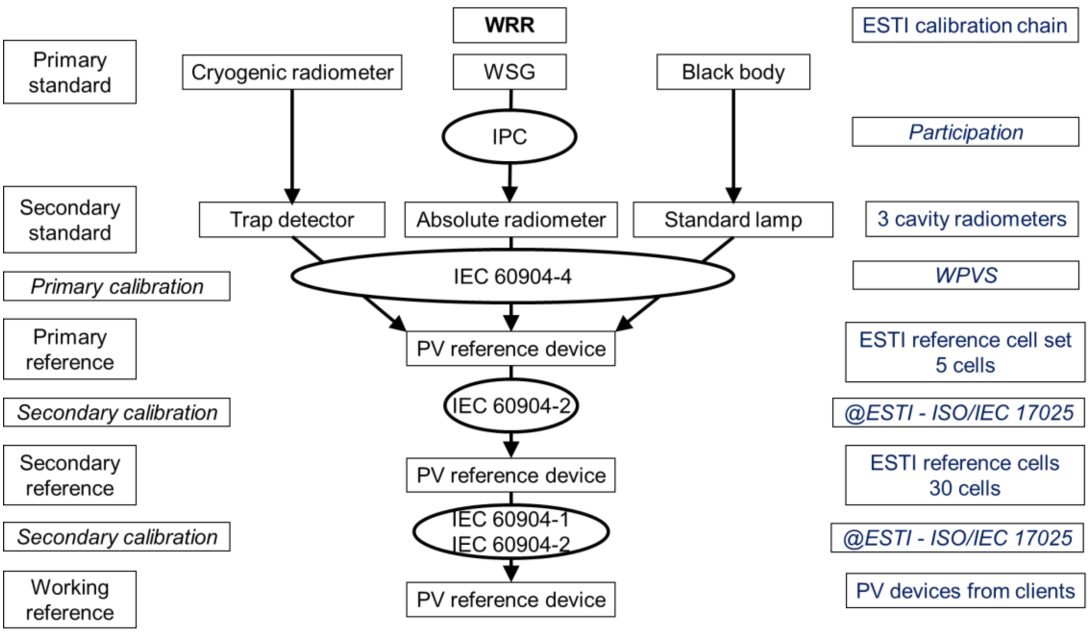
2. Solar irradiance measurement for photovoltaics

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 rely on more established measurement techniques and instrumentation. This section describes the basics of traceable solar irradiance measurements and ESTI's activities in this field, from its participation in the project teams developing international standardization down to the unique reference measurement standard for PV irradiance measurement, which is the ESTI reference cell set incorporating the World Photovoltaic Scale (WPVS) [1].

2.1 Traceability for PV

A full account has been given previously [1]. 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 like the defined PV reference spectrum IEC 60904-3 [17] 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 [21], IEC 60904-1 [22].

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, 2025.

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 World Standard Group, a group of instruments operated by the World Radiation Centre in Davos (Switzerland) and which represents the "primary standard" for solar irradiance measurement. The calibration of ESTI cavities occurs every five years against the primary standard during the International Pyrheliometer Comparison (IPC) held in Davos, which was performed in 2025 (section 3.1).

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 [23], to pyranometers according to ISO 9846 and to pyrheliometers according to ISO 9059. In 2025 ESTI finalized the purchase of other two Absolute Cavity Radiometers (PMO8), which are expected to be delivered in spring 2026, to replace two old ones (PMO6) and become the new primary reference for ESTI.

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 [24]. The WPVS 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 by a cross verification of each cell against the other four. 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 four of the five cells in the set has been confirmed 2025, while the oldest one (Stella PX102C) is showing a slight but continuous degradation. Its status within the group is now under discussion and its replacement soon is a concrete possibility. The stability check 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 En number analysis (**Table 1**). The calibration values obtained are consistent within declared measurement uncertainty if En 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 using the long-term average of all primary calibration results for these cells to assign their calibration value.

Table 1. Cross-calibration table of ESTI reference cell set showing stability of all five cells except PX102C, which is the only one having En >1.

En		**Against reference**				
		PX102C	PX201C	LCIE 930417-2	PX301C	PX304C
DUT	PX102C	NA	-1.17	-1.79	-1.40	-1.14
	PX201C	1.21	NA	-0.64	-0.23	0.03
	LCIE 930417-2	1.92	0.69	NA	0.46	0.73
	PX301C	1.48	0.23	-0.41	NA	0.27
	PX304C	1.17	-0.05	-0.67	-0.26	NA

Source: JRC, 2025.

2.4.2 Primary calibrations of PV reference cells

In 2023 and 2025 all five cells of the ESTI reference cell set were calibrated by primary calibration methods at ESTI against the Absolute Cavity Radiometers. The results are still under validation and are expected to update the calibration values of the five primary cells in the upcoming months. The five cells have a long-term historical data series of calibration values based upon primary methods only, constituted by measurements done by ESTI and by other top-level laboratories.

In the last two calibration sessions (each one consisting of a minimum of the three measurement days in clear sky conditions) two different primary methods were used: the Global Sunlight Method (GSM) and the Direct Sunlight Method (DSM), to have a metrological assessment of their mutual coherence in the actual ESTI implementation. The DSM foresees that the cell under test measures only the direct normal component of the light, therefore the device has to be positioned at the end of a collimating tube to be compared directly against the cavity radiometers. The GSM method on the contrary uses the cell as it is, but the diffuse component of the irradiance has to be measured and added to the direct component. Therefore, a shaded pyranometer is used as a second reference instrument. The two methods are similar but with quite different setups and sources of uncertainty, and their comparison is not straightforward. The results of the cells measured in both years show in **Table 2** a good agreement between the established calibration value and the two new points.

Table 2. Results of 2023-2025 primary measurements of the cells measured in both years using different methods versus the historical average values.

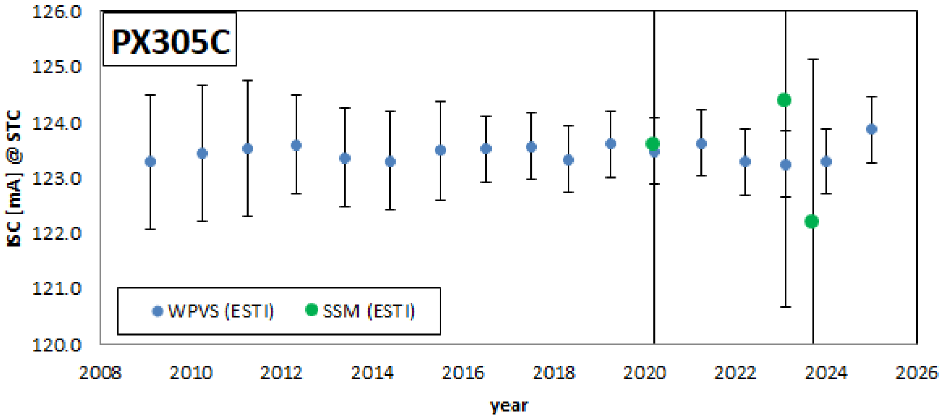
	Historical Average [mA]	**2023-DSM [mA]**	**2025–GSM [mA]**
PX201C	123.78 ± 0.26	124.28 ± 0.84	123.48 ± 1.14
PX301C	125.39 ± 0.25	125.40 ± 0.82	125.57 ± 1.15
PX304C	124.31 ± 0.27	125.08 ± 0.81	124.63 ± 1.14

Source: JRC, 2025

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. 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 is performed every year. 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 a sign of measurement reproducibility.

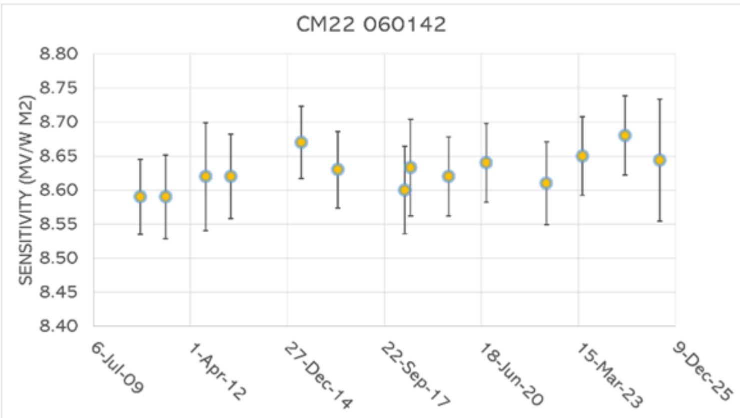


Source: JRC, 2025.

2.5 Calibration of other irradiance sensors

ESTI maintains the traceability of several pyranometers and pyrheliometers for different purposes. Pyranometers measure the global hemispherical irradiance, while pyrheliometers have a field of view limited to see only the Sun disc. Two pyranometers CM22 have a series of primary calibrations and are used as reference instruments to calibrate field pyranometers, mainly for the meteo tower, the outdoor field monitoring and the indoor light soaking system. The pyrheliometers are instead used in support to the absolute cavity radiometers to filter the sky conditions, because they have faster data acquisition rates respect to the cavities. As an example, the following **Figure 3** shows the calibration history of one of the references pyranometers.

Figure 3. Calibration history of the reference pyranometer CM22 060142 from 2010 to 2025.



Source: JRC, 2025

3. International inter-laboratory comparison measurements

ESTI participates in and organizes 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 recognized 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 Laboratory of the Rockies (NLR) 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 standardization and inter-laboratory comparisons of PV device's measurements reduces the discrepancy between labelled and verified PV module power [25].

Two critical aspects of the irradiance measurement influence the power calibration and energy yield determination for PV devices [26]. 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.

— 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 characterization, 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 30 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 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 organizing the International Spectroradiometer Intercomparison (ISRC) to gather and spread knowledge and good practices in this field.

3.1 IPC-XIV

The 14th edition of the International Pyrheliometers Comparison (IPC-XIV) was held at the Physikalisch-Meteorologisches Observatorium Davos, World Radiation Centre (PMOD-WRC) from 22nd of September to 10th of October 2025 (**Figure 4**). Participants came from 56 Institutions representing 35 countries. The event is repeated every five years 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 five pyrheliometers (CH1-040370, CH1-060460, CH1-930018, CHP1-300001 and CHP1-300002).

During the three weeks sufficient measurements were taken 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 2026. 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.

In 2025, ESTI finalized with Davos Instruments a contract for the supply of two new PMO8 absolute cavity radiometers. During the IPC-XIV they were operated by the PMOD staff together with the World Standard Group to have their WRR factors already assigned now of their delivery to ESTI (planned for Spring 2026). These new instruments are going to replace the PMO6, which are 40 years old and start experiencing technical problems.

Figure 4. Left: overview of the measurement field of the IPX-XIV (Davos, 2025); Centre: set-up with the ESTI instruments; Right: close-up of ESTI instruments.

Source: JRC, 2025.

3.2 Spectroradiometer comparison

3.2.1 International Spectroradiometer Intercomparison (ISRC)

The International Spectroradiometer Intercomparison (ISRC) is an annual event organized by ESTI in the field of solar radiation measurements. In 2025, the 13th edition took place in June. While the event was hosted in different locations across Europe (typically astronomical observatories or other research institutes) until 2023, it is now permanently held at the JRC Ispra premises. This allows a better organization in terms of logistics and infrastructure, but also the possibility to complement the outdoor measurements with indoor sessions.

In 2025 the participating spectroradiometers were assessed:

— outdoor measuring synchronously the natural solar spectrum.

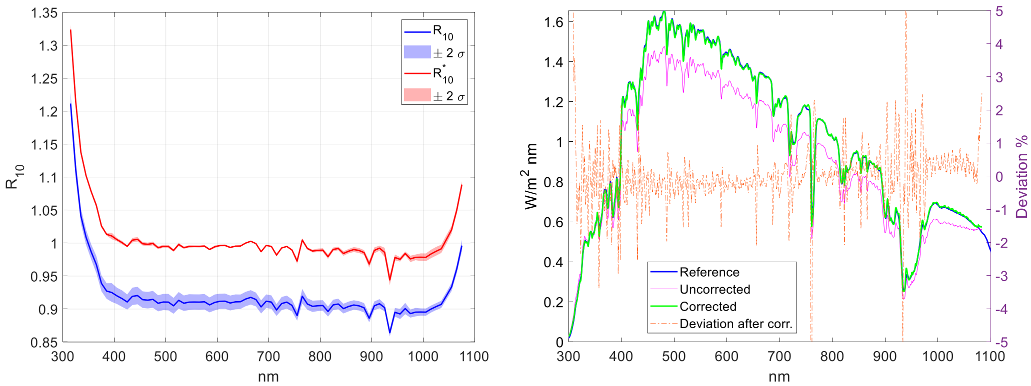
— indoor in the Apollo large area steady state simulator, allowing the estimation of the linearity behaviour of the instruments under varying irradiance levels.

— indoor using a standard lamp as light source, using the ESTI spectroradiometer calibration setup for a higher-level metrological assessment.

Started in 2011 at the site of ENEA in Portici (Naples, Italy), the first editions of the ISRC focused primarily on photovoltaic research and applications. Over the years, the range of interested participants has gradually expanded, encompassing not only laboratories in the PV field, but also space agencies, National Metrological Institutes (NMI), universities, manufacturers of measurement instruments and actors in the fields of climatology and meteorology. The number of participating instruments and their geographical distribution across the globe increased as well: in 2025 there were 31 spectroradiometers and 25 pyranometers from four continents, with a substantial increase of participants from South America.

The ISRC output is a set of correction functions ("R_{10} functions") allowing a post-processing correction of measured sunlight spectra basing upon high quality reference data taken during the ISRC, as shown in **Figure 5**.

Figure 5. Left: R10 functions for a participating spectroradiometer; Right: application of the functions to correct a measured spectrum biased by calibration issues.



Source: JRC, 2025

3.2.2 Bilateral JRC-ESA

In June 2025, a bilateral comparison between ESTI and the European Space Agency ESA-ESTEC took place at the ESTI premises. The scope of the exercise was the assessment of the ESTI MultiCAS system against the ESA spectroradiometer while measuring pulsed light generated by flash solar simulators. Measuring the spectrum of flash simulators is a core activity for both laboratories because this type of machines is still the most used for testing crystalline silicon PV modules. Both ESA ESTEC and ESTI own Pasan3B simulators, but with different optimizations: ESTI uses optical filters to tune the spectral irradiance closer to the terrestrial solar spectrum ("AM1.5" or “Air Mass 1.5” spectrum), while ESA uses different filters to tune it closer to the extraterrestrial spectrum (“AM0” or “Air Mass 0” spectrum). After the participation to the Spectroradiometer Intercomparison, several discrepancies on the ESA instrument arose in the UV part of the spectrum, which is more important above the atmosphere rather than at ground. The measurement of short-pulse light is particularly challenging due to the low level of signal collected by the instruments in a few milliseconds (in this case 10 milliseconds).

The preliminary results are still pending, but the collected data at a first analysis seem to show a significant difference between the different ESA' s optical filters AM0, thus generating a spectral non-uniform pattern on the measurement plane, and a shift at the interface between different detectors of ESA's instrument due to the low signals level.

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

In 2019, ESTI performed 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, NLR 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, 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 [27], 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 measurements for this inter-laboratory comparison in 2020, preliminary results were delivered in 2022. Based on these all participants made their internal evaluation and in 2025 a peer-reviewed article about the results and resulting improvements was drafted and is expected to be submitted and published in 2026.

3.3.2 Calibration of perovskite devices (coordinator KISTEC)

JRC is participating in a third perovskite round-robin. The intercomparison employs a hub and spoke test procedure. Organized by KISTEC as the central hub, with satellite labs including AIST, JET, CSIRO, Fraunhofer, JRC, NPL, and NLR (ex-NREL), this initiative aims to standardize the determination of steady-state maximum power (P_{max}), short-circuit current (I_{sc}), and open-circuit voltage (V_{oc}) across different laboratories. The comparison utilizes two perovskite solar cell mini modules (PSCMs) and a single cell (PSSC), Laboratories are required to perform SR measurements and assess I_{sc}, V_{oc}, and P_{max} using their routine methods. The results of this inter-comparison will contribute to the development of a technical specification for the IEC, and findings are intended for joint publication, subject to confidentiality agreements and participant consent. Ultimately, the round robin seeks to refine measurement techniques and promote consistency in perovskite solar cell evaluations globally.

4. Generation of PV reference material

Based on the calibration chain available at ESTI, 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 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 and considering the new geographical distribution of the PV module production, ESTI specializes 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). 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.

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 (2024-2027).

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 relation to new PV technologies.

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

4.2 Reference devices for clients

During 2022-2025, ESTI issues to clients and partners under its ISO/IEC 17025 accreditation as calibration laboratory a total of 132 reference measurements worldwide with associated calibration certificates that includes:

— reference standards for national or secondary reference laboratories.

— leading innovation and research centres developing world record innovative PV devices.

— Industrial level photovoltaic companies implementing innovative technologies and materials.

4.3 Metrology laboratory

The ESTI Metrology laboratory (**Figure 6**) provides calibrations for all the instruments used in the laboratories and simulators in order to maintain the traceability to the Primary or National Standard using our secondary standards calibrated on a 1–2 years basis with an ISO 17025 certificate.

The main fields of calibrations are:

— voltage/current/resistance: shunts, transimpedance amplifiers, dataloggers, multimeters, digital oscilloscopes

— temperature/humidity: temperature readers/loggers, temperature/relative humidity transmitters

For the Voltage/Current/Resistance our secondary standard is a Fluke 5730A calibrator, for the temperature an ISOTECH SPRT 909L (standard platinum resistor thermometer) with which we transfer the calibration to our working standard PT100.

Figure 6. Overview of ESTI Metrology Laboratory.

Source: JRC, 2025

Each instrument calibration produces a report for traceability that is issued and archived both in paper and digital format.

All the calibration are done using existing software (LabView) or manually, in both cases we are carry-on activities to update existing software and automate the manual procedures (were possible) to minimize human errors by writing new software.

Future laboratory improvements are foreseen where Fluke 8588A high precision digital multimeter will be implemented as a secondary standard instead of the Fluke 5730A calibrator. For temperature control and monitoring, a new setup based on oil bath will be use.

4.4 Validation and verification of PV device performance

In the rapidly evolving field of photovoltaic (PV) technology, ESTI continues to witness remarkable advancements, with several instances of groundbreaking performance being reported annually. These developments span both well-established technologies like crystalline silicon and innovative innovations such as perovskite solar cells (PSC). While manufacturers frequently announce these impressive achievements, it is essential to ensure the accuracy and reliability of their claims. Many manufacturers may not have the specialized equipment or expertise required for precise performance measurement. Therefore, the role of independent calibration laboratories becomes paramount. Free from commercial or national interests and equipped with the necessary expertise, these laboratories are responsible for verifying and validating such claims. Among them, ESTI stands out for its global recognition in independently affirming extraordinary PV device performance, a testament to its extensive experience and proficiency in measurement technology.

4.5 Co-authorship of world record PV efficiency tables

For many years, ESTI has been a co-author of the world record efficiency tables that are published twice annually in Progress in Photovoltaics [28] [29] [30] [31] [32] [33] [34]. These results are submitted to a board of authors, including representatives from four leading laboratories in PV device measurement: AIST, ESTI, NREL, and ISE-FhG. The authors conduct a thorough review of the submitted results, leveraging their extensive technical expertise and experience. Due to the esteemed nature of the authors' board, these publications are highly respected and frequently cited in the PV field.

In the period from 2022 to 2025, JRC-ESTI has independently verified world record efficiencies five times (32.5%, 33.2%, 33.7%, 34.6% and 35.0 %) from three different groups (HZB, KAUST, LONGi). In all cases, those were 1 cm^2 tandem Perovskite on Silicon cells.

5. 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 recognized 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 – like perovskites-based solar devices - are also investigated from a metrological point of view. Often these devices have 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. Beside the metrological investigation, ESTI also collaborated with JRC F2 Unit (Technologies for Health) in the context of the Exploratory Project “Recycle-PSC”, which aimed at contributing to different aspects of the entire PSC technology development, mainly by:

- developing and validating reliable measurement procedures and standards necessary to reduce uncertainties in measurement and calibration of such emerging PV products.
- developing environmentally friendly recycling processes for PSC at their end-of-life, proving the goodness of low-cost and high-efficient innovative PV products.

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.

5.1 Contributions to international standards

The contributions to international and European standards is presented in a separate report [35] and [36]. Below only the most relevant in the context of the present report are mentioned as well as pre-normative research.

Currently three staff members of ESTI are nominated for the IEC TC82 as scientific experts under a type A liaison between IEC and the European Commission [37]. Within WG2 they are project team members for several standards concerning the measurement and evaluation of PV devices. In this capacity they regularly participate in IEC TC82 WG2 meetings (in-person and online) and PT meetings (mostly online), discus technical details of standards under development or revision and draft parts of them.

- Project leader for PV reference devices

Harald Müllejans served as project leader for IEC 60904-2 (Photovoltaic devices – Part 2: Requirements for photovoltaic reference devices). Such reference devices are essential as they are used in every measurement of all PV devices produced. The latest version (Edition 4.0) was published in June 2023 as a commented version, meaning that significant changes to the previous edition were explained to the reader in detail. Subsequently the chair and secretary of IEC TC82 decided to award Harald Müllejans the prestigious IEC 1906 award in recognition of his exceptional and efficient effort as project leader for IEC 60904-2.

— Project leader for energy rating of PV devices

Teodora Lyubenova is becoming a project leader of IEC 61853-4, Photovoltaic (PV) module performance testing and energy rating - Part 4: Standard reference climatic profiles. This amendment proposes updates to the standard reference climatic profiles used for the energy rating of photovoltaic modules, ensuring consistency with recent developments in module technologies (including bifacial devices) and installation configurations defined in the amendment of IEC 61853-3 to support updated energy rating methodologies within the IEC 61853 framework.

— Key contributor to perovskite devices technical specification

One of the key gaps in the standards portfolio for PV measurements is that for perovskite-based devices. To address this, a new work item was proposed and agreed on within TC 82 WG2, i.e. IEC TS 60904-1-4: Rules for current-voltage measurements of perovskite based photovoltaic devices.

With significant input from JRC-ESTI the Committee Draft (CD) of the document was completed and sent out for comments. It has been received 43 Country Comments (CC) and are in the processes of drafting a response by early 2026.

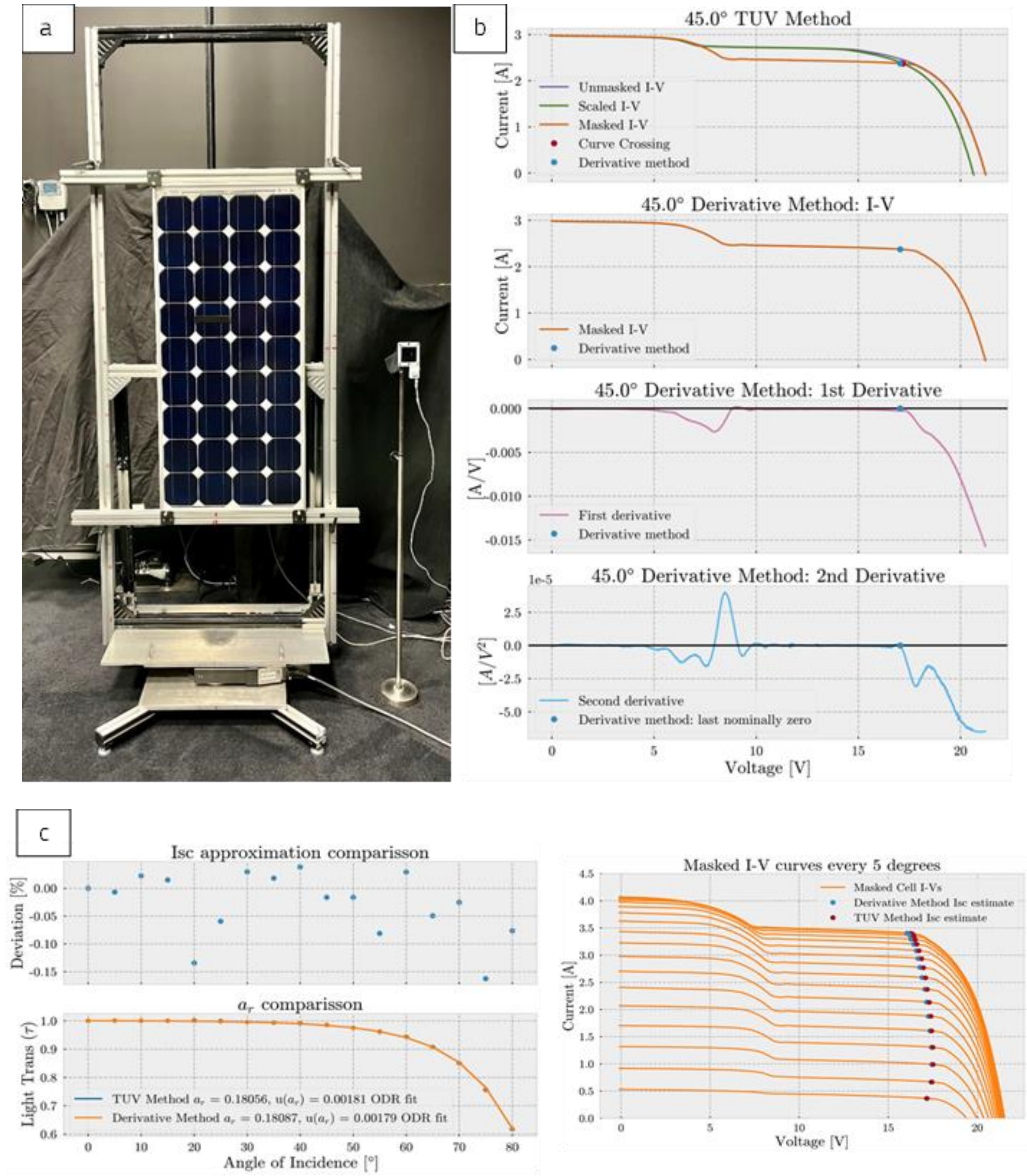
5.2 Measurement and calibration of PV devices

5.2.1 Simplified angular responsivity measurements of c-Si modules

ESTI is being developing an innovative approach to Angular Responsivity (AR) measurement for crystalline silicon (c-Si) modules, facilitating Climate Specific Energy Rating (CSER) calculations according to IEC 61853 series. This new method effectively reduces the number of required measurements by half, utilizing a single-axis rotation around the vertical axis for modules in a vertical orientation. The setup comprises a high load motorized rotary stage, an extruded aluminium frame for mounting (**Figure 7**a), and a Xenon flash bulb light source positioned approximately seven meters away, with light baffles to minimize stray light. A stationary reference cell adjacent to the rotary stage ensures correction for flash-to-flash irradiance variations. Validation of this methodology was conducted using reference measurements from an encapsulated c-Si cell, previously employed in an IAM round-robin. Post stray-light correction, all measurements except one at 85° fell within the uncertainty range of the reference laboratory. Given the general unreliability of measurements at 85°, as recommended in future IEC standards, measurements were restricted to 80°.

The proposed method diverges from the de facto standard method (originally proposed TUV) requiring two sets of current-voltage (I-V) curves at angles between 0 and 85°, by only necessitating the masked set of I-Vs. This approach identifies the current at the highest voltage where the second derivative is nominally zero as an approximation of the short-circuit current (I_{sc}) of the masked cell (**Figure 7**b), Comparative analysis reveals that the I_{sc} estimates from both methods align within ±0.2% for angles up to 80°, with negligible differences in the calculated AR coefficient (**Figure 7**c).

Figure 7. Measurement set-up: a) picture of the measurement setup; b) graphical illustration of the method compared to the TUV approach; c) results comparison between both methods for a module.



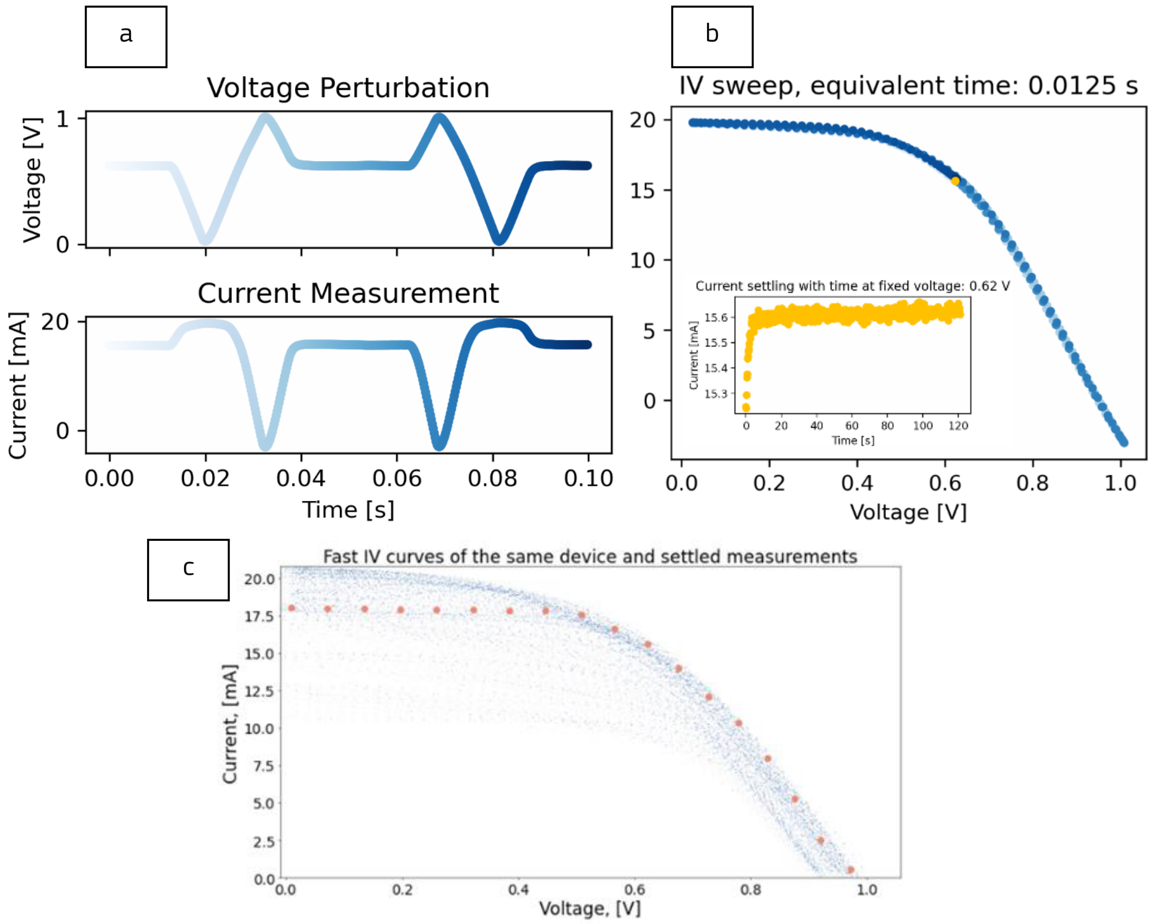
Source: JRC, 2025

In conclusion, the newly constructed AR measurement setup at ESTI has been validated against reference laboratory measurements, demonstrating consistent results from 0 to 80° post stray-light correction. This innovation not only reduces measurement requirements but also ensures negligible differences in fitting results, thereby optimizing efficiency and accuracy in AR testing of c-Si modules. Further efforts should aim at minimizing the uncertainty component associated with stray-light correction, particularly when scaling to module-level applications.

5.2.2 Measurement of perovskite solar cells

Perovskite solar cells have emerged as a promising technology in the photovoltaic industry due to their high-power conversion efficiencies and potential for low-cost production. However, their characterization presents unique challenges, notably the hysteresis and meta-stabilities that occur on varying timescales. These phenomena complicate the accurate measurement of their electrical performance, as the device behaviour can change depending on the voltage sweep rate and voltage and light bias history.

Figure 8. Representation of the measurement protocols, combining both quasi-steady-state measurements with fast I-Vs with varying sweep rates: a) the custom voltage perturbation generated by an arbitrary waveform generator, b) example of the extract I-V sweep from the voltage perturbation and the current settling at 0.62V; c) example of the measurement results combining settled measurements in orange and fast reverse and forward I-Vs at a range of sweep rates.



Source: JRC, 2025

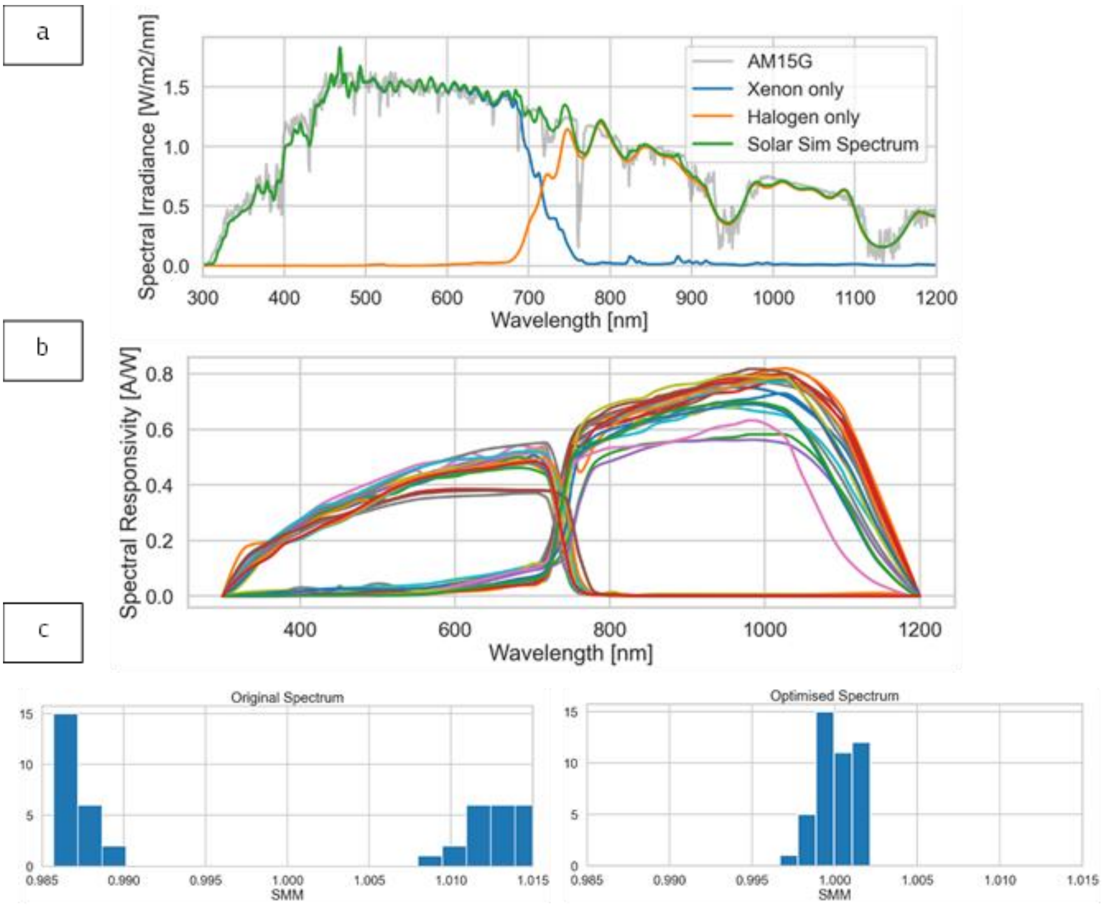
At ESTI, innovative measurement protocols have been investigated to address these challenges. These protocols involve quasi steady-state measurements where PSC are maintained at fixed voltage biases for extended periods to allow current settling. This part of the approach mitigates errors caused by rapid meta-stable phenomena and provides a more reliable indication of device performance. Additionally, the integration of fast I-V measurements with durations as short as two milliseconds complements the steady-state method by capturing instantaneous performance metrics (**Figure 8**, visual representation). This hybrid approach not only aids material scientists in identifying losses within the device stack but also assists engineers in accurately sizing photovoltaic systems.

By reporting multiple steady states and their associated fast I-Vs, ESTI's protocol provides comprehensive data that can inform both laboratory research and commercial module development. This method ensures that measurements reflect the true performance potential of PSC, thereby supporting their integration into real-world applications. The work at ESTI aims to support the standardization of measurement practices that enhance the reliability and comparability of perovskite solar cell evaluations.

5.2.3 Improvement of Solar Simulator Spectrum for measurements of perovskite PV devices

Accurate efficiency measurements of photovoltaic devices are crucial for both laboratory research and commercial applications. In the case of perovskite photovoltaics, these measurements are complicated by the spectral mismatch between the laboratory light source and the standard reference spectrum. Prolonged exposure to light and bias voltage can lead to meta-stability and degradation, increasing uncertainties in efficiency measurements.

Figure 9. Solar simulator target spectrum optimisation: a) solar simulator spectral irradiance measurement; b) set of measured Spectral Responsivities used for optimisation; c) histogram of the SMMs calculated for each device in the set before and after the spectrum optimisation.



Source: JRC, 2025

The ESTI has developed a method to optimise the spectrum of tenable solar simulators (e.g. as depicted in **Figure 9**a) to achieve accurate efficiency measurements for perovskite and perovskite-silicon tandem devices. This approach involves adjusting the solar simulator spectrum to minimize the square differences in currents that would be produced under reference conditions and the simulator's conditions. By using previously measured spectral responsivity (SR) data (**Figure 9**b), a target spectrum is identified that reduces the spread of spectral mismatch factors significantly (**Figure 9**c). This optimization procedure allows for the direct measurement of device efficiency without prior device specific SR measurements, simplifying the process and maintaining low measurement uncertainties.

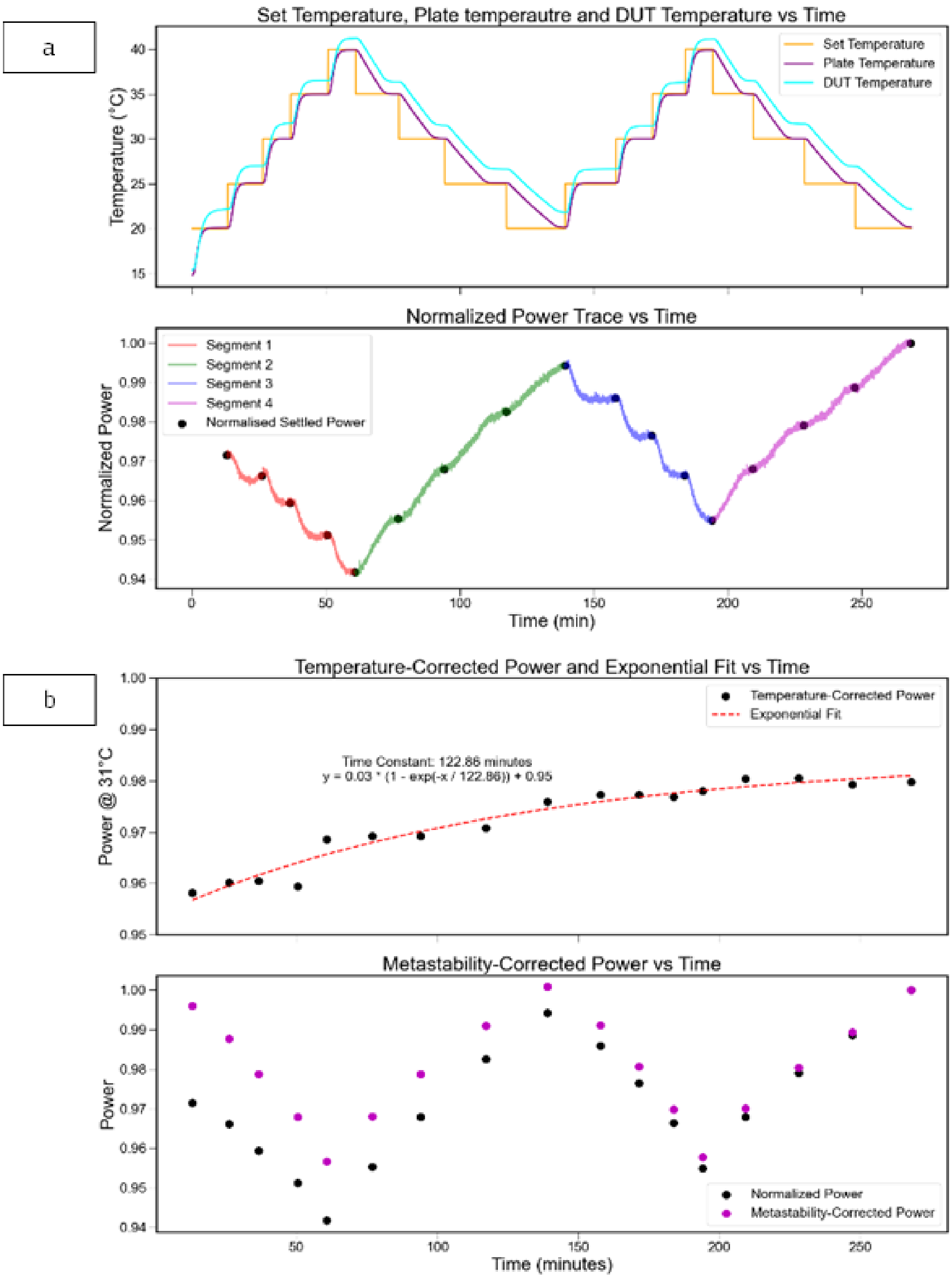
The implementation of a universal spectrum for all perovskite devices reduces the range of spectral mismatch factors and enhances the reliability of efficiency measurements. This advancement is particularly beneficial for emerging technologies like perovskite-silicon tandems, where high accuracy is essential for performance validation and optimization. The work highlights the importance of spectral optimization in photovoltaic measurement protocols and establishes a foundation for more streamlined and accurate assessments of perovskite solar cell performance

5.2.4 Measurement of the Temperature Coefficients of perovskite solar cells

Understanding the temperature coefficients of photovoltaic devices is essential for predicting their performance under varying environmental conditions. Perovskite solar cells, known for their high efficiencies, exhibit unique thermal behaviours that can affect their power output. Unusual temperature coefficients, which may be negligible or even positive, necessitate robust methodologies for accurate characterization.

The methodology developed at the ESTI addresses these challenges by incorporating precise temperature control and monitoring systems. This approach allows for the decoupling of temperature effects from measurement artefacts and device meta-stabilities. Quasi-steady-state measurements are utilized to track maximum power points (P_{max}) over extended periods, minimizing the influence of rapid meta-stable phenomena. The experimental protocol (**Figure 10**) involves repeatedly varying the temperature in a systematic V-shaped pattern to mitigate thermal hysteresis effects. This iterative process helps isolate the impacts of slow meta-stabilities and degradation, ensuring more accurate temperature coefficient measurements.

Figure 10. Experimental procedure developed at ESTI for measuring temperature coefficient of perovskite solar cells: a) systematic cyclic temperature control and measured settled power. b) estimation and correction for the slow meta-stability possible due to experimental protocol.



Source: JRC, 2025

The findings reveal the intricate relationship between temperature coefficients and meta-stabilities in PSC. By refining the measurement process, the methodology provides insights into the thermal dynamics of perovskite devices, supporting their optimization for real-world applications.

5.2.5 Recycling of perovskite solar cells: Recycle-PSC Exploratory Project

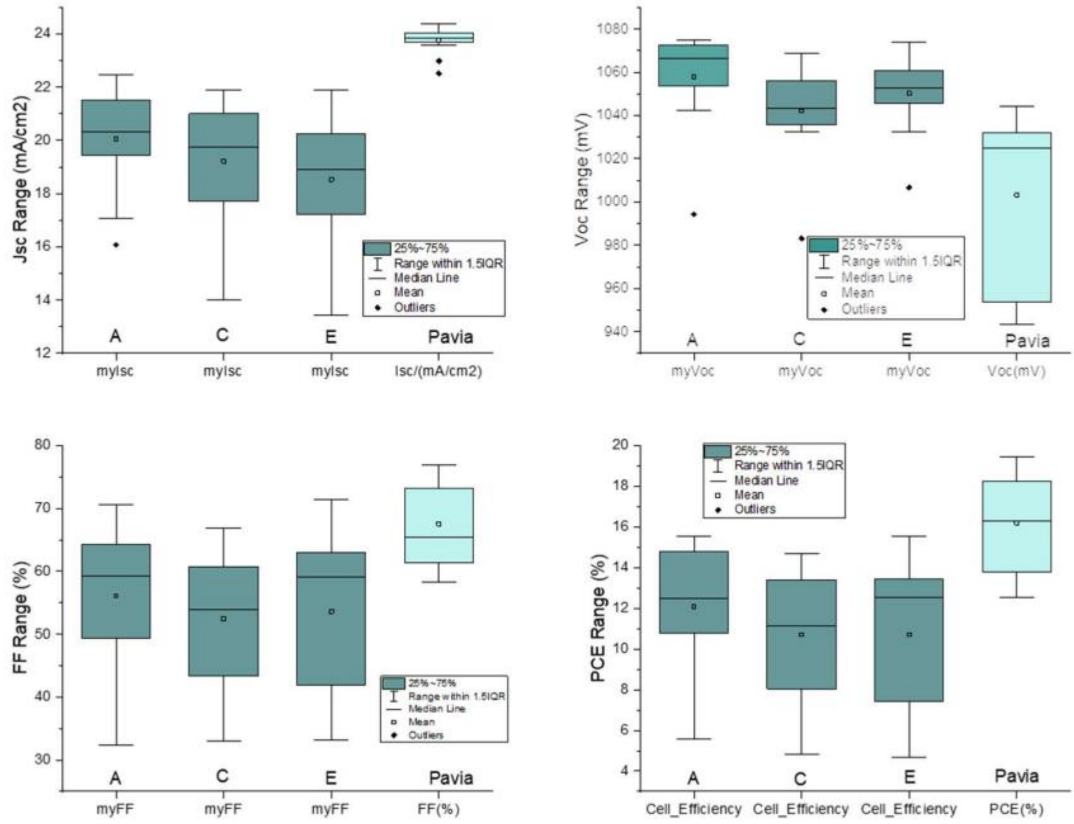
As one of the top ten science breakthroughs of the last decade, perovskite-based cells have shown an extremely rapid efficiency improvement. Their high efficiency, combined with the potential for low-cost industrial production, is attracting significant interest from top photovoltaic solar industrial producers.

Yet, for the PSC to reach full deployment to the market, a better understanding of the materials properties and the fabrication processes will facilitate major advances in efficiency, reliability, and reproducibility. In fact, perovskites perform differently from their predecessors, and defining appropriate methods to measure their performance remains a significant challenge [38]. In addition, PSC fabrication involves the use of some toxic elements such as lead and other non-eco-friendly components (like polymers for encapsulation and/or solvents for the fabrication process), which could potentially result in toxic substance leakage, environmental pollution and adverse health effects. Moreover, the application of expensive transparent conductive oxide (TCO) to substrates (such as Fluorine-doped tin oxide, indium tin oxide) and noble metal electrodes (such as gold or silver) affects almost 20% of the total PSC fabrication cost, and in a mass production these could seriously impact rare resources availability, especially noble materials, gold and indium [39].

ESTI has been involved in tackling these tasks also through the *Recycle-PSC Exploratory Project,* both directly – by testing various suitable characterization routines for PSC - as well as in collaboration with JRC-Ispra Unit F2 “Technologies for health” – by assessing recycling processes for the device at its end-of-life.

The starting point of the project was the creation of a network of collaborators - European universities and research centres - interested in providing perovskite-based devices. Since PSC can come in different layout and materials combinations, there was an attention to diversify the received structures to check whether such differences could have an impact in the measurement protocols. Having assorted PSC is of high importance also from the point of view of the recycling process, as varied materials will undergo different processes and/or treatments to get through the whole recycling chain.

Figure 11. FOMs extrapolated from I-V scans realized at different moments of the "manual I-V protocol" procedure.

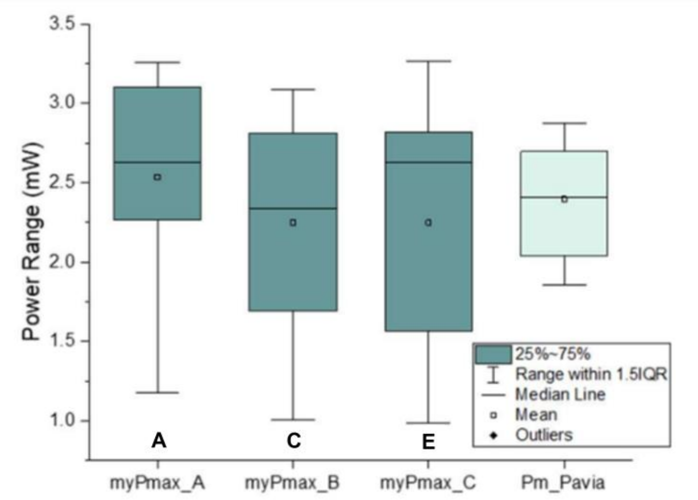


Source: JRC, 2024

As an excerpt from JRC136523 technical report, **Figure 11** depicts the Figures of Merit (FOMs) dependence with respect to the specific measurement points – where "A", "C" and "E" correspond to specific bias states at which the cell is brought and kept, before acquiring the I-V characteristics - compared to the values measured and declared by one of the partner Universities (University of Pavia). In A, C, and E, the cell is assumed to be at equilibrium. Further details on the measurement routine performed can be found [40].

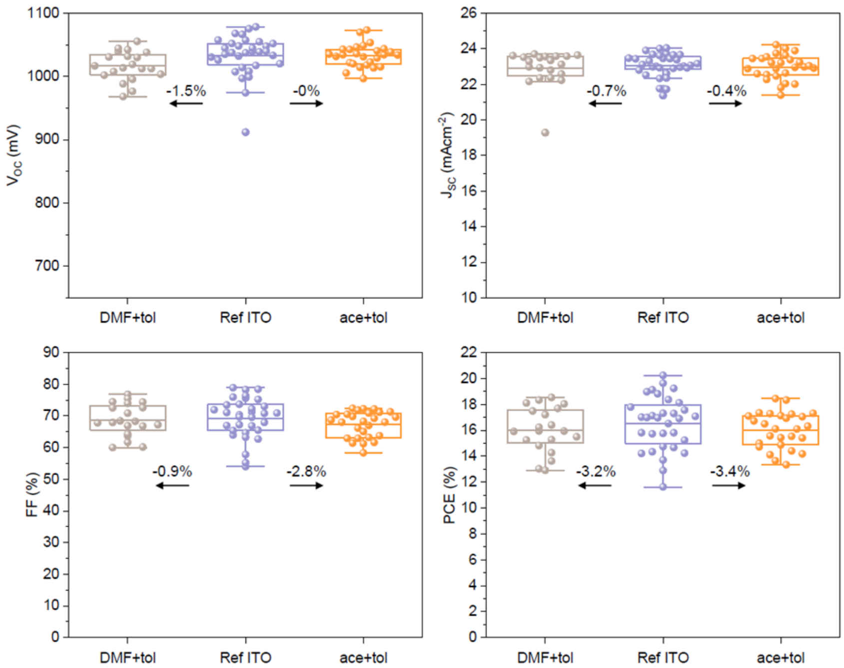
It can be seen from the **Figure 11** that while Jsc has no recovery over the full measurement cycle, the V_{oc} has a partial recovery at the end of the scan. The fill factor (FF) recovers as well, but with a wider spread at the end, due to the stress induced by the measurement, with consequent series resistance increase. Interestingly, even with all possible inaccuracies of the measurements (lack of mask, aging on devices) as well as induced stress due to the whole voltage cycling, the "stabilized" maximum power output (P_{max}) measured at point A - the most interesting one because typically considered as the reference point for a certified measurement on PSC - is on average highly comparable with values from UniPV, corresponding to freshly made devices. Therefore, in a more controlled experimental environment one should expect even higher values. Indeed, the last measurement point, E, shows a median as high as the one at A, which might suggest a partial recovery process happening in the cell (**Figure 12**).

Figure 12. Maximum Power Point (P_{max}) extrapolated from I-V scans realized at different moments of the "manual I-V protocol," compared to the same value (P_{max}) measured from the provider partner.



Source: JRC, 2024

Figure 13. Comparison between devices FOMs realized with either pristine (Ref ITO) or recycled substrates. The substrate cleaning routine was realized with either the use of effective but hazardous DMF + toluene, or with acetone + toluene.



Source: JRC, 2024

Recovering useful materials and components from PSC could reduce the life cycle impact of their manufacturing, as well as improve the feasibility and sustainability of the whole technology. Out of the various layers composing a PSC, Recycle-PSC concentrated its efforts in the TCO covered glass, which carries high economic and environmental costs with it, and therefore makes it one of the most profitable components to be potentially recycled and reused.

The collaboration between ESTI and F2 brought an interesting result in showing comparable performances between PSC fabricated with pristine TCO glass, and those realized with reused TCO glass, after an ad-hoc cleaning process developed at the JRC and based on the use of acetone, a non-hazardous, cheap and safe-to-handle solvent (**Figure 13**).

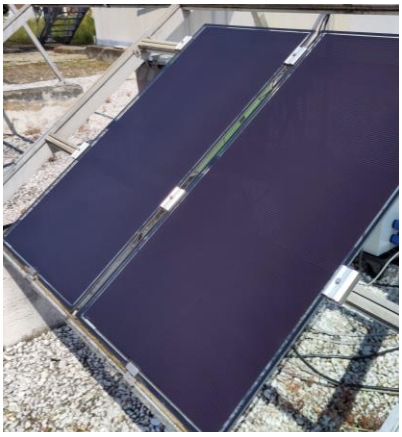
Recycled PSCs were fabricated using substrates recovered with the Dimethylformamide (DMF) or acetone treatment, and FOMs show that the two treatments yielded comparable results. PCE losses were most likely due to a non-optimal condition at the ITO interface, but overall, the recycled devices exhibit a remarkable remaining factor of over 96% [41].

5.2.6 Testing of full-size perovskite PV modules

PSCs could have a potential benefit compared to silicon solar technologies due to the cheap production cost and potentially high efficiencies. ESTI measures and calibrate the world record efficiency cells included in the NLR World Record Efficiency Table [42], as one of a hand full accredited laboratory. ESTI is involved in developing, writing and reviewing standards for c-Si technologies and for perovskite solar cells [43].

As there are today reports of companies with module production and large-scale installations [44], more independent outdoor monitoring studies of modules are needed to verify the potential of this solar cell technology. In the ESTI's outdoor monitoring site have been installed two perovskite single-junction PV modules (**Figure 14**). Before mounting the modules outdoor, ESTI developed a measurement protocol indoor for measuring settled values of the perovskite modules. The protocol was used for characterizing the perovskite modules indoor, providing a reference performance value. The measurement protocol parameters (*I-V* sweep time e.g.) were applied in the outdoor installation, such that settled values were measured, as well as to be able to compare the performance outdoor with the indoor performance.

Figure 14. The two-perovskite mono-junction solar modules in the ESTI outdoor monitoring site.

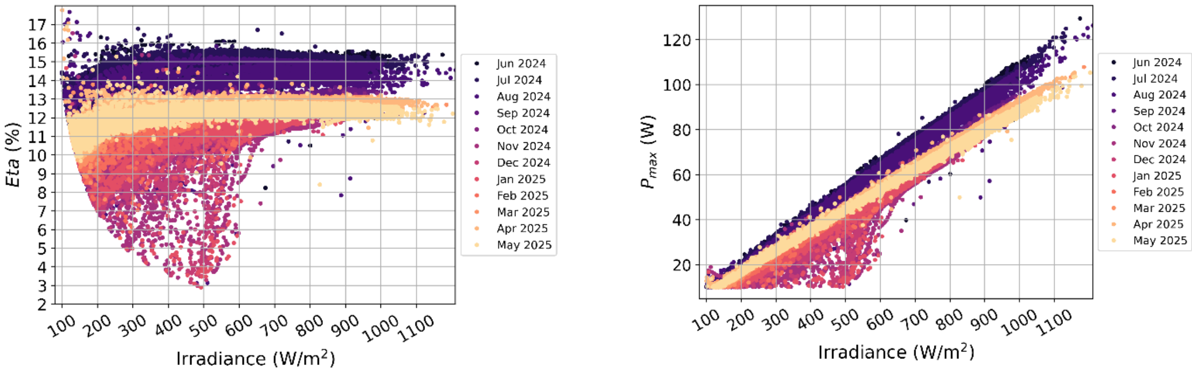


Source: JRC, 2025

The study of the outdoor monitoring of the perovskite modules was presented at the EUPVSEC 2025 by an oral presentation and in the special issue journal publication [45].

The main outcome of the study is shown in **Figure 15**, where the efficiency (left) and the P_{max} (right) as a function of irradiance, with data colour coded for month, is presented.

Figure 15. Efficiency eta (left) and P_{max} (right) for one of the modules as a function of irradiance with the data colour coded for months.



Source: JRC, 2025

The study is still ongoing at the writing of this report. ESTI will continue to investigate measurement protocol parameters for perovskite modules, as well as collecting and analysing data from the outdoor monitoring of the perovskite modules.

5.2.7 Vehicle Integrated Photovoltaics (VIPV)

As the number of electrical vehicles is increasing, so is the need for charging, which causes an increasing load on the electrical grid. Decreasing the need of charging means decreasing the strain on the grid. ESTI in collaboration with VELA (JRCs Vehicle Emissions Laboratory), performed and published a study where the potential of Vehicle Integrated Photovoltaics (VIPV) was simulated and calculated [46].

The study included simulations of the potential of VIPV on a commuter car and a light delivery van for six climatic regions and for typical daily usage profiles over a ten-year period. The analysis included the energy needs for driving and cabin temperature control. The results revealed that the grid power needed to drive such vehicles on identical routes can vary by more than 44% between different climate regions. In the best case the solar power generated can cover up to 35% of the driving range per year. This contribution can vary by a factor of 2.5 between different climates.

To take the VIPV study further after the published work [46], a comprehensive real-world assessment of VIPV technology was initiated. Two vehicles, a Plug-in Hybrid Electric Vehicle (PHEV) a Toyota Prius and a Battery Electric Vehicle (BEV) a Hyundai Ioniq5, were selected and equipped with VIPV systems as optional equipment. For pictures and specifications, see **Figure 16** and **Figure 17**.

Figure 16. The two vehicles included in the study with characteristics.

PV panel: 1 m^2
Capacity: 10.9 kWh[1]

Electric range: 72 km

VIPV added range: 6 km (claimed)

PV panel: 1.4 m^2

Capacity: 72 kWh[2]

Electric range: 451 km

VIPV added range: 5-6 km (claimed)

Source: JRC, 2025

Figure 17. The VIPV modules of the Prius (left) and of the Ioniq5 (right).

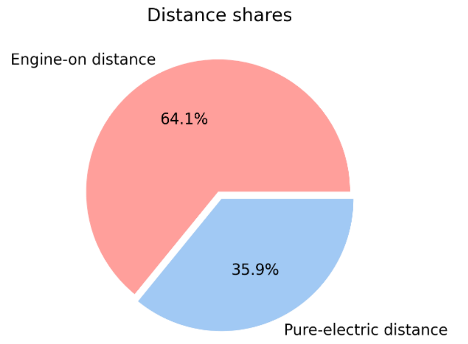
Source: JRC, 2025

A tailored data-logger system was installed in each vehicle to collect data from the on-board diagnostics, Global Navigation Satellite System (GNSS), and physical sensors measuring solar irradiance, enabling the characterisation of the solar energy received and evaluation of the total electrical energy produced.

Preliminary results of the Toyota Prius covering a time period from January 2024 to January 2025 are presented in **Figure 18**, where the driven distance (total, engine-on and pure-electric), fuel consumption and added energy to the battery from the grid as well as from the VIPV is presented. The propulsion energy obtained from each of these was obtained using conversion factors and generic efficiency values: petrol density 747.5 g/L, petrol low heating value 41.5 MJ/kg, engine efficiency 33% and electric motor efficiency 90%. Because of the charging applied by the users and the driving/ambient conditions encountered, the Vehicle under test (VUT) drove 35.9% of the distance in pure-electric mode. Calculating the shares from the propulsion energy values, 65.1% of the required propulsion energy was obtained from fuel, 32.3% from the grid (external charging of the battery) and, finally, 2.6% from the VIPV. If one calculates the VIPV addition only to the electric propulsion energy the share is 7%. The quantified VIPV benefit, despite modest, is considered worth of attention as it will decrease the strain of the grid. The study is ongoing, and further evaluations will be performed, on different time spans, for different conditions and for both cars.

Figure 18. On the left, distance travelled, consumption metrics and calculated propulsion energy. On the right, distance shares with engine-on versus pure-electric mode. Values obtained after one year of VUT usage (from January 2024 to January 2025).

Quantity	Value
Odometer	15285.9 km
Distance with engine-on	9797.7 km
Distance in pure-electric	5488.2 km
Fuel consumed	514.08 L
Grid energy into the battery	856.2 kWh
VIPV energy infotainment	68.7 kWh
Fuel energy into propulsion	1550.5 kWh
Grid energy into propulsion	770.6 kWh
VIPV energy into propulsion	61.8 kWh



Source: JRC, 2025

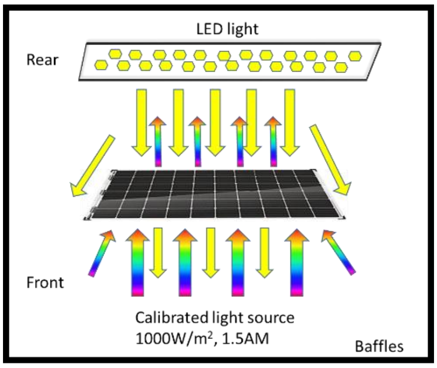
Within the work on VIPV ESTI is also a member of the IEC TC 82, working group WG2 to develop standards for VIPV characterization.

5.2.8 Measurement of bifacial PV devices

A bifacial PV module is a solar panel designed to generate electricity from both its front and rear sides, unlike traditional panels that only use the front, capturing sunlight directly and reflected light (albedo) from the ground or surroundings for increased energy yield. Bifacial devices have become a 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 soon. According to the latest available International Technology Roadmap for Photovoltaics (ITRPV) data (2025 edition) and related industry sources, bifacial solar cells are now dominant in the PV market, with about 90 % of PV cell production in 2025 [47]. This reflects the widespread adoption of bifacial technology at the cell level in global manufacturing.

The publication, in 2024, of the updated Technical Specification (TS) IEC TS 60904-1-2 for the measurement of current-voltage characteristics of bifacial PV devices [48] standardized various methods for measuring bifacial PV: natural sunlight, a single-side illumination using the equivalent irradiance method and a double-sided illumination approach. There is a lack of experience reported regarding testing of bifacial PV devices under double-side illumination using two light sources. Thus, at ESTI has been developed testing methodology using double-sided solar simulator based on an existing large-area long pulse flash solar simulator and a low-cost LED-based rear bias light for studying and validating the double-side indoor testing approach for current-voltage (I-V) characterization of bifacial modules. The applied approach is based on the simultaneous illumination of both sides of the bifacial device with two separate different light sources (**Figure 19**). The method aims to provide a simple and easy-to-adapt application in the industrial space, by modifying the existing single- side illumination solar simulators used by the manufacturers for PV quality control.

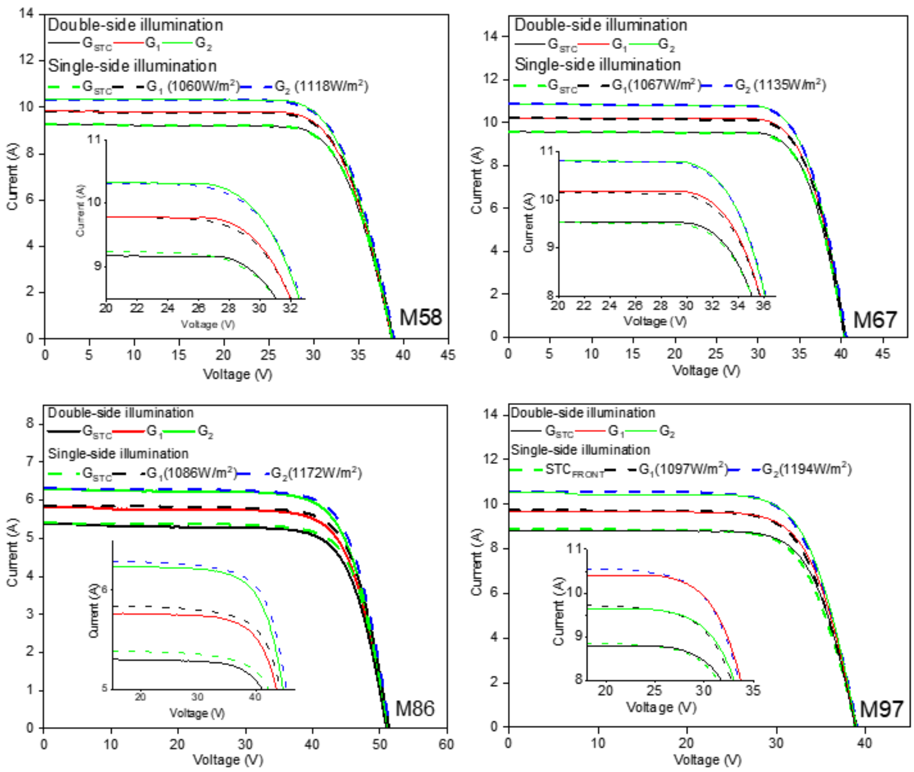
Figure 19. Double-side measurement set up.



Source: JRC, 2025

In the present work different bifacial PV module types of representatives on the market are considered for characterization in order to obtain more relevant information on their electrical behaviour under double-side simultaneous illumination conditions. For this purpose, modules with different bifaciality factor (60% < φ > 90%) are analysed on the prototype system (**Figure 20**, from M57 i.e. means 57% bifaciality to M97).

Figure 20. I-V curves of the DUTs characterized by double and single-side illumination approaches. Inset graphs show the zoomed area of the I-V curve closed to P_{max}.

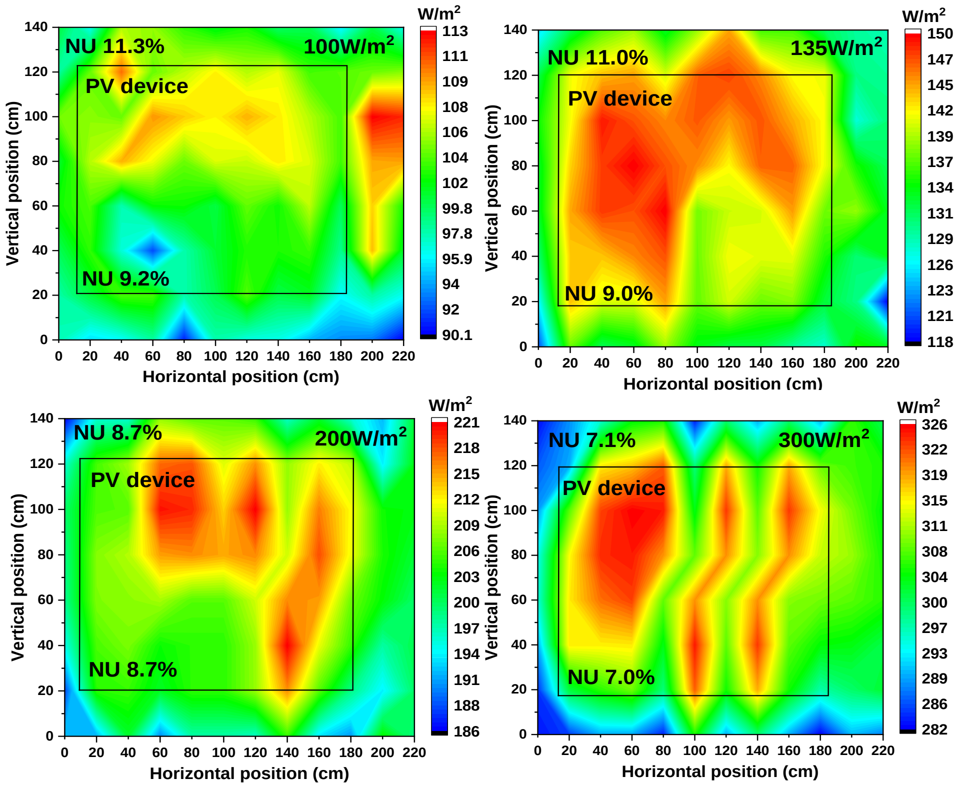


Source: JRC, 2025

I-V curves of the DUTs characterized by double and single-side illumination approaches are given in **Figure 20**. Inset graphs show zoomed areas of the I-V curves closed to P_{max} to appreciate better the existence of differences in shape and position of the plotted results.

Spatial distribution maps of the rear irradiance produced by the LEDs on the test plane corresponds to irradiance levels at 100 W/m², 135 W/m², 200 W/m² and 300 W/m² (**Figure 21**). The square represents the module position on the test plane, and the axis indicates the dimensions of the solar simulator illuminated surface. From the maps on **Figure 21** can be evaluated that the irradiance distribution is not homogeneous along the testing area, displaying zones with lower and higher illumination, mostly closed to the borders that varying with irradiance levels with no defined trend.

Figure 21. Spatial LED irradiance distribution maps at different irradiance levels. The square stands for the DUT position on the test plane.



Source: JRC, 2025

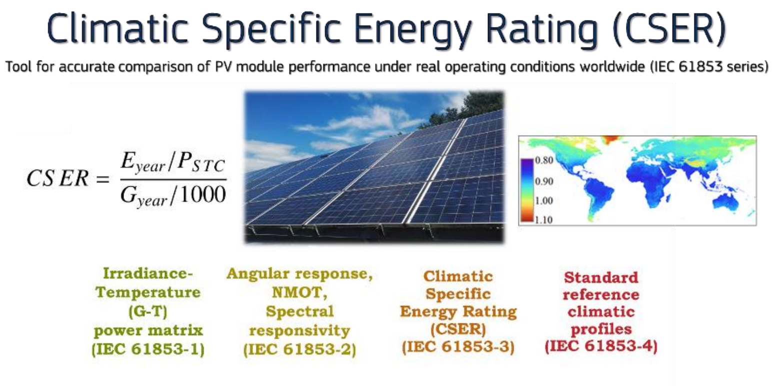
The rear-side non-uniformity (NU) in the double-side illumination system varies with applied LED voltage, classifying the prototype solar simulator in Class C (>200 W/m²) according to the applied parameters. The rear side LED irradiance distribution is different at varying irradiance levels and in ranging about 10%. LED flashes demonstrate stable temporal short-term behaviour during measurements. The present investigation, focused on a double-side indoor simulator based on LED rear bias light and long-pulsed simultaneous illumination on the front side, revealed an adequate I-V measurement of bifacial PV modules.

5.3 Energy rating of PV modules

5.3.1 Indoor energy rating

The IEC 61853 standard series aim to provide a standardized measure for photovoltaic module energy rating, namely the Climate Specific Energy Rating (CSER), parameter that allows comparing different PV devices as close as possible to real operation conditions (**Figure 22**). CSER might be of relevance to PV manufacturers since they may be obligated to estimate and provide it in their product specifications. This study is focused on Silicon heterojunction technology (HJT), one of the solar PV that has gained huge industrial popularity over the last decade being one of the most effective processes for increasing efficiency and power output. We characterized three HJT devices, from the same production batch according to the specifications outlined in IEC 61853-1 [20]. The goal is to assess the reliability and repeatability of performance analysis and to determine whether testing three modules is strictly necessary or if the number of tests can be reduced to avoid time-consuming measurements. This aspect is particularly relevant when evaluating the electrical performance of complex photovoltaic devices as it is the case with high capacitive HJT modules.

Figure 22. Schematic representation of IEC 61853 standard series, Climate Specific Energy Rating equation and a map with the six-reference climatic condition worldwide.

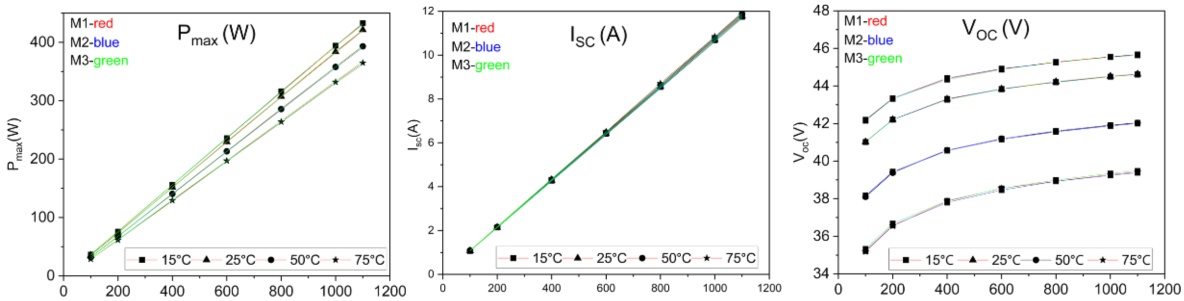


Source: JRC, 2025

HJT has been gaining popularity over the last decade due to its rapid technological developments and cost-effectiveness. The advanced manufacturing processes, premium raw materials, and specific cell design of these PV modules make them highly appealing to consumers, commercials and academic field, establishing HJT devices as a compelling option in the industry. However, this technology presents challenges as “dark ageing” i.e. degradation during extended storage in low light and high capacitive effect, for accurate characterization. The present work is of relevance to PV manufacturers that may be obligated to estimate and provide the CSER values in their information sheets due the future Ecodesign [12] and Energy label [13] legislation and for PV experts’ that are involved in the revision of IEC 61853 standard series.

Three commercial heterojunction c-Si devices from the same production batch have been characterized after been previously light soaking procedure. The irradiance- temperature (G-T) matrix of the modules was acquired at large-area pulsed-solar simulator coupled with controlled heating chamber by applying multiflash procedure [49]. Summary of the parameters obtained from the performance matrices are shown in **Figure 23**, where is shown the dependence of P_{max}, I_{sc}, V_{oc}, with respect to G and T. The P_{max} and I_{sc} exhibit linear dependence with respect to G and T. The V_{oc}, FF and n increase logarithmically up to 400-600W/m^2.

Figure 23. Representation of P_{max}, I_{sc}, V_{oc}, with respect to G and T.



Source: JRC, 2025

After obtaining all input parameters as required in IEC 61853-3, the climatic specific energy rating (CSER) is calculated according to equation 1:

$$CSER = \frac{E_{mod,year}/H_{p,year}}{P_{max,STC}/G_{ref,STC}}$$

Eq. 1

$E_{(mod, year)}$ is the module energy yield obtained for one year, i.e. the total energy produced.

$H_{(p, year)}$ global in-pane irradiance G for the reference climate for one year.

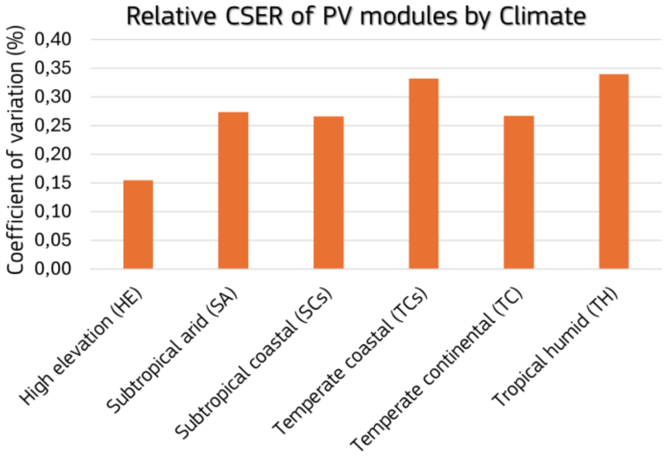
$P_{(max, STC)}$ is the module power output at STC conditions.

$G_{(ref, STC)}$ is irradiance at STC conditions ($1000Wm^{-2}$).

The CSER values range between 0 and 1, with the best PV performance corresponding to higher values.

The CSER for all tree devices have been computed. The coefficient of variation (%) i.e. CSER relative to the mean value for each climate conditions of all PV module are represent in **Figure 24**. Homogeneous distribution of the CSER is observed for almost all climate, being slightly inferior "high elevation" that present is the lowest variation (~0.15%), while the highest variation is in Tropical humid (TH) (~0.34%).

Figure 24. CSER variation by climate.



Source: JRC, 2025

CSER values across the modules are close, but not identical. The lower standard deviation and coefficient variation values reveal consistent PV behaviour. The results suggest that fewer tests might be enough for reliable CSER determination. The results highlight the value of Climatic Specific Energy Rating analysis (CSER), as it enables realistic real-world performance energy generation prediction.

Table 3. CSER determined for each device and climate: HE-High Elevation; SA- Subtropical Arid; SCs-Subtropical Coastal; TCs- Temperate Coastal; TC- Temperate Continental; TH- Tropical Humid.

Climate / Module	**HE**	**SA**	**SCs**	**TCs**	**TC**	**TH**
M1	0,974	0,926	0,964	0,973	0,972	0,923
M2	0,976	0,926	0,966	0,977	0,975	0,925
M3	0,977	0,930	0,969	0,979	0,978	0,929
$Mean_{CSER}$	0,9759	0,9273	0,9660	0,9763	0,9750	0,9256
STD_{CSER}*	0,00151	0,00254	0,00257	0,00324	0,00261	0,00315
CV_{CSER} (%) **	0,1551	0,2735	0,2660	0,3321	0,2673	0,3401

*STD_{CSER} - standard deviation of CSER (M1, M2, M3) for each climate.
** CV_{CSER} – coefficient of variation= STD /Mean (%).

Source: JRC, 2025

The analysis (**Table 3**) shows that the CSER values of the three HJT devices are highly consistent between climates, with coefficients of variation below 0.4% in all cases. The lowest variation occurs in High elevation (HE) (~0.15%), while the highest is observed in Tropical humid (TH) (~0.34%). These results, together with the highly consistent electrical behaviour of the devices suggest that repeating tests on three modules may give only marginal additional insight. Moreover, the uncertainty estimation (UC) of the energy yield and CSER are in the order of 2 to 4% so such module-to-module variation is statistically insignificant. The study suggests that testing laboratories could potentially optimize their measurement protocols by reducing the number of devices tested without significantly affecting reliability.

5.3.2 Outdoor energy rating

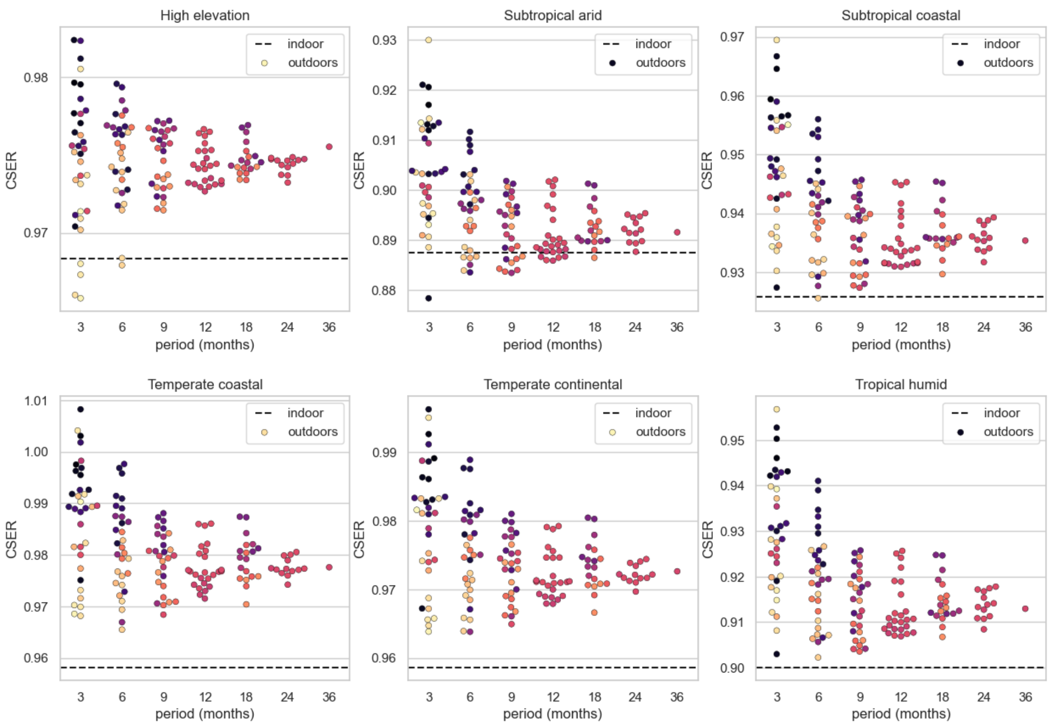
5.3.2.1 Monofacial PV devices

Up to now, research has focused on the implementation of different algorithm mechanism to determine the input parameters and to calculate the CSER values based on indoor measurement performance rating data (based on power matrix G-T measurements). However, there is a lack of studies that validate the real outdoor PV performance field data with its corresponding indoor opponent measurement approach according to IEC 61853. Thus, there is not sufficient information about the minimum period for data to be monitored and collected from the PV field as well as the periodic repeatability needed to compile the G-T power matrix conditions. The energy rating standard states that one year of monitoring or estimating (calculating) of the input parameters would be sufficient to define accurately the yearly PV energy yield output and the CSER parameter.

In the present study, we analysed outdoor field data for a period of 36 month of a polycrystalline PV module (monofacial) that has been installed in a specific Energy rating test array at the ESTI in order to understand how the length (and seasonality) of the data acquisition period impacts reliability of G-T power matrix values, particularly in relation to CSER calculations.

To understand the influence of period length on the CSER result we group the data first by reference climate and then by period length in **Figure 25**. Each subplot accounts for a reference climate; within subplot the x-axis represents the length of the data collection period, and the different CSER values (corresponding to different initial month) are scattered along the y-axis, with a slight horizontal shift to better observe all points. Each CSER value is coloured according to the period of the year that the measurements span: lighter shades correspond to warmer months, darker tones to colder periods. Measurements spanning multiples of 12 months feature all the same colour since they span both cold and warm months. Finally, the CSER value computed using indoor measurements is plotted as a dashed line.

Figure 25. Average relative standard deviation of experimental CSER values as a function of the measurement period.



Source: JRC, 2025

On **Table 4**, CSER values as a function of the measurement period is shown. For a period of 3 months the CSER values show a large dispersion, indicating that the collected data is not representative enough for populating the power matrices reliably. The dispersion for 6 months is smaller and becomes acceptable for 9 or 12 months. 18 months do not yield a noticeable improvement over 12 months, and a longer period is probably too long for practical purposes

Table 4. Average relative standard deviation of experimental CSER values as a function of the measurement period.

Months	**3**	**6**	**9**	**12**	**18**	**24**
Average rel. std (%)	1.0	0.8	0.6	0.4	0.4	0.2

Source: JRC, 2025

The statistical variation of CSER values computed from outdoor data depends strongly on the length of the measurement period used to populate the power matrix. A period of 9 or 12 months provides a good compromise between accuracy and time-resources. A 6-month period can provide satisfactory results if it is not cantered around the winter months. However, further attention must be paid to the systematic errors in the outdoor measurements and their influence in the fitted power matrices.

5.3.2.2 Bifacial PV modules

The European Commission's Joint Research Centre is upgrading its Photovoltaic Geographic Information System (PVGIS) to estimate energy yield from bifacial photovoltaics. Bifacial PV modules can absorb both direct and reflected light, increasing overall power output by up to 20%. The current PVGIS version lacks a bifacial module option, but users can make estimates by adjusting the peak power using the Bifacial Nameplate Irradiance (BNPI) value ($P_{BNPI} = P_{max} * (1 + \varphi * 0.135)$. where φ is power bifaciality coefficient) or calculating front and rear side performance independently (for vertical systems). The new PVGIS 6 Python version will include a detailed approach to calculate rear-side irradiance. Experimental data from the JRC's ESTI form part of the validation process. The aim to provide a reliable method for estimating energy yield from bifacial photovoltaics, which is suitable for online information systems designed to provide quick and reliable estimates on PV performance, also for non-expert users and with limited data input requirements. The study has been accomplished thanks to the collaboration between the European Commission Joint Research Centre and the National Physical Laboratory, UK, which facilitated the scientific visit of Lavanya Malarkannan to the JRC's Ispra site.

The work describes the extension of this capability in the new PVGIS 6 Python version to cover power generation bifacial PV modules, considering two configurations: a) open-rack systems, typically equator facing with tilted panels, installed either on flat roofs or on open ground, and b) vertical- mounted systems, typically in an east-west facing set-up. This prototype enhances the new software's capabilities by integrating advanced algorithms that calculate total effective irradiance from both the front and rear sides of bifacial modules, streamlining the modelling process for improved energy yield predictions. This approach not only strengthens the scientific foundation of the analysis but also enhances the usability of the new PVGIS software for researchers and professionals, thereby facilitating more effective electrical performance assessment of bifacial PV technologies.

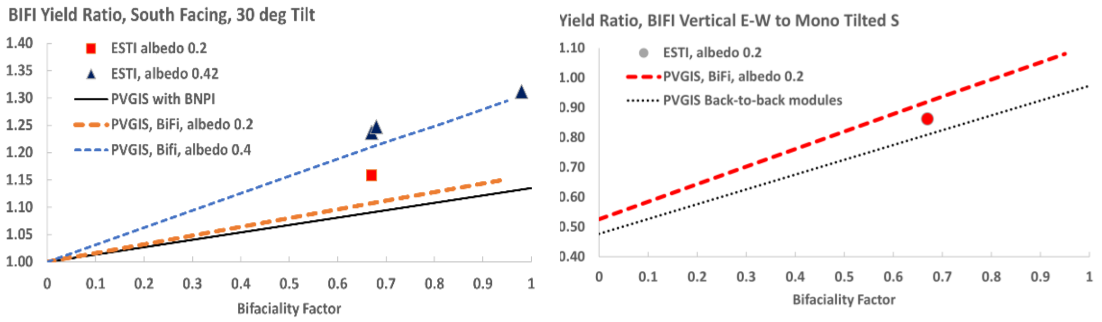
Figure 26. Performance testing set-up for bifacial modules in the ESTI outdoor test field.

p-PERC type 60 cells frameless glass-glass (φ= 67.3%, $Pmax_{f=}$ 294W, $Pmax_{r=}$198W)

Source: JRC, 2025

The PVGIS model estimates has been validated with experimental data from the JRC's ESTI (**Figure 26**). This comprises performance data from vertical and tilted systems in the ESTI outdoor testing facility and, importantly, power matrix data (IEC 61853-1) for bifacial modules used in the outdoor testing. The bifacial model captures the effect of increased albedo seen in the experimental data, whereas the bifacial nameplate power approach is insensitive to albedo (**Figure 27**). The experimental data for the PERC modules with 70% bifaciality and 0.2 albedo indicate a gain of 16%, higher than that estimated by the PVGIS model. For the high albedo case (0.4), the model estimates are closer to the observed gains: bifaciality values of 67-68% (p-PERC glass-glass) result in a gain of around 25%, while the bifaciality of 98% (n-PERC glass-glass) results in an increased performance of 31.2% in comparison to the monofacial device (c-Si).

Figure 27. The effect of the module bifaciality and albedo on the bifacial yield ratio for a south-facing tilted system (left) and east-west vertical system (right) in Ispra, Italy.



Source: JRC, 2025

The prototype version 6 of PVGIS enhances the new software's capabilities by integrating advanced algorithms that calculate total effective irradiance from both the front and rear sides of bifacial modules, streamlining the modelling process for improved energy yield predictions. To validate the approach, PVGIS model estimates are compared with experimental data from the JRC's ESTI. The experimental data comprises performance data from vertical and tilted bifacial systems in the ESTI outdoor testing facility combined with power matrix data (measured with solar simulators in accordance with the IEC 61853-1 standard) for the bifacial modules used in the outdoor testing.

5.4 Determination of the PV Module Temperature (NMOT)

The performance of a PV installation depends on various parameters, among them the temperature of the PV module. The temperature of the PV module is in turn, a function of ambient temperature, irradiance, wind speed and the mounting system. The IEC 61853 standard series describe how to obtain the PV module temperature to calculate the Climate Specific Energy Rating (CSER), a parameter to compare the performance of a PV installation between different climatic zones. More specifically the IEC 61853-2:2016 describes; spectral responsivity, incidence angle and module operating temperature measurements. The standard specifies how to determine the coefficients (u_0 and u_1) by the Faiman equation (Eq. 2)

$$T_{module} = T_{amb} + \frac{G_{POA}}{u_0 + u_1 \times WS}$$

Eq. 2

The Faiman equation describes the relationship between module temperature (T_{module}), ambient temperature (T_{amb}), incident solar irradiance (G_{POA}), wind speed (WS) and the two parameters u_0 and u_1 which describe the irradiance and the wind dependency, respectively. The determination of the u_0 and u_1 is done by collecting data of module temperatures over a range of environmental conditions and then following the data analysis described in the IEC 61853-2. The nominal module operating temperature (NMOT) can be calculated for the conditions; T_{amb} = 20°C, G_{POA} = 800 Wm^{-2}, WS = 1ms^{-1} with the obtained u_0 and u_1 according. The NMOT can be used as an indicator for temperature induced losses.

During 2023 an instrumentation with three c-Si PV modules was installed in the ESTI outdoor monitoring site according to IEC 61853-2:2016 (see **Figure 28**). In 2023 and 2024 two scripts were written as well as evaluated for deriving the two coefficients u_0 and u_1 according to IEC 61853-2:2016 (method 1) and according to a non-filtering method described in literature [50] (method 2).

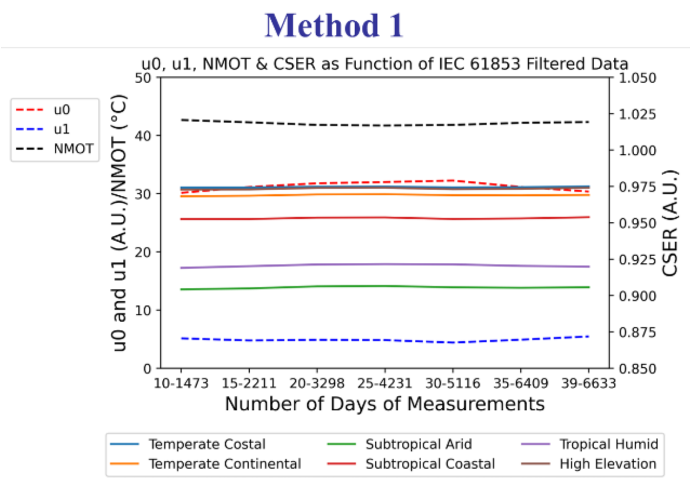
Figure 28. Installation of module operating temperature measurements according to the IEC 61853-2:2016 at the ESTI outdoor monitoring test site.

Source: JRC, 2025

The IEC 61853-2:2016 includes a requirement of a wind speed span of 4 ms^{-1}, for the determination of u_0 and u_1. After over a year of data collection, it could be concluded that the ESTI outdoor monitoring test site does not meet the wind speed span condition since a wind speed span of up to 3 ms^{-1} was registered. In literature it has been argued that the filtering requirements in IEC 61853-2:2016 are too stringent and that the standard therefor has been hard to apply [50]. ESTI therefore investigated and compared the IEC 61853-2:2016 based filtering method (method 1) with a published [50] alternative method, non-filtering method (method 2).

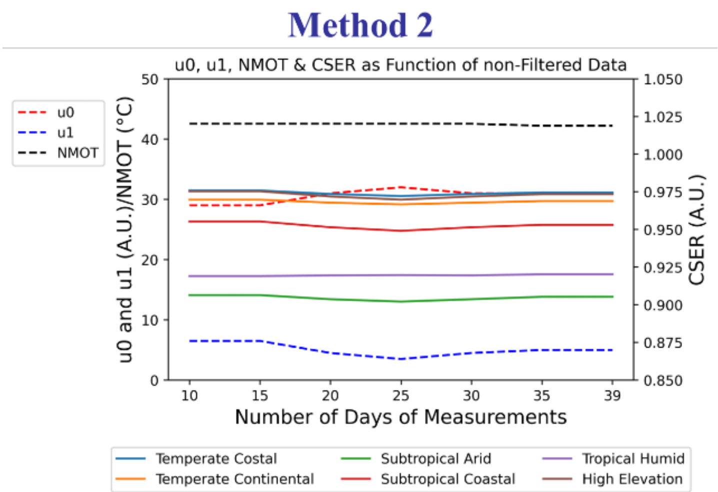
The IEC 61853-2:2016 based filtering method (method 1, **Figure 29**) was evaluated even though the data did not meet the wind speed span condition. The evaluation was performed on one of the modules in the installation.

Figure 29. Evaluation of the u_0 and u_1 determination, as well as NMOT and CSER values according to IEC 61853-2:2016 (method 1). On the y-axis the u_0, u_1, NMOT and CSER values and on the x-axis the number of days of measurements with the resulting filtered data points.



Source: JRC, 2025

Figure 30. Evaluation of the u_0 and u_1 determination, as well as NMOT and CSER values according to proposed method in literature [50] (method 2).



Source: JRC, 2025

In **Figure 30**, the resulting u_0 and u_1 parameters according to method 1 and method 2 are presented, as well as the resulting NMOT[1] and the CSER values for the different climatic zones (according to IEC 61853-3:2016 and IEC 61853-4:2016), all as a function of number of days of measurements and the resulting filtered data points (for method 1). As can be seen in **Figure 29**, 10 days of measurements (as specified in the IEC 61853-2:2016), with the number of filtered data

[1] NMOT is calculated according to Faiman equation for T_{amb} = 20°C, G_{POA} = 800 Wm^{-2}, WS = 1 ms^{-1}

are enough, further measurements are not affecting the outcome. It can be seen how the obtained NMOT and the different CSER values are consistent between the methods and throughout the increasing amount of measurement days and data, reflecting that both methods are stable.

6. 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-) organized by the JRC.

6.1 Peer-reviewed scientific publications

In 2022 and 2025 a total of 17 peer-reviewed publications were published with ESTI authorship (**Table 5**). They are cited in the relevant sections of this report together with the description of the respective work. In addition, conference contributions (usually published as a full paper in the conference proceedings) are also listed.

Table 5. Overview of different dissemination type with ESTI authorship published in 2022 and 2025.

Source	Impact factor	Number of publications	References
Progress in Photovoltaics Research and Applications	7.6	11	[28], [51], [29], [52], [30], [31], [32], [33], [53], [54], [34]
Solar RRL	4.7	2	[55], [56],
IEEE Journal of Photovoltaics	2.6	1	[57]
EPJ Photovoltaics	1.6	3	[58], [59], [60]
Conference contributions	NA	38	Table 6-8

Source: JRC, Pupsy, 2025.

6.2 Conference and Exhibition

6.2.1 EU PVSEC: overview

The European Photovoltaic Solar Energy Conference and Exhibition (EUPVEC) Conference is the world's largest Photovoltaics 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, who provides the overall coordinator the scientific programme.

The first of these conferences has been organised and established by the European Commission in 1981 (Stresa, IT), 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, deployment, grid integration, 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 noticeably short. The industry of manufacturing equipment plays a key role, as they find immediately research results to be transferred into commercial products.

The United States, being commercially active in PV since 1956 (the photovoltaic cell was invented by Bell Labs in 1955), host a series of very prestigious PV conferences since 1961, organised by IEEE, and scheduled every 12 months. Asia holds similar conferences with strong research orientation since 1986, alternating between a location in Japan and any other Asian or Pacific country, including China and India. The first AfricaPVSEC conference was held in Durban, South Africa in February 2014. The Commission, via the JRC, supported the event.

6.2.2 JRC role in EU PVSEC

The JRC supports the Conference since 1996 by providing the scientific programme coordination. This includes chairing a scientific committee of about 200 international high-level scientists and industry experts from all over the world, which review the papers received after a public call for papers. The Committee typically receives up to 1,000 papers, and selects presentations in plenaries, orals and posters. The fine-tuning and invitation process is coordinated by the JRC, which receives high visibility. 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 successful every year to date. In recent years participation has decreased (especially since the Covid-19 crisis impacted the travel habits of many), but still over 1,500 registered participants attend.

The JRC contributes at several levels:

— provides the Chair of the International Scientific Advisory Committee (ISAC), Piotr Szymanski, Director of JRC.C.

— provides the Technical Programme Chair (Robert Kenny, JRC.C.2) who leads the scientific committee.

— contributes with several members of the scientific committees and by oral and poster presentations as well as chairing sessions.

— JRC.C.2 regularly has a prominent booth in the exhibition area.

6.2.3 39th EU PVSEC (8th WCPEC), Milan, 2022

The technical programme for this truly global event 8th World Conference on Photovoltaic Energy Conversion (26-30 September, Milan, Italy) is jointly organized by the three principal regional photovoltaic conferences, the European Photovoltaic Solar Energy Conference (EU PVSEC), the Photovoltaic Specialists Conference (IEEE PVSC) and the International PV Science and Engineering Conference (PVSEC). The scientific contributions from Unit JRC.C.2 is detailed in **Table 6**.

Table 6. Scientific contributions at 39th EU PVSEC.

Contribution	Title	Authors	Affiliation(s)
Plenary	Reflecting the Energy Transition from a European Perspective and in the Global Context – Relevance of Solar Photovoltaics Benchmarking Two Ambitious Scenarios	Christian Breyer, Dmitrii Bogdanov, Manish Ram, Siavash Khalili, Eero Vartiainen, David Moser, Eduardo Román Medina, Gaëtan Masson, Arman Aghahosseini, Theophilus Mensah, Michael Schmela, Raffaele Rossi, Walburga Hemetsberger, Arnulf Jäger-Waldau	LUT University; Fortum Growth Oy; Eurac Research; Tecnalia; Becquerel Institute; SolarPower Europe; European Commission,JRC, Italy
Oral	Developing Strategies for Reliable Performance Evaluation of Perovskite Solar Cells: State-of-the-Art at the ESTI	Giorgio Bardizza, Blago Mihaylov, Diego Pavanello, Harald Müllejans, Ewan Dunlop	European Commission, JRC, Italy
Oral	Investigation on Linearity of Spectroradiometers	Diego Pavanello, Harald Müllejans	European Commission, JRC, Italy
Oral	Differentiation of PV Devices According to Energy Rating Standard IEC 61853	Ana Gracia Amillo, Robert P. Kenny, Diego Pavanello	European Commission, JRC, Italy
Oral	Cities as Pioneers of the Energy Transition: Evidence and Challenges from the Covenant of Mayors and the EU Cities Mission	Giulia Ulpiani, Valentina Palermo, Giulia Melica, Nadja Vetters, Paolo Bertoldi	European Commission, JRC, Italy
Visual	Improving Spectral Responsivity Measurements by Correcting for Filter Bandwidth	Clara Edmonds, Harald Müllejans	European Commission, JRC, Italy
Visual	Simplified Angular Responsivity Measurements of c-Si Modules	Blago Mihaylov, Harald Müllejans, Tony Sample, Ewan Dunlop	European Commission, JRC, Italy
Visual	Proposal for the Extension of the Energy Rating Standard Series IEC 61853 to Bifacial Modules	Robert P. Kenny, Ana Gracia Amillo, Teodora Lyubenova, Diego Pavanello	European Commission, JRC, Italy
Visual	Improvement of a LED Bias Light System for the Double-Sided Characterization of Bifacial Devices	Teodora Lyubenova, Robert P. Kenny, David Shaw, Diego Pavanello	European Commission, JRC, Italy

Visual	Thermal Influences of Rooftop Photovoltaic Panels on Building Performance: A Meta-Analysis	Delia D'Agostino, Danny Parker	European Commission, JRC, Italy; Florida Solar Energy Centre, United States
Visual	Helping Prosumers with Location-Specific Solar Radiation and PV Performance Data	Nigel Taylor, Ana Martinez Fernandez, Nikos Alexandris, Gianpiero Arcaro, Anatoli Chatzipanagi, Fernando Fahl	European Commission, JRC, Italy, Piksel, Italy, GFT Italia S.r.l.,

Source: EUPVSEC, 2022

6.2.4 40th EU PVSEC, Lisbon, 2023

The key message from the conference was that photovoltaics offers a unique pathway to mitigating climate change [61]. Indeed, Diana Ürge-Vorsatz, Vice-Chair of the Intergovernmental Panel on Climate Change (IPCC) underlined that while climate change is now a reality, the PV community is already providing answers. According to the International Monetary Fund (IMF) fossil fuel subsidies surged to a record $7 Trillion in 2022 [62] and scaling back subsidies would reduce air pollution, generate revenue, and make a major contribution to slowing climate change. This is despite the fact that for some time solar PV has been consistently cheaper than new coal- or gas-fired power plants in most countries, and solar projects now offer some of the lowest cost electricity ever seen according to the International Energy Agency (IEA) [63]. The community echoes the IMF, IEA and IPCC and calls for the elimination of wasteful subsidies for fossil fuels and increased investments in a clean energy future.

Building on a rapidly expanding production and deployment rate and 1.5 TW of global installed capacity expected by the end of 2023, the PV community discussed the pathways and challenges towards becoming a major clean energy source over the next few decades, with full sustainability and circularity.

Silicon remains the backbone of photovoltaic industry. New cell structures with passivating contacts as TOPCon or heterojunctions have allowed the continued efficiency improvement of industrial cells by 0.5%/year. Best silicon cells have achieved efficiencies of 26.8% getting close to the theoretical limit. That makes it necessary to work on a new generation of cells such as perovskite silicon tandem cells which have already proven excellent performance in the lab (>33%). A novel PV technology, perovskite, has reached the market, with a 100 kWp system having been realised with 90 W modules which passed both the IEC61215 and IEC61730 tests.

Despite technological improvement a major challenge is the sustainability of PV production, i.e. reducing use of energy and critical materials. A new generation of encapsulant materials (POE, EPE), polymeric back and front sheets is one of the hot topics in PV module manufacturing. Ensuring PV modules are fully sustainable, considering elements such as minimizing use of critical raw materials (e.g., silver), lowering carbon footprint, extending the durability and lifetime of the products and securing a successful recycling are also critical considering the expected rapid expansion to the multi-TW era.

There are recent developments in the integration of PV in different areas such as BIPV, VIPV, floating PV, Agri-PV, and PV on roads leading to an ever more diversified application landscape. Novel module materials and technologies are presented, and dedicated reliability and outdoor testing approach to ensure their deployment. Fully using the existing built infrastructure is estimated to provide a significant percentage of the future electrical generation needs. It is very encouraging to see how operational data is shared and data driven operation and maintenance strategies are becoming reality. Although only slightly touched upon this year, AI is also entering the PV sector, and we expect disruptive innovation soon.

Various scenarios for renewables, policy implications, and global challenges, shed light on the future trajectory of PV in the energy transition. Societal challenges and public acceptance are also critical, such as the role of citizen engagement and energy communities in driving the adoption of PV. The scientific contributions from Unit JRC.C.2 is detailed in **Table 7**.

Table 7. Scientific contributions from Unit JRC.C.2 at 40th EU PVSEC.

Contribution	Title	Authors	Affiliation(s)
Plenary	Net-Zero Growth in the Solar PV Sectors: An International Analysis of Manufacturers and Policies	A. Arcipowska, S. Blanco Perez, M. Jakimow, B. Baldassarre, D. Polverini	European Commission JRC, Spain; European Commission DG GROW, Belgium
Plenary	Development of Quality and Certification Standards	Tony Sample	European Commission, JRC, Italy
Plenary	Roofs, Roads, Reservoirs – The Potential for Applied PV in Europe	Georgia Kakoulaki	European Commission, JRC, Italy
Oral	The Role of PV within New EU Building Targets to Achieve Climate Neutrality	Delia D'Agostino, Carmen Maduta, Robert Kenny	European Commission, JRC, Italy
Oral	Energy Rating of PV Modules – Uncertainties Associated with (G-T) Power Matrix Measurements in Accordance with IEC 61853-1	Giorgio Bardizza, Werner Herrmann, H. Maaroufi, A. Schmid, M. Rauer, B. Provost, L. Prieur, G. Bellenda, G. Friesen, C. Xu, S. Riechelmann, H. Sträter, S. Winter, Tony Sample, Harald Müllejans, Diego Pavanello, J. Dubard	TÜV Rheinland Solar; Fraunhofer ISE; Certisolis; SUPSI; ISFH; PTB; European Commission, JRC, Italy
Oral	Analysis of Climate Conditions upon the Driving Distance of Photovoltaics-Powered Vehicles	M. Yamaguchi, K. Nakamura, R. Ozaki, N. Kojima, Y. Ohshita, T. Masuda, T. Nakado, K. Yamada, K. Okumura, A. Satou, T. Tanimoto, Y. Tomita, Y. Ota, K. Araki, K. Nishioka, C. Thiel, A. Tsakalidis, A. Jäger-Waldau, T. Takamoto, Y. Zushi	Toyota Technological Institute; Toyota Motor; Nissan Motor; University of Miyazaki; European Commission, JRC, Italy
Oral	Towards a Recyclability Index for Photovoltaic Modules: Methodology,	D. Polverini, F. Alfieri, C. Spiliotopoulos, A. Arcipowska	European Commission DG GROW, Belgium; European Commission,

	Challenges and Policy Implications		JRC, Spain
Oral	Assessing Energy Access and Poverty in Cities: The Role of PV as Driver for Action	Valeria Palermo, Marco Pittalis	European Commission, JRC, Italy
Oral	A Snapshot of the Global PV Market – 2022	Gaëtan Masson, Arnulf Jäger-Waldau, Izumi Kaizuka, Johan Lindahl, José Donoso	IEA PVPS; European Commission, JRC, Italy; RTS Corporation; Becquerel Sweden; UNEF
Oral	The Role of Digital Operation Technology for Photovoltaic Mini-Grids in Sub-Saharan Africa: Impact and Benefits of Advanced Remote Monitoring Systems	Marco Pittalis, Sandor Szabó, Morgan Moner Girona, A. Sancho, M. Zopoulou	European Commission, JRC, Italy; Trama TecnoAmbiental; SE4ALL
Oral	Measuring Perovskite Solar Cells Fast and Slow	Blago Mihaylov, Harald Müllejans, Tony Sample, Ewan D. Dunlop	European Commission, JRC, Italy
Visual	Indications of Early Climate Change Impacts Revealed within Weather Files for Predicting Photovoltaic System Performance in Europe	Delia D'Agostino, David Parker	European Commission, JRC, Italy; Florida Solar Energy Centre, Cocoa, USA
Visual	Floating Photovoltaics, a Solution to Smart Combination of Hydro- and Solar Power	Georgia Kakoulaki, G. Rocio, Sandor Szabó	European Commission, JRC, Italy
Visual	Trends of EU Research and Innovation in Photovoltaics	Anatoli Chatzipanagi, Nigel Taylor	European Commission, JRC, Italy

Source: EUPVSEC, 2023

6.2.5 41st EU PVSEC, Vienna, 2024

The European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC) at the Austria Centre Vienna, hosted over 1,800 experts from sixty countries between 23–27 September 2024. The event highlighted over 1,100 presentations on the latest innovations, reinforcing its status as the premier platform for photovoltaic research and collaboration.

The 41st edition reflected the world's transition to a multi-terawatt PV era. Each day, more PV capacity is installed worldwide than a typical nuclear power plant, producing most of the cheapest electricity available. However, such rapid growth does come with challenges. Throughout the conference, experts explored crucial questions, such as selecting the most appropriate locations for deployment, ensuring increasingly sustainable manufacturing practices, and fostering social acceptance of solar technologies. Silicon solar cells, which remain by far the largest segment of the market in the short and mid-term, continue to demonstrate improvements in efficiency and process simplification, resulting in lower costs. Research is focused on critical raw material (CRM) constraints, for example reducing consumption of silver. Meanwhile, perovskite materials continue to attract significant research interest, particularly in tandem cell configurations. The event also highlighted efficiency gains and progress in stability and reliability studies. Sustainability remains a key concern, with ongoing studies on recycling techniques and module design for easier end-of-life recycling.

Silicon solar cells continue to demonstrate efficiency improvements due to ongoing research. Nevertheless, a focus of research is now on silver replacement and CRM reduction (including Si). Process simplification also further supports the these aims, while at the same time reducing manufacturing costs.

Silicon bottom cells are the basic building blocks of perovskite-silicon tandem solar cells, and research is ongoing, including recombination junction assessment and optimization for this application. There is increased interest in silicon cells for space applications due to the deployment of low Earth orbit communication satellite constellations.

Chalcogenides (Kesterite, CIGS) continue to demonstrate increased efficiencies. Perovskites and tandems with perovskites are an increasing area of research. Satisfactory progress has been made on tandem and triple-junction devices with perovskite-CIGS tandems (19.9% module), all-perovskite tandems (19.7% flexible tandem module), perovskite-Si tandems, perovskite-perovskite-Si (3V open-circuit voltage), and all-perovskite triple-junction tandems. Outdoor testing of perovskite devices is important to detect failure mechanisms.

The design, manufacturing, and measurement and reliability of photovoltaic modules continues to be one of the larger areas of interest. Module manufacturing is improved through new encapsulants and interconnection techniques. Modules are increasingly being designed to facilitate recycling at their end of life, an important sustainability objective. Innovative technologies, such as perovskite materials, are introducing new challenges in characterisation and standards.

The field of systems and applications of PV is the largest at the conference, demonstrating the raising maturity of the sector. PV systems is increasingly employing non-intrusive methods such as daylight photoluminescence imaging. Machine learning is being used to monitor the performance.

The wide range of applications of PV is rapidly developing, such as for agrivoltaics, with numerous studies looking at system performance and the impact on crop yield – which can also be positive in arid climates. Floating PV, for example on reservoirs or onshore, is being field-tested and showing enormous potential. In BIPV, a lot of work is looking into improving the integrating custom elements, such as coloured modules.

An important objective is the achievement of a fully circular economy, and recycling techniques and several schemes for module recycling are being studied.

The integration of PV into energy systems is a major theme. Novel approaches to grid integration, storage and new electricity market designs were presented.

The social dimension is increasingly being studied to understand the needs and demands of society and to evaluate the social acceptance of PV.

The scientific contributions from Unit JRC.C.2 is detailed in **Table 8**.

Table 8. Scientific contribution at 41st EU PVSEC.

Contribution	Title	Authors	Affiliation(s)
Plenary	The Potential of Agrivoltaics in the EU's Green Deal	Anatoli Chatzipanagi, Georgia Kakoulaki, Nigel Taylor, Robert Kenny, Sandor Szabo	European Commission, JRC, Italy
Oral	Climate Specific Energy Rating (CSER) Analysis of Outdoor PV Field Data	Ismael Medina, Teodora S. Lyubenova, Ewan Dunlop	European Commission, JRC, Italy
Oral	Cost-Effective Energy Transition: Rooftop PV in European Union Buildings	Carmen Maduta, Delia D'Agostino, Sofia Tsemekidi-Tzeiranaki, Luca Castellazzi	European Commission, JRC, Italy; Network Research Belgium, Herstal, Belgium
Oral	Rooftop PV Potential Using a Digital Building Stock Model	Georgia Kakoulaki, Ana Martinez, Nigel Taylor, Sandor Szabo, Robert Kenny	European Commission, JRC, Italy
Oral	A Snapshot of Global PV Market – 2023	Gaëtan Masson, Mélodie de l'Epine, Arnulf Jäger-Waldau, Izumi Kaizuka, Amelia Oller Westerberg, José Donoso	IEA PVPS Task 1; European Commission, JRC, Italy; RTS Corporation; Becquerel Sweden; UNEF
Visual	Optimizing Solar Simulator Spectrum for Accurate Efficiency Measurements of Perovskite Photovoltaics	Blago Mihaylov, Harald Müllejans, Tony Sample, Ewan Dunlop	European Commission, JRC, Italy
Visual	Developing a Simplified I-V Translation Methodology in Accordance with IEC 60891:2021 Correction Procedure	Wenhao Xu, Yating Zhang, Qi Gao, Christos Monokroussos, Harald Müllejans, Werner Herrmann, Giorgio Bardizza	TÜV Rheinland; European Commission, JRC, Italy; TÜV Rheinland Solar
Visual	Using the Equivalent Cell Temperature for Power Matrix Calculations	Hanna Ellis, Harald Müllejans, Teodora Lyubenova, Diego Pavanello, Ewan Dunlop	European Commission, JRC, Italy
Visual	An Investigation on the Uncertainty of Fill Factor	Diego Pavanello, Tony Sample, Harald Müllejans	European Commission, JRC, Italy
Visual	A Verification and Correction Methodology for Spectroradiometers under Natural Sunlight	Diego Pavanello, Seonyong Park, Antonio Romano, Gianni Leanza, Edoardo Celi, Alessandro Minuto, Mauro Pravettoni, Shin Woei Leow, Flavio Valoti, Tobias Weigner, Kevin Murray	European Commission, JRC, Italy; ESA; ENEA; RSE; TII; SERIS; SUPSI; PVLAB; Northwest Regional College
Visual	Enhancing Spatial Resolution and Expanding Spatiotemporal Coverage of PVGIS Datasets	Olympia Gounari, Nigel Taylor, Ana Martinez, Nikos Alexandris	TRASYS International; European Commission, JRC, Italy

Visual	Assessing the Role of Photovoltaic Systems in Meeting the Energy Needs of Data Centers in Africa: A Bottom-Up Analysis	Marco Pittalis	European Commission, JRC, Italy
Visual	Power Matrix Validation of Long-Term Outdoor PV Field Data	Ismael Medina, Teodora S. Lyubenova, Ewan Dunlop	European Commission JRC, Ispra, Italy

Source: EUPVSEC, 2024

7. Contribution to EU policies

Solar photovoltaic technology is one of the major renewable energy technologies playing a key role in the decarbonisation of society and in achieving the climate and energy targets. Globally, cumulative installed solar PV capacity reached approximately 2.2 TW by the end of 2024, representing a year-on-year increase of about 29%. In the same year, around 550 GW of new solar PV capacity was installed worldwide, marking a record level of annual deployment and demonstrating the continued rapid scale-up of PV projects globally [64]. Solar PV accounted for more than 75-80% of all new renewable power capacity installed in 2024, confirming its leading role in global clean energy expansion. Looking ahead, the International Energy Agency forecasts approximately 4,600 GW of new renewable capacity additions globally over the period 2025-2030. However, achieving more ambitious climate objectives - such as the tripling of global renewable capacity by 2030 pledged at COP28 - will require stronger policy frameworks, enhanced financing mechanisms, and accelerated grid integration, as solar PV accounted for the majority of recent downward revisions in renewable capacity projections [65].

In 2025, EU installed 65.1 GW of new solar PV, a slight 0.7% contraction from the 65.6 GW installed in 2024. This marks the first year-on-year annual decline since 2016, with two more years of decline to follow. The market is set to return to 2025 values only by the end of the decade. SolarPower Europe's annual EU Solar Market Outlook reveals that, despite the market decline, the EU has reached its 2025 solar installation target of 400 GW, with a total fleet of 406 GW. However, the EU solar target of 750 GW by 2030 is now slipping out of reach. In our most-likely scenario, SolarPower Europe projects that total EU solar will only reach 718 GW. The slowdown is partially attributed to an ailing residential solar segment, which was responsible for 28% of newly installed EU capacity in 2023, but only 14% in 2025. To achieve EU solar goals, policymakers must redefine energy security around renewable electrification, adopt a comprehensive energy system flexibility strategy, implement permitting procedures, and boost the rooftop solar market [66].

In the context of the Green Deal Industrial Strategy for Europe that plans to support the "green transition" and to make EU industry more competitive and autonomy globally, it is of key importance to ensure affordable and sustainable energy that could guarantee energy security and independence in Europe. Newly installed PV capacity is projected to be over 320 GWac by 2025 and almost 600 GWac by 2030 (REPowerEU and EU solar strategy) [67]. The PV modules installed in the European Union (EU) should be sustainable and durable; this can be attained by means of regulatory measures, in particular in the framework of the Ecodesign Directive (2009/125/EC) [12] and the Energy Labelling Regulation (EU) 2017/1369 [68]. These policy regulations are focused to boost quality of products on the market and to shape sustainable consumer behaviour by providing the information needed to make informed choices.

Photovoltaic (PV) modules are identified as strategic and priority products due to their rapid market growth, massive deployment, and strategic relevance for the energy transition. As a result, their large-scale deployment must be aligned with resource efficiency and waste management objectives, leading to the involvement of multiple regulatory measures governing PV products in the European Union.

The Ecodesign framework establishes requirements for the environmental performance of energy-related products placed on the EU market. While it does not yet impose product-specific mandatory requirements for PV modules, it provides the legal basis for the introduction of future binding implementing measures. The Ecodesign framework addresses the entire life cycle of a product, from production to end-of-life, by setting minimum requirements related to material use, durability and reliability, repairability and dismantling, resource efficiency, energy consumption during production, and carbon footprint. In this context, Ecodesign acts upstream, shaping how PV modules are designed and manufactured.

The WEEE Directive (2012/19/EU) [14] establishes rules for the collection, treatment, recovery, and recycling of waste electrical and electronic equipment. Since 2012, photovoltaic modules have been explicitly included within its scope. For PV modules, the Directive introduces Extended Producer Responsibility (EPR), under which manufacturers are financially and operationally responsible for the end-of-life management of their products. It sets minimum performance targets, including an 85% collection rate, 80% recovery, and 75% recycling by weight of PV modules. The WEEE Directive therefore acts downstream, focusing on end-of-life management and the circularity of PV modules.

Together, these two policy instruments support the objectives of the European Green Deal, REPowerEU, the Critical Raw Materials Act, and the Circular Economy Action Plan. They operate in a complementary and synergistic manner: while Ecodesign promotes design-for-recycling by encouraging PV modules to be designed in ways that facilitate disassembly, material recovery, and recyclability, the WEEE Directive enforces end-of-life obligations by requiring PV modules to be collected and recycled. In this way, Ecodesign enables manufacturers to comply with WEEE requirements more efficiently and at lower cost, reinforcing a coherent life-cycle approach to the sustainability of PV modules.

7.1 Ecodesign Directive and Energy Labelling updates

Ecodesign Directive (2009/125/EC) and the Energy Labelling Regulation (EU) 2017/1369 for photovoltaic products as solar panels and inverters establishes minimum sustainability, performance, and circularity requirements for these energy-related products. The proposals under both legislative instruments have been developed with direct technical and scientific support from experts of the Joint Research Centre and have been coordinated by the European Commission's Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs (DG GROW), in close collaboration with the Directorate-General for Energy (DG ENER) and the Directorate-General for Environment (DG ENV). The measures are currently at the interservice consultation stage and are awaiting a final decision for implementation.

In 2017 the European Commission launched a preparatory study to analyse the feasibility of implementing sustainable policy instruments to PV products with the aim of creating a more sustainable European PV market. The study has been proposed by JRC's Unit B5 "Circular Economy and Industrial Leadership" (JRC-Seville) [15], responsible for analysing the PV market and prospects, modelling potential policy scenarios, and assessing life cycle aspects of PV products available on the market, including life cycle assessment (LCA) and policy analysis. Unit C2 "Energy Efficiency and Renewables" (JRC-Ispra) supported the development of the Methodology for the Ecodesign of Energy-related Products (MEErP) [69], pre-normative standardization framework [11] and contributed to defining requirements for the Energy Labelling Regulation [70] [71]. In collaboration, Unit D3 "Land Resources & Supply Chain Assessments" (JRC-Ispra) developed a set of harmonised rules for accounting the carbon footprint of PV panels, based on the Environmental Footprint method developed by the European Commission (Commission Recommendation (EU) 2021/2279) and the Product Environmental Footprint Category Rules (PEFCR) for photovoltaic products, enabling their application in a regulatory context [72].

In support of the EU's ongoing efforts to implement measures under both legislative instruments for photovoltaic products, the European Climate, Infrastructure and Environment Executive Agency (CINEA) commissioned a dedicated study on the development of standardisation methods for Ecodesign and energy labelling of PV products. The study, entitled "Development of standardisation methods for eco-design and energy labelling of photovoltaic products" [73] is supported by DG GROW and the Directorate-General for Research and Innovation (DG RTD) and is currently ongoing and executed by CENER (Spain), TÜV Rheinland (Italia), and PTB (Germany). The main objective of the project is to develop robust methodologies for calculating and testing the energy yield of bifacial PV modules, as well as assessing the long-term degradation of both monofacial and bifacial PV modules. This work addresses the current lack of standardised methods that could otherwise be used directly within the legislative framework. The JRC expert team from Unit C2 is a member of a reviewer board for the project, analysing the project outputs to ensure scientific robustness and consistency with EU policy objectives for potential regulatory implementation.

The proposed regulation is currently approaching its final stage, it is under interservice consultation stage. The updated product scope now explicitly covers photovoltaic (PV) modules and inverters, while PV systems have been excluded from the scope. The regulation applies to both monofacial and bifacial PV devices, based on crystalline silicon and emerging thin-film technologies. Bifacial PV modules have been included due to their rapidly increasing market penetration and growing relevance in utility-scale and commercial applications.

This work presents technical updates currently under evaluation during the preparation of the regulatory measures. These updates concern the methodology for calculating the Energy Efficiency Index for Modules (EEI_M) - a key parameter displayed on the energy label-as well as the introduction of a simplified energy label design and a revision of the granularity of the energy efficiency index, including the definition of energy label classes.

7.1.1 Proposed energy label for PV modules (monofacial and bifacial)

— Methodology to determine Energy Efficiency Index (EEI)

The applied methodology is governed by the product scope of the Regulation, i.e., individual PV modules placed on the EU market and intended for use in PV systems for grid-connected electricity generation. The PV modules are energy generating products and their '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. The parameter used to define the ability of the product to generate electricity over time is expressed by the so-called energy efficiency index (EEI, $kWhm^{-2}$). That is the ratio between the estimated annual energy yield (kWh) per unit area (m^2) of the PV module:

$$EEI = {}^{EY_Y}/_{A_M}$$

Eq. 3

EEI is the Energy efficiency index for a module placed in a European reference climate, expressed in $kWhm^{-2}$.

EY_Y is the energy yield from a photovoltaic module over one year under the climatic conditions in the corresponding reference climate, assuming no degradation, expressed in kWh.

A_M is the area of the photovoltaic module, expressed in m^2.

The EEI is calculated according to the methods defined in the IEC 61853-x series [20] [74] [19] [18]. The required input parameters and normative applied are shown in **Table 9**.

Table 9. Methodology applied for the estimation of EEI for monofacial and bifacial PV modules.

PV device	**monofacial**	**bifacial**
Energy yield	IEC 61853-3	IEC 61853-3 IEC 61215-1:2021 IEC TS 60904-1-2:2019
Area	Module	
Timeline	First year of installation	
Climatic conditions	"Subtropical arid," "Temperate coastal" and "Temperate continental" (EN IEC 61853-4)	
Installation	Predefined (IEC 61853-3)	

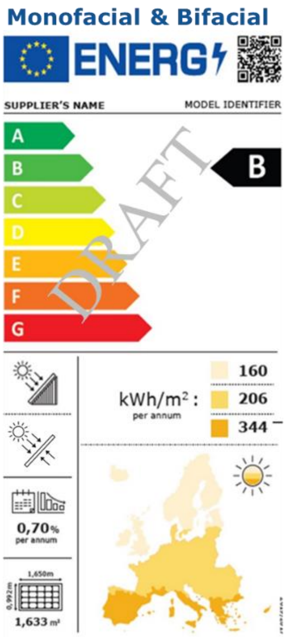
Source: JRC, 2025

The procedure used for the calculation of the energy yield of bifacial devices and thus to define the CSER is also following the IEC 61853 standard series as there is not a specific standard available for energy rating of bifacial PV. However, instead of applying P_{max} at STC (STC, Standard Test Conditions) as it is used for monofacial modules, in the procedure for calculating the energy yield of bifacial devices it is proposed the use of P_{BNPI} (Power at Bifacial nameplate irradiance, BNPI). This is the power output of the module obtained under irradiance corresponding to 1000 Wm^{-2} on the module front and 135Wm^{-2} on the module rear, applied in any method allowed by IEC TS 60904-1-2 (2019) and the irradiance conditions defined in IEC 61215-1 (2021).

The EEI is used to specify the quality of the PV product's performance. It is placed on the label and determine the energy class of the product. The energy label for photovoltaic modules aims to give information on the energy yield of the module, allowing on the one side installers and designers, and on the other side private individuals considering investment in photovoltaic systems, to have immediate and comparable information on the product performance and to be easily able to use this in a purchasing decision. An example of the latest version of the proposed label is shown in the **Figure 31**. The design represents a PV module that would be installed in one of the climate conditions that are representative for Europe, named, 'temperate coastal,' 'temperate continental' and 'subtropical arid' The scale of energy efficiency classes ranging from A to G and corresponds to "the best" (class A) and "the worst" (class G) (**Figure 31**, Table).

The label is based on the energy efficiency index (EEI, $kWhm^{-2}$) and will helps consumer to receive product information quickly via a QR code. It must be registered in the European Product Registry for Energy Labelling database (EPREL) for public access and consultation [75]. Additional information regarding module lifetime degradation rate and dimensions are suggested to be included. The EEI_M values will be also placed on the label to provide guidance to the consumer as to how much energy the product would generate per year.

Figure 31. Example of a possible energy label for PV modules (bifacial and monofacial). Table represents the energy classes and module energy efficiency index (EEI) granularity.



	Module Energy Efficiency Index, EEI_M (kWh/m^2)		
Energy Class	Subtropical arid	Temperate coastal	Temperate continental
A	> 679	> 308	> 396
B	[679 – 598]	[308 – 271]	[396 – 349]
C	[598 – 511]	[271 – 235]	[349 – 305]
D	[511 – 427]	[235 – 197]	[305 – 256]
E	[427 – 372]	[197 – 168]	[256 – 218]
F	[372 – 318]	[168 – 140]	[218 – 181]
G	≤ 317	≤ 139	≤ 180

Source: JRC, 2025

The label simplifies consumer choice by offering a unique label for both type of modules. It represents a simple instrument for an informed choice of the most efficient and sustainable products. The energy classes have been developed to incentivize technological improvements in the PV manufacturing sector and help ensure installation of only quality and sustainable product in Europe.

7.2 Circular Economy of PV modules

ESTI is supporting activities related to the recycling and reuse of PV panels. In specific, the group is working in collaboration with several JRC units (B5, B7, C7, D3, E3) and DG Environment on the Administrative Agreement (AA) on supporting Circular Economy Policy developments as part of the Competitiveness Compass (CEP2CAA) in support of the WEEE (Waste from electrical and electronic equipment).

The Waste Electrical and Electronic Equipment (WEEE) Directive 2012/19/EU was established to address the environmental impact of waste electrical and electronic equipment. In specific the Directive aims at the prevention of waste generation from electrical and electronic equipment (EEE) and encourages the re-use and recycling of such products. Our rule is to support the task regarding PV panels on Recycling efficiency, recovery of materials and possibly recycled content as well as preparation for reuse targets.

8. Conclusions

The work described in this report can be summarize as follows:

- The PV industry is based on the highly efficient crystalline silicon PV technology. Therefore, the assessment of electrical performance and energy generation 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, emerging PV technologies based on new materials, such as perovskite solar cells or VIPV. 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.
- 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 131 calibration certificates to clients from 2022 to 2025. 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.
- 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).
- By providing independent, evidence-based scientific research support to EU policies and addressing key priorities for a strong and sustainable Europe.

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List of abbreviations and definitions

AIST National Institute of Advanced Industrial Science and Technology, Japan

AM Air mass

AR Angular Responsivity

BEV Battery Electric Vehicle

BIPV Building Integrated Photovoltaics

BNPI Bifacial Nameplate Irradiance

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

CSER Climate Specific Energy Rating

CSIR Council for Scientific and Industrial Research, South Africa

CSIRO Commonwealth Scientific and Industrial Research, Australia

DC Direct current

DNI Direct normal irradiance

DSM Direct Sunlight Method

DUT Device under test

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

EUPVEC European Photovoltaic Solar Energy Conference and Exhibition Conference

FF Fill factor (%)

FhG-ISE Fraunhofer Institute for Solar Energy Systems, Germany

GNSS Global Navigation Satellite System

GSM Global Sunlight Method

HJT Heterojunction technology

HZB Helmholtz-Zentrum Berlin, Germany

IEA International Energy Agency

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

IEEE PVSC Photovoltaic Specialists Conference

IMF International Monetary Fund

IPC International Pyrheliometer Comparison

IPCC Intergovernmental Panel on Climate Change

ISAC International Scientific Advisory Committee

ISFH Institute for Solar Energy Research in Hamelin, Germany

ISO International Organization for Standardisation

ISRC International Spectroradiometer Comparison

ITRPV International Technology Roadmap for Photovoltaic

JET Japan Electrical Safety & Environment Technology Laboratories, Japan

JRC Joint Research Centre

KAUST King Abdullah University of Science and Technology, Saudi Arabia

KISTEC Korea Infrastructure Safety & Technology Corporation, South Korea

LED Light Emitting Diode

MJ Multi-junction (PV device)

ms millisecond

NIR Near Infrared light

NMI National Metrology Institute

NLR National Laboratory of the Rockies, USA

NREL National Renewable Energy Laboratory, USA

NPL Natonal Physical Laboratory, United Kingdom

NZIA Net Zero Industry Act

NU Non-uniformity

PHEV Plug-in Hybrid Electric Vehicle

PMOD Physikalisch-Meteorologisches Observatorium Davos, Switzerland

PSC Perovskite solar cell

PSSC Perovskite single solar cell

PSCMs Perovskite solar cell mini modules

PTB Physikalisch-Technische Bundesanstalt, Germany

PV Photovoltaic(s)

PVGIS Photovoltaic Geographic Information System

PVSEC International PV Science and Engineering Conference

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

STC Standard Test Conditions

TC Temperature Coefficient

TCO Transparent conductive oxide

TS Technical specification

TÜV Technischer Überwachungsverein, Germany

UC Uncertainty

UV Ultraviolet light

VELA Vehicle Emissions Laboratory at JRC (Ispra), Italy

VIPV Vehicle Integrated Photovoltaics

VUT Vehicle under test

W Watt

Wh Watt hours

Wp Watt peak (as measured at STC)

WPVS World Photovoltaic Scale

WRC World Radiation Centre

WRR World Radiometric Reference

WSG World Standard Group

List of figures

List of tables

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