Metro-PV

Publishable Summary for 19ENG01 Metro-PV
Metrology for emerging PV applications

Overview

The next generation of solar devices with higher conversion efficiencies, compared to conventional single junction silicon solar cells, will be based on emerging PV technologies (e.g. perovskite-on-silicon tandem). In the field of Industry 4.0 applications the use of indoor-PV is gaining momentum. However, there is still a lack of measurement capabilities that realise performance measurements with low uncertainties for emerging PV applications. This project will reduce the reference solar cell calibration uncertainty that successively affects all subsequent calibrations and performance measurements in the traceability chain. In addition, international standards will be developed, including measurement procedures for emerging PV technologies. The uncertainty of the PV calibration chain will be reduced and thereby, in a wider perspective, the financial uncertainty of investments.

Need

According to current forecasts, the largest share of the entire future energy supply including electricity, heat, mobility and industrial processes will be based on solar power. The enormous investments required for this transition need to be metrologically underpinned by a corresponding expansion of the quality infrastructure.

Perovskite-based cells have emerged as one efficient and low-cost option, which European organisations are seeking to rapidly scale-up and commercialise in applications such as PV integrated into buildings and vehicles and indoor energy-harvesting.

This project will improve the European metrology for emerging PV technologies such as perovskite-on-silicon tandem devices and indoor-PV devices to support this huge challenge.

The photovoltaic world market is worth about 100 billion Euros per year. New systems attract investment based on the estimated energy yield, which depends critically on the power rating under different conditions. Thus, every percent of measurement uncertainty leads to a financial uncertainty of 1 billion Euros. Studies predict a further increase in the market share of emerging PV that is required to preserve the high growth rates of PV. Therefore, lower measurement uncertainties as well as realistic standards are needed to reduce the financial uncertainty and thus safeguard the investments required to achieve EU's Green Deal targets.

Objectives

The overall goal of this project is to provide the necessary metrological infrastructure, techniques and guidance to accelerate time-to-market for emerging photovoltaic (PV) technologies, which have the potential to significantly reduce the cost of photovoltaic energy, the most important future energy source.

The project focuses on the traceable measurement and characterisation of emerging PV applications.

The specific objectives are:

1. To validate the suitability and reduce the uncertainty, associated with measuring the nominal power of PV devices, within the calibration chain according to the IEC 60904 standard series. This should include multi-junction PV devices and devices constructed from perovskite materials.
2. To determine the uncertainty sources related to the output power of PV modules. This should include development of models to quantify the uncertainty sources that are associated with measurement of the I-V curve in accordance with IEC 60904-1 and spectral irradiance and spectral response of PV devices in accordance with IEC 60904-8.

3. To define a quality metric for the behaviour of PV modules in shady locations such as urban areas in order to quantify the benefits of shade-tolerant module designs.
4. To prepare a classification of PV-based energy-harvesting devices for the Internet of Things (IoT) applications, by developing and validating traceable methods for evaluating their performance in low light (indoor) conditions and their sensitivity to influencing factors e.g. the pulse-width modulation of modern efficient light sources.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (accredited laboratories, instrumentation manufacturers), standards developing organisations (IEC, especially IEC TC82 and IEC TC113) and end users (e.g. photovoltaics industry). In addition, to contribute to revision of the IEC 60904 standard series.

Progress beyond the state of the art

This project will improve the accuracy of the measurements needed for the calibration of reference solar cells, by using the limitations of existing standards as a starting point in order to further reduce the lowest uncertainty in the world. Also, procedures for the evaluation of uncertainties will be established, i.e. brought to standardisation bodies. Furthermore, a metric will be developed to rate the shading sensitivity of PV modules. To improve the use of indoor-PV for the energy supply of IoT devices, the results of this project will contribute to international standardisation. As standardisation has thus far focused on outdoor applications, the development of new calibration facilities for indoor-PV with irradiance levels 100 to 1000 times lower than under standard outdoor conditions goes beyond the state of the art.

The most accurate primary calibrations of WPVS type reference solar cells are performed by PTB. The "world record" lowest uncertainty is 0.4 %, using PTB's Laser-DSR facility. As these calibrated solar cells act as references and thus as the starting point of the traceability chain for the performance rating of the solar cells and solar modules manufactured by industry, a reduction of this important quantity is crucial.

This project aims to reduce the expanded uncertainty to a value down to 0.35 %, or even below, to successively affect all following calibrations and performance measurements in the traceability chain. In addition, there is a rising demand for calibrations of emerging PV devices (e.g. for perovskite solar cells). Due to their properties (e.g. response time) it is challenging to measure and calibrate these devices with low uncertainties. The uncertainties will be reduced from 3 % to 2 %. The activities within this project will also allow a reduction of the lowest available uncertainty of emerging PV devices.

The standards concerning measurement issues (the IEC 60904 standard series) describe procedures for the determination of *I-V* curves and of the spectral responsivity of PV devices, but they regularly lack documentation for determination of the uncertainty of the measurements. This determination of the uncertainty is often requested by the users of the standards. The project will remedy the deficiency of the IEC 60904 standard series by writing technical reports on how to calculate the measurement uncertainties.

State of the art energy rating procedures are currently not applicable to the emerging technologies (e.g. perovskite-on-silicon tandem). The existing methods and calculations do not consider the non-uniformity of irradiance in shady urban areas. In this project, a metric will be developed to rate the shading sensitivity of PV modules. This metric will improve the accuracy of energy yield determination.

In the area of indoor-PV, standardisation has just started recently. Indoor PV is used for autarkic energy supply of energy harvesting Internet of Things applications, e.g. for communication and sensor issues. No standards are currently available, although they are important for Industry 4.0 applications. The research activities within this project will contribute significantly to the ongoing standardisation processes by providing the necessary technical input.

Results

Validation of suitable reference devices and measurement procedures

PTB has developed a traceable calibration method for WPVS cells with an uncertainty of 0.35 %. The improvements were achieved by using a better fibre coupling and by improvement on the monitor principle. A final report about this improvement including a comprehensive measurement uncertainty analysis was written.

To develop a traceable calibration method for standard Si modules with an uncertainty of 1.0 % and an extension on perovskite solar cells, TÜBİTAK ordered new simulator (cell simulator) for the measurement of the emerging PV devices. In addition, TÜBİTAK has already reduced its uncertainty to 1.2 % by using spectral band pass filters for an improved spectral mismatch correction. The uncertainty budget including optical, electrical, thermal, reference standards contributions was prepared by TÜBİTAK. It was also shown that after getting traceability from PTB with the reduced uncertainty of 0.35%, the uncertainty for their calibrations of standard silicon devices will be reduced to below 1.0%. JRC is now ready to measure the spectral responsivity. Work is continuing towards reducing uncertainty below 1.0 %. ISFH updated the measurement routines of their fully integrated measurement system, for combined SR and I-V testing. For multi-junction solar cells LED and filtered halogen bias lights for the top and bottom cells are successfully integrated and tested. Light I-V measurements are performed with an LED-based sun simulator. The optimized measurement software allows adapting the light source to spectra that results in the AM1.5G currents of the individual sub cells. First tests on perovskite on silicon tandem two terminal test cells were successful. FhG performs a manual maximum power point tracking, which takes into account the slow transient response of emerging PV devices, in order to determine the power of these devices. To improve the homogeneity of the bias light, FhG has installed LED bars with central wavelengths of 467, 530 and 850 nm. Non-uniformity at or below 10% according to IEC 60904-8-1 is now fulfilled for large-area emerging PV devices.

Aalto and PTB have purchased emerging perovskite modules and cells from Solaronix to be used in a round-robin intercomparison. A comparison protocol was written. A round-robin based on reference cells has already started. The other round-robin using Perovskite modules is about to start in January 2023.

To adapt, develop, test and improve reference cells for use in the calibration of emerging PV devices, a screening analysis has been carried out by FhG. An extensive set of perovskite top and Si bottom cell spectral responsivities as well as reference cell spectral responsivities have been considered and the matching index between them has been calculated. A KG3 filter has yielded best spectral match for perovskite top cells, RG695- or RG715-filtered A+ reference cells show best agreement for Si bottom cells. Additional cells with RG715 filter were manufactured. FhG has furthermore investigated the irradiation-induced increase of the filter temperature. By means of an analytical model, the effect was reproduced and its effect on different measurement configurations (DSR method, flash I-V measurement, steady-state I-V measurement) quantified. Additional measurement uncertainties have been determined to be 0.2 % for RG695- and 0.3 % for RG715- and RG780-filtered reference cells. Thus, filter and solar cell combinations optimal for perovskite/Si tandem solar cells have been identified and the corresponding reference cells have been produced. The reference solar cells have been calibrated by PTB.

Evaluation of uncertainty sources related to the output power and energy of PV modules

To determine the measurement uncertainties related to the output power of PV modules within the IEC 61853-3 energy rating standard, as a first step an intercomparison regarding the Climate Specific Energy Rating (CSER) calculation was performed. An initial blind comparison using PV module data experimentally determined by TÜV Rheinland revealed discrepancies of 14.7 % rel. in the calculated CSER of the different participants. Four subsequent intercomparison phases were performed, during which best practices were established and ambiguous steps in the procedure were clarified. Thereby, the deviations could be reduced to below 0.1 %. The good agreement was confirmed by analysing the data of a second PV module in a final blind intercomparison. A joint publication on the results of the intercomparison and best practices in the calculation of the CSER of PV devices was written and presented at EU-PVSEC-37 and accepted for publication in IEEE Journal of Photovoltaics. 5 project collaborators (PV Performance Labs, NPL, DTU, TNO, Univ. Delft) participated at the round robin. The draft spreadsheet for uncertainty calculation is available and has been discussed at the 27 m project meeting with all partners, especially PTB, JRC, SUPSI, ITRI, LNE and Certisolis.

Definition of a quality metric for the sensitivity of PV modules power output in shady locations

To develop a quality metric defining the shading tolerance of PV modules, indoor- and outdoor facilities were adapted for the measurement of the shading tolerance. A metric was developed and tested using the facilities. A presentation for internal discussion was prepared. A quality metric has been presented at WCPEC8 in September 2022 and is currently being tested by several laboratories in an intercomparison campaign.

Characterisation and classification of PV-based energy-harvesting devices for Internet of Things (IoT) applications

As a summary of the state of the art, a chapter on the “Characterization and Power Measurement of IPV Cells” was written and published. In addition, several facilities for the measurement of the special indoor characteristics, needed for characterisation of the energy-harvesting devices for IoT applications, were built and characterisation measurements were performed. A possible set of indoor-adapted measurement conditions to be met by the facilities was published in the book. Aalto has studied various cells used for energy harvesting, and selected one Epishine cell, and one Amorphous silicon cell to be used in a round-robin intercomparison. The cells (including a reference cell to go with the energy harvesting cells) have been preliminarily tested for dynamic spectral responsivity, and electrical parameters at varied illuminance levels of 20 lx - 1200 lx.

Impact

As of the first quarter of the project, a chapter on the "Characterization and Power Measurement of IPV Cells" was written and published in the book entitled "Indoor Photovoltaics". At three-quarters of the project time, two open access publications were produced highlighting project outcomes. Furthermore, five presentations and three posters on project results were presented at international and European conferences, such as NEWRAD 2021 and the European Photovoltaic Solar Energy Conference and Exhibitions (EU PVSEC) in 2020, 2021 and 2022.

The project leadership in several important standardisation projects related to PV metrology has been taken over by members of the consortium, e.g., revisions to the standards IEC 60904-8, IEC 61853-1, IEC 61853-2 and IEC 61853-3. The consortium has also contributed to a new normative document IEC/TS 62607-7-2.

A Wiki about PV metrology (wiki.pvmet.org) was built and published online. Over the time further articles were written and existing articles were updated.

Impact on industrial and other user communities

This project directly supports the PV community, i.e. PV manufacturers and suppliers, with new and improved measurement capabilities for emerging PV technologies and applications. In addition to the PV industry, the defined measurement procedures for indoor-PV could be utilised by all industries that are using self-sustaining Internet of Things devices with a PV power supply. Industry 4.0 concepts using wireless sensor technologies from the Internet of Things ecosystem will benefit from the project due to the more accurate determination of the device efficiency in a realistic indoor lighting environment.

Hence, this project will support the penetration of these emerging PV products (perovskite-on-silicon tandem solar cells/modules and indoor-PV) into the PV market. This will enable cost reductions in PV applications.

Impact on the metrology and scientific communities

The development of reference PV devices for emerging PV technologies and procedures for their calibration, sets an important basis for the metrology and scientific PV community. The improved facilities and procedures elaborated within this project will allow NMIs, calibration laboratories, and research institutes to gain competence in the field of emerging PV technologies and enable traceable measurements to be conducted with the lowest possible uncertainties (2 % instead of 3 %).

So far, the consortium has developed two new measurement services with reduced measurement uncertainties and reference cells for emerging PV devices which are ready for commercial exploitation.

Impact on relevant standards

The project will enable the extension of existing standards (e.g. IEC 61853) to a more precise estimation of the energy output of a PV installation, thereby reducing the financial risk to investors and leading to higher investment in this type of renewable energy. Technical reports on the measurement uncertainties of the most important measurement standards (IEC 60904-1 and the IEC 60904-8) will be produced. These will complement the existing standards by providing a detailed uncertainty assessment, whilst removing their current significant limitations. In addition, this project will contribute to developments of new standards for indoor-PV.

Longer-term economic, social and environmental impacts

According to a 2020 European Commission report, PV "is uniquely positioned to help achieve the EU's energy transition and climate change objectives as well as to support EU jobs and economic growth in the context of the Green Deal."[1] "To reach a 55 % GHG emissions reduction [by 2030], it is estimated that the cumulative

[1] Photovoltaics: Technology Deployment Report 2020, EUR 30504 EN, European Union, ISBN 978-92-76-27274-8, doi:10.2760/827685, JRC123157. https://op.europa.eu/en/publication-detail/-/publication/4fac82d6-6b55-11eb-aeb5-01aa75ed71a1/language-en

PV capacity in the EU and the UK would need to reach 455–605 GWDC. This implies a CAGR between 12 and 15 %."[2] [3] (CAGR: Compound Annual Growth Rate).

At the start of the project, the annual value of the global market for photovoltaics was estimated at 100 billion Euros. This is expected to grow significantly in the years ahead as emerging PV claim an ever-larger market share. Attracting continuing investment in the technology depends on providing the means to reduce the financial risks for investors. A percentage improvement in the uncertainties of measurements used to determine the power ratings of PV applications, and by extension their estimated energy yields, would reduce the total financial uncertainty of investments by 1 billion Euros.

The harmonised measurement methods for new technologies together with reduced measurement uncertainties will contribute to a clear reduction of the investment risk. It will empower consumers by enhancing a metric for PV efficiency based on energy output under European climate conditions by adding uncertainty evaluations to it and considering shading effects. This will allow a risk assessment of these predictions that is currently less precise, and thus it will enable system planners and financial institutions to optimise their services. Some decisions on how to invest public (government) and private (industry/consumers) money in PV are being made based on power and efficiency numbers that do not correlate with the energy output under operational conditions and give limited indication of the risks involved. These risks are related to the financial pay back expectation, and for systems consisting of tandem modules, the physical properties may lead to operation under conditions which result in significantly lower outputs than expected. Better understanding and harmonised characterisation of the effects on the energy generation of emerging PV technologies will significantly mitigate the investment risks for end users.

Based on the project's outputs, industry will be able to optimise their emerging products for more realistic operating conditions. This will increase the competitiveness of PV industries where Europe holds a leading position.

Foreseeable impacts of the project are:

- Fair and impartial assessment of emerging technologies. This reduces deployment risk and accelerates time to market. For SMEs especially, it is important to show their achievements in a timely manner. Delays affect the R&D development and potential market impact of EU technology.
- Local certification of PV efficiency. This avoids IP-leakage that has been reported especially in the certification of some thin-film devices.
- The development of a high-quality traceable measurement technique will protect European enterprises and end-users against cheap, but low-grade photovoltaic products.
- Support for sustainable and renewable European energy generation.
- The typically decentralised energy generation pattern of photovoltaic systems supports local employment policy and thus improves the socioeconomics in Europe.
- The dissemination of good metrology practice and novel PV measurement methodologies to European industry will enhance productivity by the improvement of quality control and hence reduced wastage.
- Appropriate PV metrology, based on the characteristics, will enable photovoltaic systems to thrive in an even more competitive power market, potentially enabling PV systems to bid subsidy-free into the free power market.

This project will meet the essential requirements for reducing the investment risk associated with initiating new large-scale PV installations, for removing barriers to entering the marketplace and thus it will accelerate the overall cost reduction of photovoltaics by delivering key enabling metrological research.

[2] "Clean Energy Transition – Technologies and Innovations Accompanying the document REPORT FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT AND THE COUNCIL on progress of clean energy competitiveness" Brussels, 14.10.2020 https://eur-lex.europa.eu/resource.html?uri=cellar:871975a1-0e05-11eb-bc07-01aa75ed71a1.0001.02/DOC_1&format=PDF

[3] Jaeger-Waldau, A, et al, How photovoltaics can contribute to GHG emission reductions of 55% in the EU by 2030, Renewable and Sustainable Energy Reviews, Volume 126, 2020, 109836 https://publications.jrc.ec.europa.eu/repository/handle/JRC119156

List of publications

[1] P. Kärhä, Janne Askola, Kinza Maham, Timo Dönsberg and Erkki Ikonen, "Differential spectral responsivity measurements of large bifacial solar cells", *NEWRAD 2021 Conference Proceedings*. https://doi.org/10.5281/zenodo.4882794

[2] Vogt, Malte Ruben, Stefan Riechelmann, Ana Maria Gracia-Amillo, Anton Driesse, Alexander Kokka, Kinza Maham, Petri Kärhä et al. "PV module energy rating standard IEC 61853-3 intercomparison and best practice guidelines for implementation and validation." *IEEE Journal of Photovoltaics* 12, no. 3 (2022): 844-852. https://doi.org/10.1109/JPHOTOV.2021.3135258

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

<table>
<tr><td colspan="2">Project start date and duration:</td><td>01 September 2020, 36 months</td></tr>
<tr><td colspan="3">Coordinator: Stefan Winter, Dr., PTB Tel: +49 531 924 140 E-mail: stefan.winter@ptb.de
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<tr><td>Internal Funded Partners:
1. PTB, Germany
2. Aalto, Finland
3. IMBiH, Bosnia and Herzegovina
4. LNE, France
5. TUBITAK, Türkiye</td><td>External Funded Partners:
6. FhG, Germany
7. ISFH, Germany
8. JRC, European Commission
9. SUPSI, Switzerland
10. TÜV Rheinland, Germany (withdrawn from 31 October 2021)
11. TÜV RH Solar, Germany (joined from 1 November 2022)</td><td>Unfunded Partners:
12. Certisolis, France
13. ITRI, Taiwan</td></tr>
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