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1 Executive Summary

Introduction

Photovoltaics (PV) are devices made up of solar cells that use the properties of semiconductor materials to convert energy from the sun into electricity. When PV devices are sold, they are classified according to their energy output. Prior to this project, the energy output of PV was measured under standard test conditions (STC) specific to the USA, and of little relevance to real operating conditions in Europe. This could lead to inaccurate estimates of the energy generated when used under real operating conditions.

This project developed a new classification system of PV devices based on their energy output under different climate zones that led to the new standard IEC 61853. This reliable data enables governments and industry to make informed decisions over which PV technologies are most suitable.

The Problem

The photovoltaic (PV) world market volume is approximately 50 billion Euros per year. PV devices are sold according to their output power as measured under standard test conditions (STC). These conditions represent a cloudless sunny day in the middle of the USA, with an artificial and unrealistically low device temperature. The climate conditions in Europe differ significantly from this and since device efficiency depends on a combination of device properties and the environmental conditions, the current peak-efficiency metric leads to inaccurate estimates of the energy generated under real operating conditions. Hence a classification of PV devices regarding their energy production is urgently needed.

The Solution

The consortium set out to solve this problem by developing a new metric that is not based on the peak power but on the energy yield for standardised climate zones. Therefore, hourly irradiance and weather conditions had to be extracted out of satellite and ground based data for a standard year and for a representative place for each climate zone. Using the calibration capacities built up within the project, the solar device properties, required for the new metric, can be determined. Both the comprehensive solar device properties and the tabulated irradiance data serve as input parameters within the new metric that can calculate the standardised energy yield of the solar device for each climate zone.

Impact

Early impact will result from three IEC standards for an energy based metric: 1) the required solar device measurement methods, 2) the irradiance and weather data for all important climate zones and 3) the mathematical model needed to combine 1) and 2) into a standardised yearly energetic yield. Input was developed for these and submitted to the IEC TC82 by the consortium. Two of the developed standards have the status “Committee Draft for Voting” and the standard about the measurements has already been published.

To spread knowledge about the new standards, several global activities were carried out to inform the PV community about the mission and the advantages of the new energy rating standards. This included many different overview talks to many different stakeholder groups (PV calibration labs, PV manufacturers, meteorologists, conferences and workshops inside and outside of Europe). For example, the consortium organised an international workshop where the results of the project and the new Energy rating standards were presented to around 100 international participants including several international policy makers and stakeholders of the International Energy Agency. In addition, a three-day training course was organised by the consortium for stakeholders.

The application of these standards will reduce the former financial uncertainty in energy yield estimation of several 500 million Euros per year significantly, as the new energy-rating standards will be based on much more realistic weather- and irradiation conditions than the former standard test conditions.

To enable the application of the new standards, the measurement capabilities were extended to fulfil the needs of the PV industry. The stakeholders already made use of the new services. In addition, they already bought the improved reference solar cells for the transfer of the solar cell efficiency with lower uncertainties to their industry laboratories.

2 Project context, rationale and objectives

In recent years there has been a large increase in the rate of PV installations in Europe and the world market is now worth around 50 billion Euros per year. Once installed, PV operation generates no greenhouse gases and no pollution, and this has led to the rapid adoption of the devices as a viable energy source.

The STC conditions used to classify PV devices prior to this project represented peak power on a cloudless sunny day in the middle of the desert in the USA, with an artificial and unrealistically low device temperature. The climate conditions in Europe differ significantly from this and specific examples of the difference in climatic conditions between the USA desert and Europe include:

- Device operating temperature: USA unrealistic 25 ºC, Europe 40 ºC or 50 ºC
- Solar spectrum: significantly different, depending on the time of the day and weather conditions
- Angle of solar radiation falling onto the PV device: significantly different

Since device efficiency depends on a combination of device properties as well as on the environmental conditions, the previous STC led to inaccurate estimates of the energy generated under real operating conditions which can have financial consequences. Decisions on how to invest public (government) and private (industry/consumers) money on PVs were also made based on power efficiency numbers that did not correlate with energy output under operational conditions.

Prior to this project, PV manufacturers, sellers and end users needed a revised classification for PV devices i.e. one that gave energy production under specific defined (standardised) climatic conditions appropriate for the range of geographical areas (such as Spain, UK, Italy, France) in which the devices will be installed and operated. This is particularly relevant in Europe where PV systems of different technologies are operated in a wide range of climatic conditions.

Other requirements for improved measurements for PV devices included spectral (measurements at different wavelengths of light) and angular measurements, as well as improved reference devices, and reduced uncertainty.

Scientific and technical objectives

This project developed a new classification system for PV devices based on their energy output under different operational conditions. The project addressed the following scientific and technical objectives:

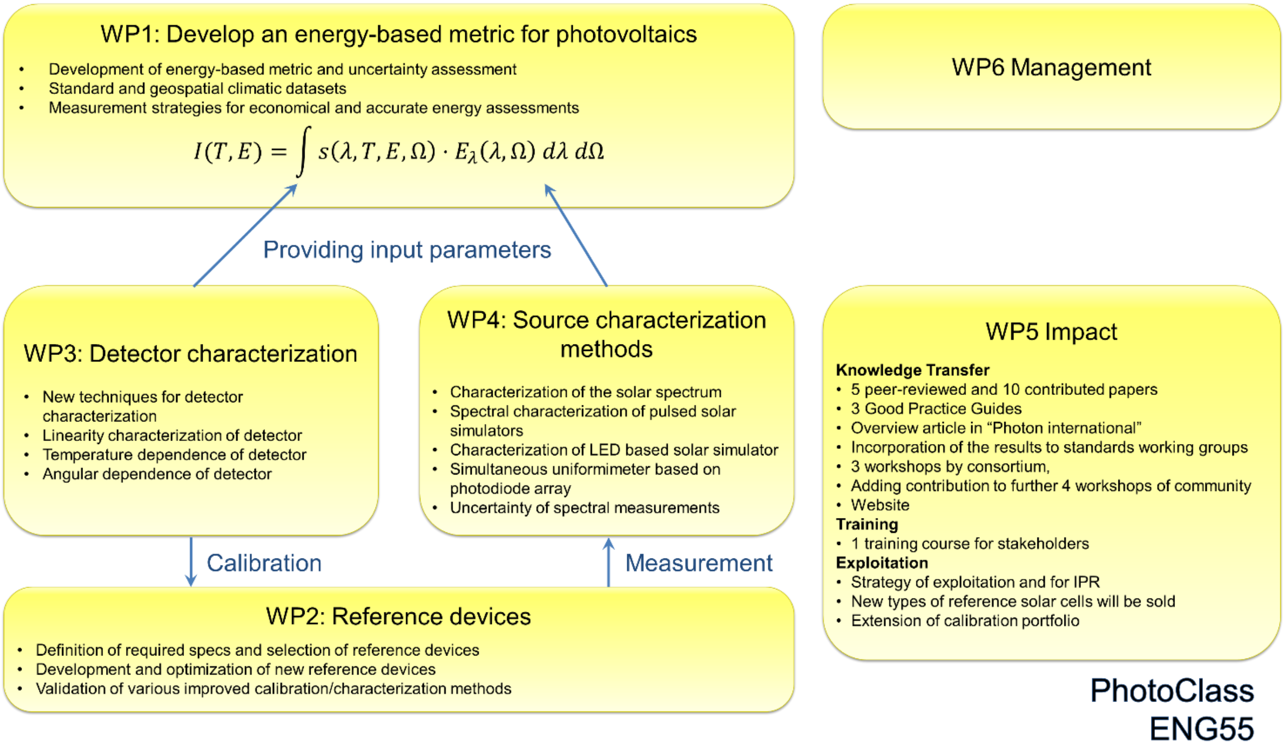
1. An energy based metric for PV efficiency will be developed and its uncertainty budget will be assessed. Standardised environmental data-sets will be defined for Europe and beyond.

   For the calculation of the standardised yearly yield, the metric combines the properties of the solar devices with the irradiance conditions of a selectable climate zone. Therefore, the following objectives were needed to enable and validate an accurate measurement of both.

2. Robust and improved characterisation methods with accuracy sufficient for the parameters necessary for the new metric (e.g. spectrally resolved angular dependency of the responsivity, low light performance, and temperature dependency) will be developed.
3. The measurement uncertainty for the absolute measurement of the natural and simulator irradiation conditions, spectrally and angularly resolved, will be reduced. The upper limit of the measured wavelength will be extended from 1050 nm to 2000 nm.
4. The spectrally and angularly resolved measurements of solar devices will be validated by comparison with integral measurements. Primary traceability and harmonisation of indoor/outdoor characterisation methods will be established.
5. New reference devices will be developed for an accurate SI traceable calibration process from the cell to the solar park. In addition, procedures for their application will be developed.

3 Research results

Structure of the PhotoClass Project



Objective 1: A metric (energy based) for PV efficiency will be developed and its uncertainty budget will be assessed. Standardised environmental data-sets will be defined for Europe and beyond.

The successful development of a metric for PV efficiency, based on energy output under European climate conditions within the PhotoClass project (objective 1), allows a risk assessment to be undertaken based on these predictions, which was not previously possible. This will enable system planners and financial institutions to optimise their services. In former times, decisions on how to invest public (government) and private (industry/consumers) money on PVs were being made based on power efficiency numbers that do not correlate with energy output under operational conditions and they give no indication of the risks involved.

The respective standard IEC 61853-3 for the calculation of the standardised yearly yield was mainly written by the PhotoClass consortium and this has been published as a committee draft for voting.

The testing of the yield calculation model, using the IEC 61853 draft standard method, on sample metrological data from JRC was done by REG(LU). The software development is complete.

The feasibility of constructing climatic data sets that can be used to perform energy rating on PV modules in Europe has been studied. In the last few years spectrally resolved irradiance data have become available using satellite data. These data have a spatial and temporal resolution that is sufficient for performing the energy rating calculations for any location in Europe. However, the accuracy of the energy rating calculation is limited by uncertainties in the PV module measurements that are used with the climatic data to produce the energy rating values. The consortium attempted to quantify the uncertainty in the energy rating calculations due to the module measurements. Using measured data for a number of crystalline silicon PV modules the module performance ratio was calculated for different locations in Europe and the variability in the Module Performance Ratio (MPR) due to the various measurements was estimated. Variations in the measurements of the angle-of-incidence effect will in most cases change the MPR by less than 0.1 % although for one module the change in MPR from the different measurements was about 0.3 %. Variations in the measurement of the spectral response changes the calculated MPR very little, with a standard deviation of 0.02-0.04 % depending on the location. The strongest influences on the MPR are given by the measurements of module temperature and of module power as a function of irradiance and module temperature. The measurements of module temperature may cause the MPR to vary with a standard deviation of up to 1 %, although for some modules this is lower. The influence of the power matrix measurement can change the MPR with a standard deviation of 0.5-1.3 %. This is highest in the northernmost locations. Overall, the variability of the MPR due to the different measurements may reach a standard deviation of about 1.3 %, although this is generally lower in southern locations. Given these results the uncertainty of MPR, due to the module measurements, is estimated to be about 2 %. Calculations of MPR for c-Si and CdTe modules over Europe show that the MPR varies from less than 0.9 to nearly 1.0 in Europe (excluding extreme cases such as high mountains). The range of MPR values is somewhat smaller for CdTe mainly due to the smaller temperature coefficient. Combining this result with the uncertainty value, the consortium would suggest that three data sets for energy rating for the climates in Europe would be a good number. This would allow a reasonable variation in MPR values that result from the different data sets. It should be noted that the present study is limited to an area south of 60° N. It may be necessary to add a further data set for the regions further north. At the moment the satellite-based spectral solar radiation data have not been validated for high latitudes. As an alternative, ground station data could be used if available. Based on this study the consortium would propose four different climatic data sets for energy rating in Europe. These are available for download.

A further part of this objective was to provide guidelines for the implementation of the energy rating in an accurate and cost-effective manner. This was analysed by NPL with support by TUV Rheinland. The recommendations are based on the combination of a measurement-cost model and an energy-rating accuracy model that enabled the exploration of different measurement scenarios corresponding to the performance of only a subset of the measurements required by the energy rating standards. Example scenarios that offer little loss of accuracy in exchange for a significant reduction in the measurement cost were selected.

While individual cost-accuracy models will be particular to a specific test laboratory, the results of our generic study suggest a set of rules for choosing good measurement scenarios.

By avoiding the angle-of-incidence measurements and by reducing the performance matrix measurements to just 6 points, it is possible to save a total of 64 % of the measurement cost with only a 0.1 % increase in the 95 % confidence interval for the energy rating. The figure above hints at the rules for selecting these 6 points; at least one measurement at 100 W m-2 and low temperature appears to be critical, while at least two measurements at a higher temperature (one high irradiance, one moderate irradiance) are also important.

If a laboratory needs to perform a non-standard energy rating measurement with the minimum acceptable measurements, it is recommended that they try one of these optimum scenarios. However, care should be taken to validate that the extrapolation method does not introduce significant errors through artefacts in its function. One way to do this would be to measure the complete, or almost complete, matrix for a selection of modules, then to compare the full energy rating to the energy rating achieved when most of the data points are omitted. Caution should be taken when measuring modules that are expected to perform very differently to the module types on which the validation has been performed.

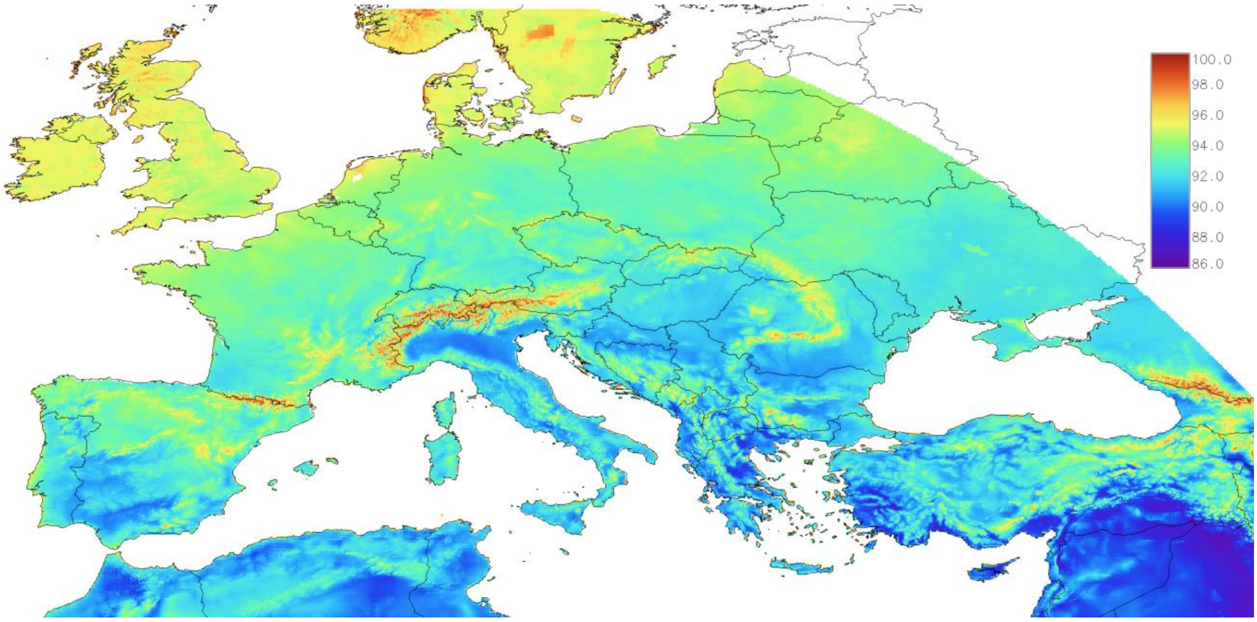


Figure 1: Map of yearly average MPR for c-Si modules in Europe, in percentage points. The calculation was made for modules inclined at 20º from the horizontal, south-facing. Local shadowing has not been taken into account. **Conclusion: The difference between the realistic energy yield, according to the new energy rating standard and the energy yield based on the traditional Standard Test Conditions (STC), is up to 14 %, depending on the climate zone.**

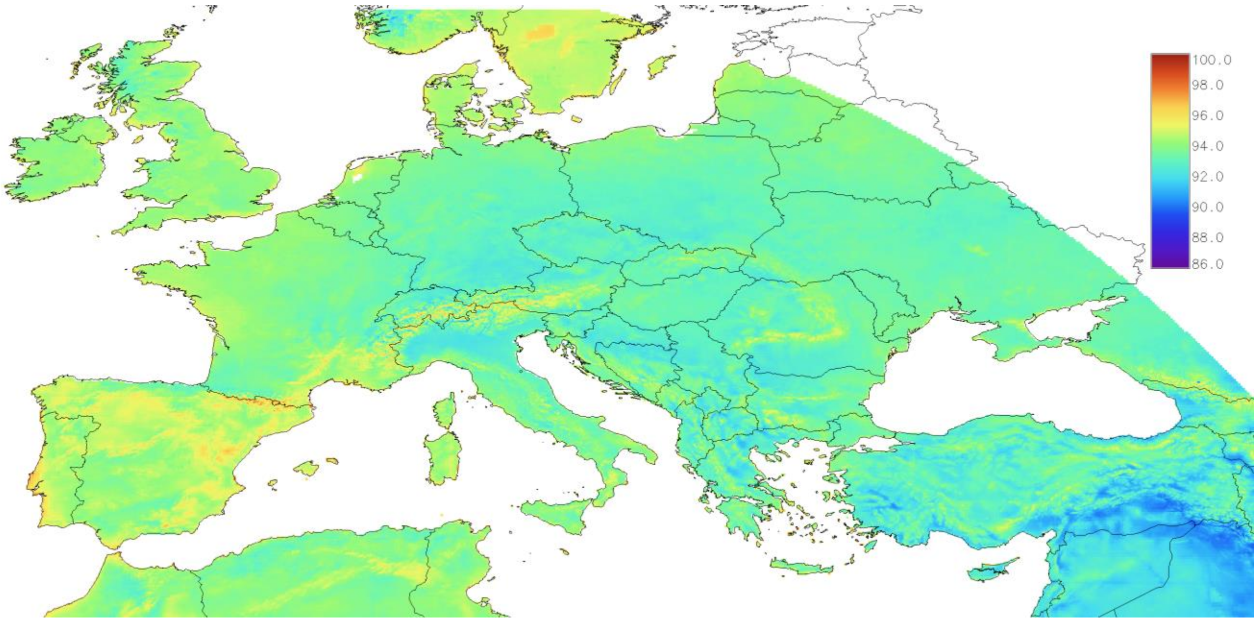
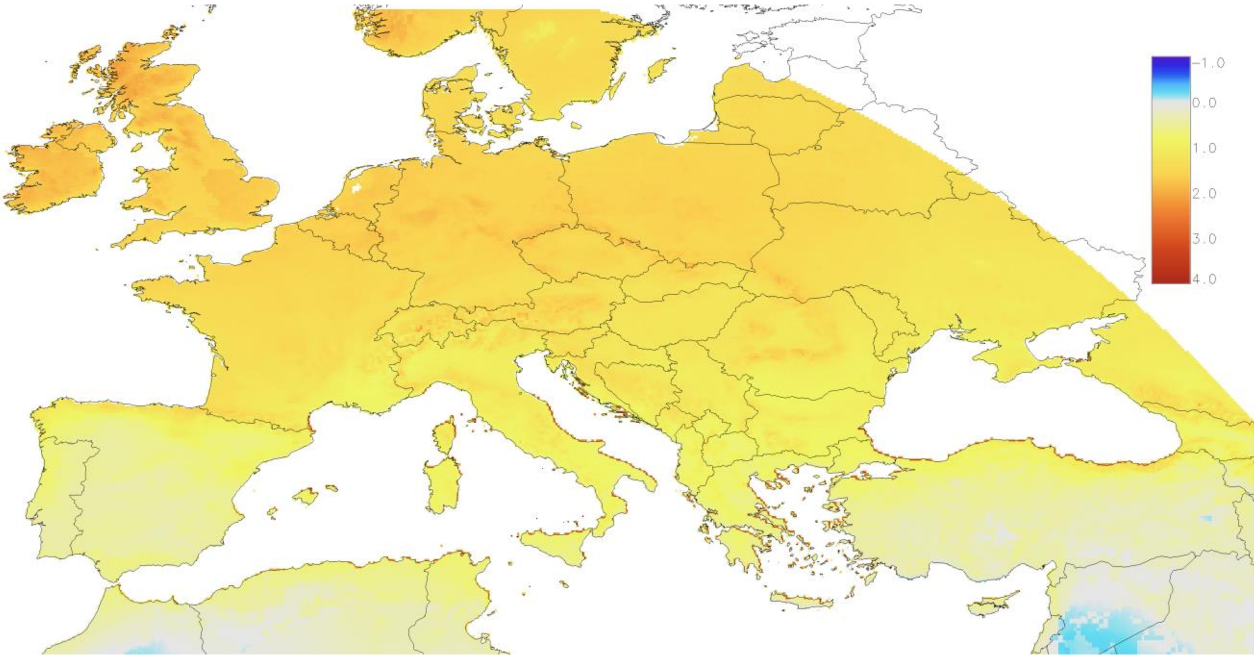


Figure 2: Map of yearly average MPR for CdTe modules in Europe, in percentage points. The calculation was made for modules inclined at 20º from the horizontal, south-facing. Local shadowing has not been taken into account.

a)



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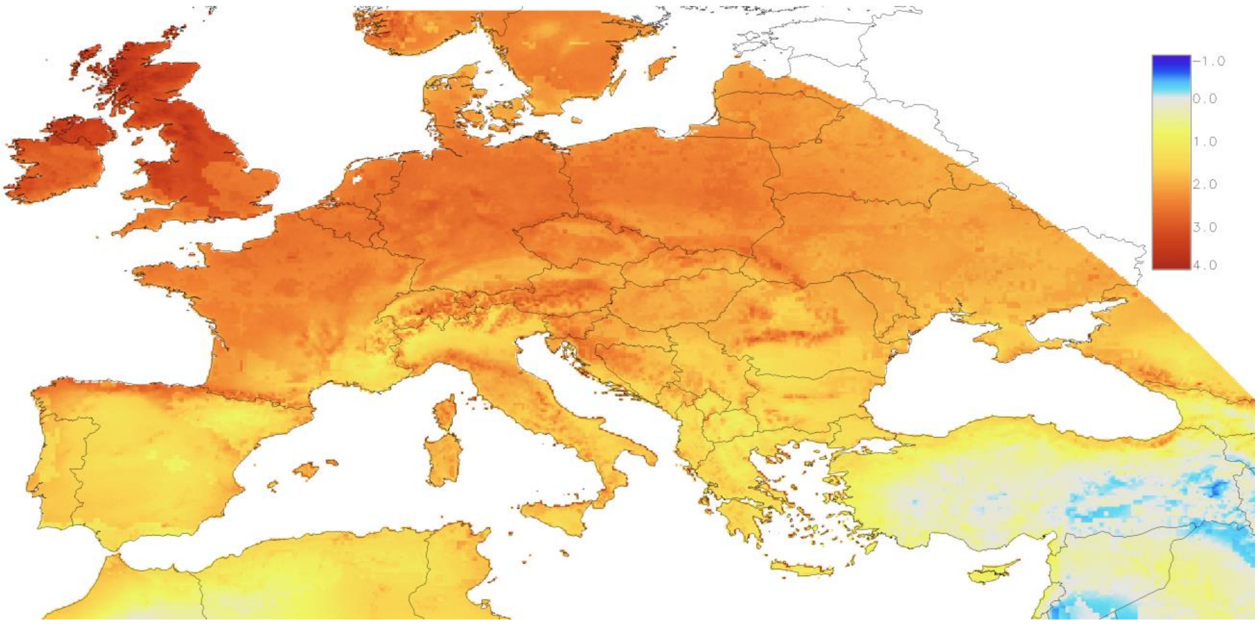

Figure 3: Maps of yearly average loss/gain due to spectral effects calculated according to Eq. 5. a) c-Si modules, b) CdTe modules.

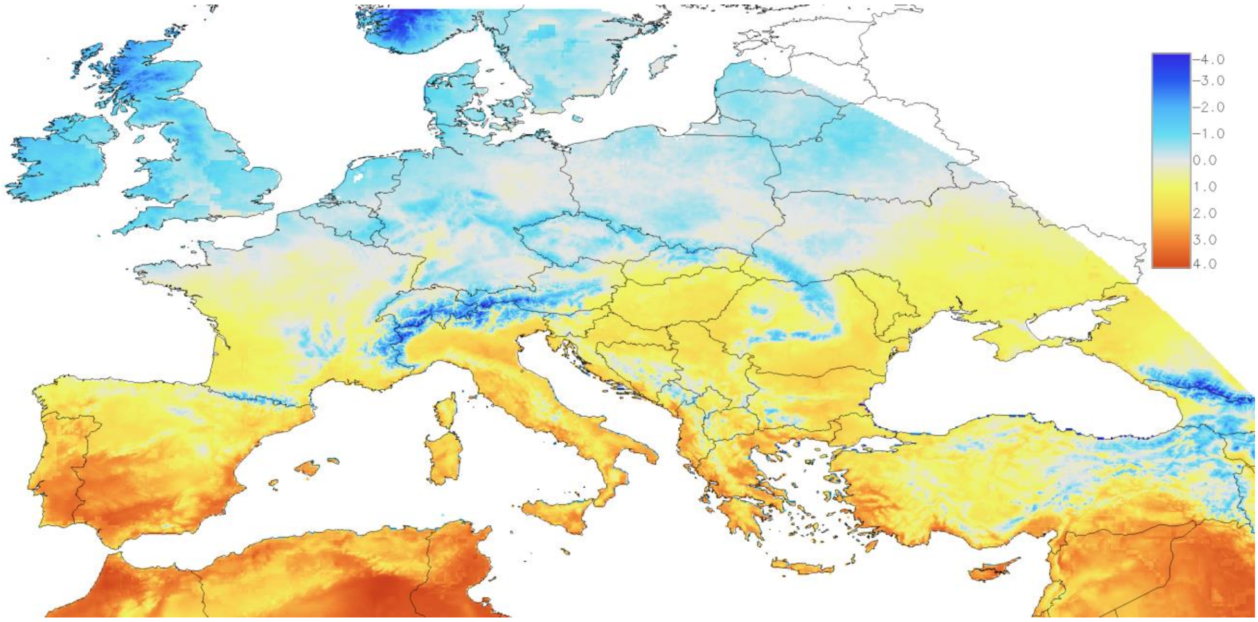

Figure 4: Map of the difference in MPR between CdTe and c-Si modules, given in percentage points. **Conclusion: If the output of these different module types is compared according to the traditional STC, the result would have a systematic climate zone dependent error of up to +- 4 %. This error is eliminated by using the new energy based metric.**

Objective 2: Robust and improved characterisation methods with an accuracy sufficient for the parameters necessary for the new metric (e.g. spectrally resolved angular dependency of the responsivity, low light performance, and temperature dependency) will be developed. This will include solving metrological challenges for new PV technologies.

The metrological challenges for new PV technologies will be solved, thus improving the availability of methods for the determination of efficiency and the energy output of solar devices with a reduced measurement uncertainty; and consequently, with a reduced financial uncertainty.

The required standard IEC 61853-2 for the measurement of solar devices was written mainly by the PhotoClass consortium and it was finally published during the project.

In addition to a standard, new and enhanced measurement capabilities are required, to enable companies to apply the standard with low measurement uncertainties. For this reason, the facilities have been upgraded and successfully tested for linearity measurements between 50 W/m²and 1000 W/m². PTB has implemented a halogen lamp array at the Laser-DSR facility. REG(FhG) has implemented a set of metal meshes in their sun-simulator facility. REG(LU) and LNE have implemented an irradiance variation into their PASAN III-b solar simulator facilities. JRC has implemented and tested a new procedure (using a set of shutters) on its large area steady-state solar simulator. In summary, all facilities for irradiance dependent measurements have been improved to realise irradiance from 50 W/m² - 1000 W/m².

Within this project a novel approach to measuring the surface response profile of a photovoltaic cell using techniques from signal processing theory was developed by NPL and REG(LU). The intention was to demonstrate that it is possible to identify the presence of defects and areas of aberrant surface response significantly faster than can be seen using a traditional raster scanning technique (see Fig. 5). The consortium showed two approaches, the first is a compressive mapping technique where binary, orthogonal, structured illumination patterns are projected onto the device before performing a convex minimisation procedure to recover the response map from an incomplete measurement series. The second technique more fully incorporates compressed sensing theory, which is outlined before presenting the first prototype results and this indicates a vast improvement in the time needed to observe strong features in the response map compared with both the previous technique, and the raster method. Critical to this technique is the concept that it will always require fewer measurements than a raster scan method, if there are no significant differences in implementation between the two, which would result in an increased time per measurement.

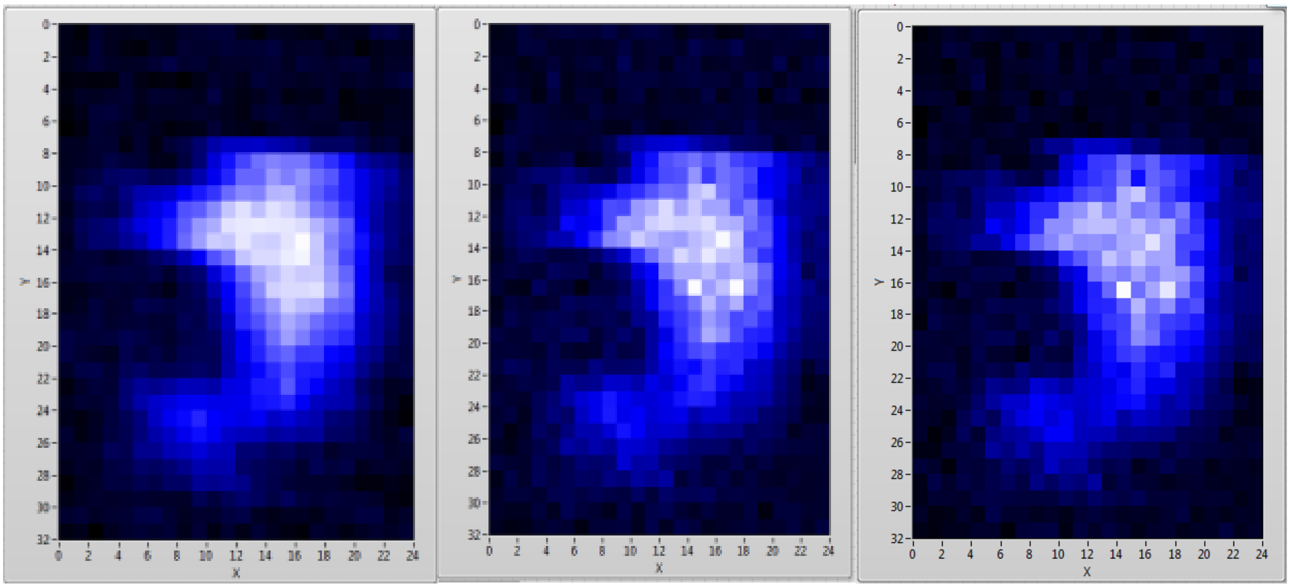

Figure 5: A comparison of the reconstruction of the spatial response of the photovoltaic when defined using only the Left: 1 % and Middle: 0.5 %, most significant coefficients in the Discrete Cosine Transform domain. For comparison purposes the image on the Right shows the recovered spatial response map of the PV when measured using a raster technique with the same configuration.

VSL has developed a SR facility based on a supercontinuum laser. This supercontinuum laser replaces the conventional lamps in the setup. With this light source VSL achieved several orders of magnitude higher monochromatic power, extending the applicability of the SR method to larger solar cells and to mini-modules. The use of a supercontinuum laser as a high-power broadband source in a SR facility is beyond the state-of-the-art.

The total uncertainty, especially of non-Si solar cells, has been reduced by the implementation of a Fourier-Transform-Spectroradiometer (FTS) to ensure the most accurate traceability of the wavelength of the radiation behind a monochromator. A reduction of the wavelength uncertainty from 0.3 nm to less than 0.05 nm was obtained, even if the bandwidth of the monochromator is more than 10 nm. The validation was performed against an external HeNe-laser.

This was performed in two steps. First, the alignment and wavelength scale of the FTS was checked as the *internal* HeNe-interferometer could be misaligned and this could lead to the wrong wavelength scale. For validation, the centre wavelength of an *external* stabilized HeNe-laser is determined using the FTS.

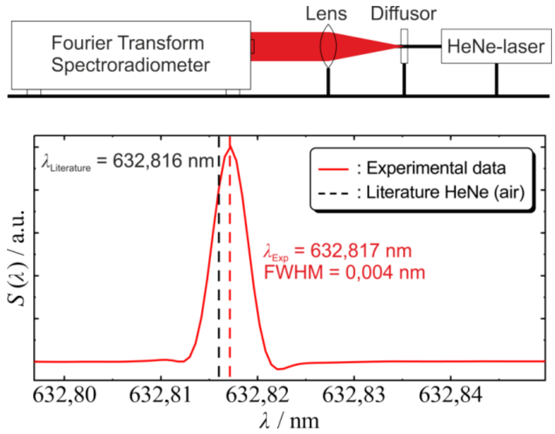

Figure 6: Top: The experimental setup for validating the wavelength scale of the FTS; Bottom: The measured peak, and its centre wavelength, of the external HeNe-laser relative to the literature value.

Figure 6 shows the experimental setup as well as the resulting FTS spectrum. The measured centre wavelength of 632.817 nm deviates from the literature value by only 0.001 nm. Note that the wavelength value used considers the refractive index of standard air. According to the full width at half maximum (FWHM) of the HeNe peak of 0.004 nm and a typical natural linewidth of the HeNe-laser in use of < 0.002 nm, the spectral resolution of the FTS can be estimated to be < 0.003 nm. In conclusion a standard uncertainty of $u(\lambda_{FTS})$ < 0.004 nm (k = 1) was assigned to the wavelength scale of the FTS. Since this uncertainty is only related to the internal HeNe laser alignment, this wavelength uncertainty contribution should in principal be independent from the chosen entrance optics.

In a second step, the FTS is used for the calibration of the centre wavelength of the other light sources, especially the output of a monochromator. A typical wavemeter cannot be used for this purpose as a wavemeter can only measure radiation with a narrow FWHM of less than 1 nm or even less than 0.1 nm, but behind the monochromator the radiation has a FWHM of up to 10 nm. The setup was built and an uncertainty analysis was performed. In conclusion three major uncertainty contributions were quantified leading to the following uncertainty budget:

Radiometric calibration	u(λ_rad)	< 0.020 nm
Wavelength calibration	u(λ_WL)	< 0.023 nm
Short term stability	u(λ_stability)	< 0.030 nm
Total	u (k=1)	< 0.043 nm

The aim for this upgrade to have a wavelength uncertainty of U(λ) < 0.10 nm was successfully met and with an additional safety margin.

In order to take the direction of the (direct and diffuse) light into account, the PV devices can now be measured for their angular dependence. This is important, if an indoor calibrated solar cell is to be used outdoors, because neglecting the angular dependency can cause errors of up to 1 % due to the diffuse blue light from all directions. On cloudy days, this effect can increase the error to up to 10 %, if no correction is performed. PTB could extend its portfolio by offering the measurement of the angular dependence of solar cells. There have already been several official calibrations made for stakeholders from outside of this EMRP project.

In detail, the primary calibration facility for reference solar cells, with the capability to measure optical losses in dependence of the spectrum and angle of incidence of PV devices, such as reference solar cells and mini-modules with active areas of up to 156 mm² x 156 mm², was improved. After a comprehensive characterisation of the setup and measurement method, it was possible to derive a detailed measurement uncertainty budget for the angular dependent spectral responsivity measurement. Measurement results, of the angular dependent spectral responsivities were obtained for a diversity of different PV devices. Depending on the device strong differences in the responsivities were observed particularly in the UV and IR wavelength regions, for varying angles of incidence. The measurement results obtained with the primary setup were validated in a comparison against a broadband facility and this provided a fixed lamp spectrum. The impact of an angular dependent spectral mismatch problem was outlined. Finally, the significance of the PV devices azimuthal symmetry for angular dependent PV device characterisation was shown. Furthermore, based on this characterisation method a variety of investigations, regarding the impact of diffuse light components on high accuracy PV device performance measurements and energy rating, are now feasible.

PTB also significantly extended its calibration service portfolio to the end user community by covering the primary calibration of the short circuit current of 6” reference solar cells and reference mini-modules, with an uncertainty of <0.8 %. This will enable the industry to improve the optimisation of their products.

In addition to these scientific highlights the measurement capabilities for linearity, the temperature coefficient, and the angular dependence of solar devices were significantly improved by PTB, INTA, JRC, LNE, NPL, VSL, TÜV Rheinland, REG(FhG), REG(LU) and REG(ISFH).

Objective 3: The measurement uncertainty for the absolute measurement of the natural and simulator irradiation conditions, spectrally and angularly resolved, will be reduced. The upper limit of the measured wavelength will be extended from 1050 nm to 2000 nm.

The current state-of-the-art reference cells used to calibrate various PV device technologies are based on crystalline silicon material. However, silicon material has a limited spectral response (about 300 nm to 1100 nm), which results in a spectral mismatch when used to calibrate PV devices made from different materials with extended spectral responses beyond that of silicon. Spectral properties, linearity and device stability depend not only on the material used, but also on the cell technology and structure, which has a major impact on these properties. The limitations of such reference devices for the indoor calibration of PV devices contribute further to the resulting uncertainty in device efficiency determination. A scientific publication about this topic was submitted for review and an announcement was performed in the IEC TC82 working group about this topic in order to start a new work item proposal about this topic within the follow up EMPIR JRP 16ENG02 PV-Enerate. A further step in reducing the main measurement uncertainty component has been performed by more accurately determining the distance between the light source and the detector by the implantation of an optical confocal displacement sensor.

When using a pulsed solar simulator special care must be taken for non-linearity effects. The calibration of the array spectroradiometer that is used for pulsed sun simulator spectral irradiance measurement should be performed according to the following procedure:

- Linearity calibration including dynamic range and time integration linearity
- Wavelength scale calibration
- Spectral irradiance scale calibration using spectral irradiance lamps

Linearity calibration is important to ensure accurate measurements as there are large differences in the irradiance level between calibration measurements and sun simulator measurements.

The work for this objective was performed by LNE, INTA, JRC, PTB and REG(FhG).

Objective 4: The spectrally and angularly resolved measurements of solar devices will be validated by comparison with integral measurements. Primary traceability and harmonisation of indoor/outdoor characterisation methods will be established through a NMI level intercomparison.

This objective provides the ability to develop a precise and realistic energy based metric. Not only has the detector, e.g. the solar device, had to be angular resolved. Equally import is the angular resolved measurement of the sky radiance. For this reason, a “Sky scanner” was built that contains three spectroradiometers with a tube as entrance optic and that can be rotated hands-free to all directions of the sky and partly even to the ground to include albedo effects. The “Sky scanner” was a beyond the state of the art development as until now satellite data have been used for determining irradiance conditions.

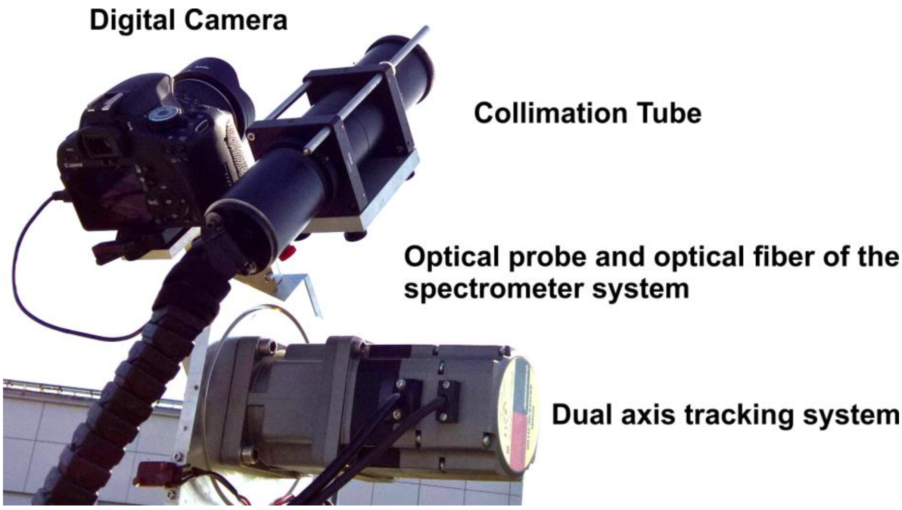

Figure 7: Picture of the new outdoor sky scanning facility. The picture shows a collimation tube (slope angle of 1° and an opening half-angle of 2.5°) as a probe for the spectrometers and a two axis sun tracker. Additionally, a camera is mounted. The camera was equipped with a wide-angle lens that takes pictures of the sky to document the sky cover. Three array-spectroradiometers are used to measure the spectrum. The spectrometers are equipped either with a Si-, an InGaAs- or an ext. InGaAs-detector, which have been previously calibrated against a standard lamp and spectral lamps. This allows a traceable measurement of the solar spectrum from 220 nm up to 2150 nm.

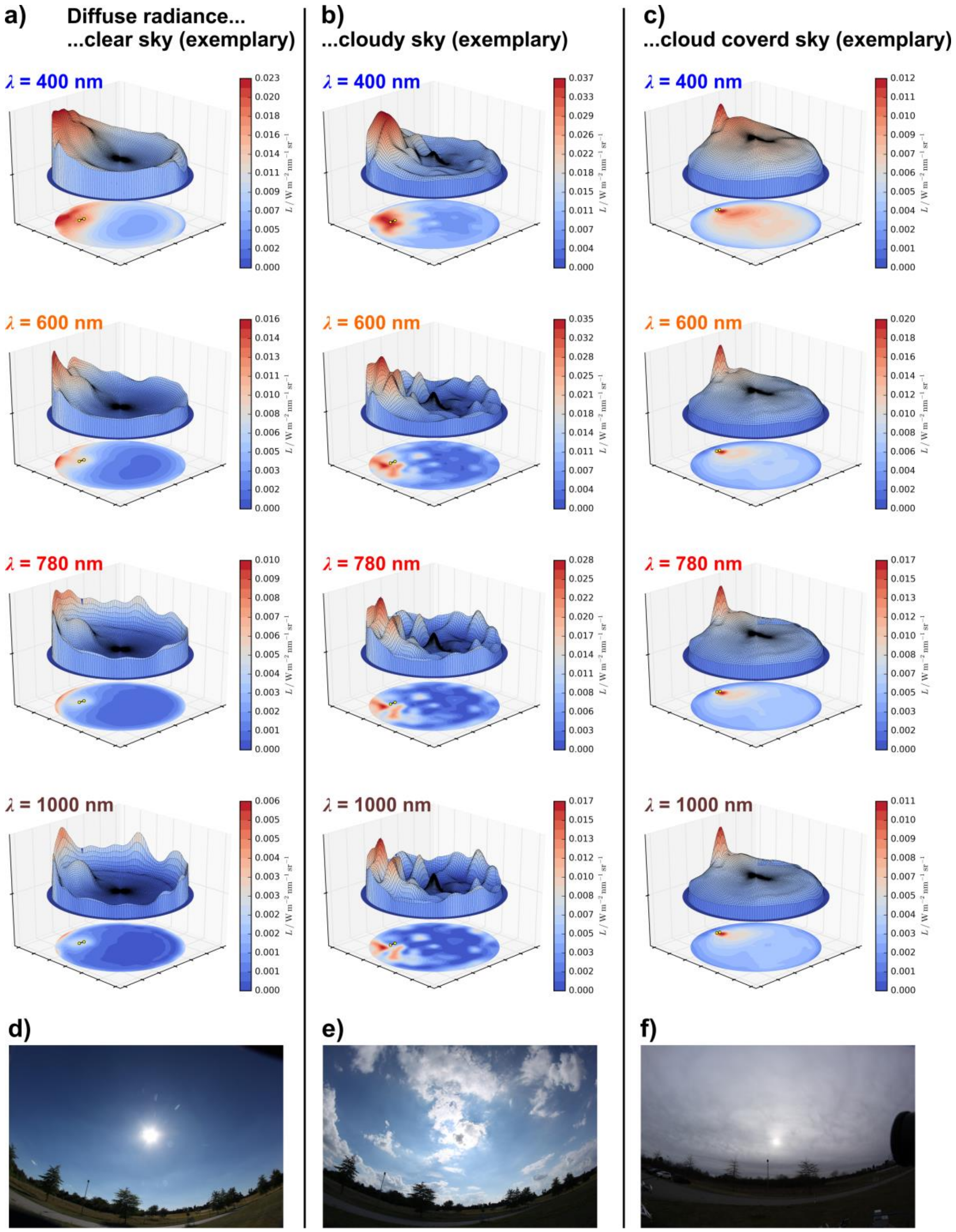

Figure 8: Results of the sky scanning. Radiance distributions at λ = 400 nm, 600 nm, 780 nm and 1000 nm for a a) clear sky, b) cloudy and c) heavily clouded day. d)-f) Documentation pictures of the cloud cover for each sky scanning measurement.

PTB has developed a fully automated outdoor facility (see Fig. 9), combining the sky scanner with the calibration capability for solar cells. With this facility, the short-circuit current of different types of solar cells and the corresponding cosine-weighted solar spectra have been measured. Here the results of a calibration are shown for the filtered Si solar cell against a Si solar cell on a clear sky day. The calibration is evaluated with the data sets that were obtained in order to compare the DSR indoor calibration value for the I_{STC} with the short circuit current determined in outdoor conditions. These calculations led to a final deviation of 0.25 % with an uncertainty of 1.5 % (k = 2).

Figure 9: Picture of the new outdoor facility. In the centre of the picture you can see the solar cells mounted on a two axis sun tracker. The solar cells are mounted on water cooled Peltier elements. On the left-hand side, a cosine-corrected probe is mounted for three spectroradiometers, which uses the data from the sky scanner.

The respective standard IEC 61853-4 including the climate data sets with the irradiance conditions to be used for the calculation of the standardised yearly yield was mainly written by the PhotoClass consortium (mainly JRC with support from REG(LU), TUV Rheinland, PTB and SUPSI) and it has been published as a committee draft for voting.

Objective 5: New reference devices will be developed for an accurate SI traceable calibration process from the cell to the solar park. In addition, procedures for their application will be developed.

The aim of this work was to develop new PV reference devices that exhibit a device stability of better than 0.1 %, and which provide a wider coverage of operating spectral range and linearity.

The optimisation covers two main parts. The first one is the optimisation of the solar cell inside the housing. Various cell structures have been optically and electrically investigated to evaluate their use as reference devices. The manufacturing process of the selected cell technologies have been investigated in each step of the process chain. Reference wafers have been processed and characterised within each process step in order to reveal and prevent artefacts and contamination.

Cells with a dielectric passivation layer on the back are used which feature an improved infrared response. The change from p-type to n-type Si base material has improved the stability of the reference cells by enhancing the tolerance against contamination, which could cause degradation during operation. The quality assurance has been improved by the frequent use of different processes and cell characterisation techniques.

Criteria could be defined from these characterisation measurements to guarantee the relevant reference cell properties.

For reference cells with an infrared filter the process chain has been simplified to ensure higher process yield using a simpler cell structure. The front side metallisation was improved to ensure higher stability due to better contact. The metallisation on the back surface was improved for better solderability. The cutting process of the cells from the wafer was evaluated.

The second part of the optimisation covers the housing. The housing and the manufacturing process of the encapsulation was revised and the electrical wiring was improved. For the shunted version of the device (outdoor version) a plug for the electrical connection and an additional service plug was introduced which can simplify device quality assurance. The T-sensor position and mounting was evaluated and improved. In addition, the thermal conduction through the housing was enhanced by a factor of 2. The filtering for spectral adaption was investigated and possibilities to improve the adaption were evaluated. Optimised filtered cells can now be provided.

An accelerated stability test using UV irradiation at PTB showed the high stability of the new WPVS reference solar cells.

VTT characterised and provided 2 reference modules and 4 reference mini-modules selected with optimised performance.

A successful field test of all of the reference devices was performed by the implementation of a round robin. The participants were PTB, VSL, LNE, JRC, NPL, SUPSI, TÜV Rheinland, REG(FhG), REG(LU) and REG(ISFH).

Figure 10: Optimised reference solar cell.

All these improvements are included in the available version of the WPVS reference solar cells. Using these stable reference devices, a measurement intercomparison between eight participants was performed. The new reference devices of Fraunhofer ISE (REG(FhG)) are commercially available and were already bought by several European stakeholders.

4 Actual and potential impact

Dissemination of results

31 presentations were given at scientific conferences, including 16 presentations at the European PV Solar Energy Conference and Exhibition (EU PVSEC) 2014, 2015, 2016 and 2017.

A paper describing the project's results won a Best Paper Prize at the 11th Photovoltaic Science Application and Technology conference, and the Student Award during the 31st European PV Solar Energy Conference and Exhibition.

The consortium organised an international workshop at SUPSI (University of Applied Sciences of Southern Switzerland) where the results of the project and the new energy rating standards were presented to around 100 international participants, including international policy makers and stakeholders.

The project also hosted a three-day training course at JRC on best practice for PV measurement procedures. The training course was attended by members of the scientific community from higher education and public research organisations and was highly praised by the participants.

The work of the consortium has led to 30 publications in proceedings and peer-reviewed journals, including Solar Energy, Energies, IEEE Journal of Photovoltaics, and Measurement. A contribution to the largest PV conference worldwide, the EU-PVSEC, was selected for publication in a special edition of the renowned PV journal Progress in Photovoltaics (for comparison only 20 out of more than 1100 contributions were selected).

Three good practice guides were written, and are available from the project website:

1) Photoclass good practice guide - angle of incidence measurements
2) Photoclass good practice guide – linearity measurement
3) Photoclass good practice guide – temperature coefficient measurement

Contribution to standards

Three standards for the standardised energy yield estimation of solar devices for different climate zones were developed and submitted by the consortium:

- IEC 61853-2 Photovoltaic module performance testing and energy rating – Part 2: Spectral responsivity, incidence angle and module operating temperature measurements (objective 2)
- IEC 61853-3 Irradiance and weather data for all important climate zones (objective 1)
- IEC 61853-4 Mathematical model to combine the measurement methods with irradiance and weather data to a standardised yearly energy yield

The first of these standards is fully published, and the second two successfully passed the 'Committee Draft for Voting'.

These new energy-rating standards are based on much more realistic weather and irradiation conditions than the former standard test conditions. The application of the new standards should significantly reduce the previous financial uncertainty in energy yield estimations, which was 500 million Euros per year.

Early impact

- New temperature coefficient measurement facilities and revised measurement uncertainties were set up at the JRC in Ispra, Italy (objective 2).
- New PV performance measurement facilities and revised measurement uncertainties were set up at the JRC in Ispra, Italy (objective 2).
- New PV device linearity measurement facilities were set up at the JRC in Ispra, Italy (objective 2).

- New measurement of PV power rating (IEC 61853-1) measurement facilities and revised measurement uncertainties were set up at the JRC in Ispra, Italy (objective 2).
- Measurement facilities for angular dependency (integral and wavelength dependant) of the short circuit current of solar cells at PTB. Measurements have been requested and performed for one calibration laboratory and one NMI (CENAM in Mexico), both outside of the project (objective 3 and 4).
- A new generation of reference solar cells are commercially available at FhG in Germany, and measurements for calibration laboratories, NMIs (including PTB), manufacturers and PV engineering companies have been performed using these (objective 5).

Future potential impact

The work of this project to develop and standardise models for energy rating, and the associated measurement procedures and facilities, mean that a much more realistic determination of the standardised climate zone dependant yearly energy yield can be achieved.

5 Website address and contact details

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