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Harmonized procedures for long-term energy yield measurements and performance evaluation of PV modules in outdoor conditions

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ABSTRACT

As yet, procedures for long-term tests of photovoltaic modules in outdoor conditions have not been considered by international standardization committees. Although many laboratories perform long-term PV outdoor tests, a commonly agreed and standardized procedure has so far not been adopted. The European Distributed Energy Resources Laboratories' (DERlab) approach to filling the gap of international standardization has led to the development of a basic protocol that complies with European and international standards, while providing specific common guidelines and procedures for measuring the energy yield of PV modules for at least one year in outdoor conditions. The DERlab procedures for long-term PV module testing are described in this paper, and the range of analyses that can be derived from the data, such as module degradation, are discussed. The paper also presents the DERlab approach to measuring module performance in outdoor conditions, which can be used to complement energy-rating methods suggested in international standards. DERlab has created consistent measuring procedures that allow the direct comparison of the energy yield of solar modules taking into account the site-specific factors of different locations and varying climatic conditions, as well as a maintenance guideline.

Why perform long-term outdoor tests on PV modules?

Among the issues affecting technical certification and reliability, the main parameter of interest concerning PV modules is the energy yield. For this reason, long-term PV module tests are carried out to give site-specific reports about the module performance. Long-term outdoor measurements are not repeatable like laboratory measurements, but they allow a direct comparison between the energy yields of different module types under varying weather conditions. In the interests of customers and of the industry, many PV laboratories perform long-term outdoor tests, but, because of the lack of international standardization, these tests are partly performed in accordance with internal procedures. The European Distributed Energy Resources Laboratories (DERlab) has reacted to the lack of standardization by setting up a protocol that provides specific requirements and guidelines for performing PV outdoor tests over a period of at least one year.

Another aspect to consider is the modelling of energy yield. There are numerous performance models and algorithms in existence, both commercially available (such as PVSyst [1] and the Sandia Array Performance Model [2]) and proprietary. The output of these models often drives technical and financial decisions regarding the modules to use in a system, and whether a system is worth financing. Performance data from controlled outdoor module testing, at both the module level as described in the DERlab proposal, and at the systems level, are highly useful for validating model algorithms and energy yield predictions [3].

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Outdoor measurements in international standardization

Statements about outdoor testing for various purposes can be partly found in international standards. The standards for design qualification and type approval of terrestrial PV modules – IEC 61215 for crystalline silicon and IEC 61646 for thin film – suggest an outdoor exposure of the test modules to an irradiation of 60kWh/m^2. The purpose of the outdoor test is to "make a preliminary assessment of the ability of the module to withstand exposure to outdoor conditions and to reveal any synergistic degradation effects which may not be detected by laboratory tests" [4,5].

Although the exposure time is very short for detecting long-term effects like degradation, the standards require no visible damage at the end of the exposure time; in addition, the drop in maximum output power may not exceed 5% of the measured value before the test, and the leakage resistance has to fulfil the same criteria as in the initial measurements. Furthermore, these standards allow the determination of the electrical power under standard test conditions (STC) (irradiance intensity: 1000W/m^2, module/cell temperature: 25°C, irradiation spectrum: AM 1.5 in accordance with IEC 61215) and the nominal operating cell temperature (NOCT) under natural sunlight [5]. However, the realization of these requirements in outdoor conditions is quite difficult and for most regions not practicable during the whole year. That is why most PV laboratories use a module-scale solar simulator. Procedures in natural sunlight are also given, to some extent, in

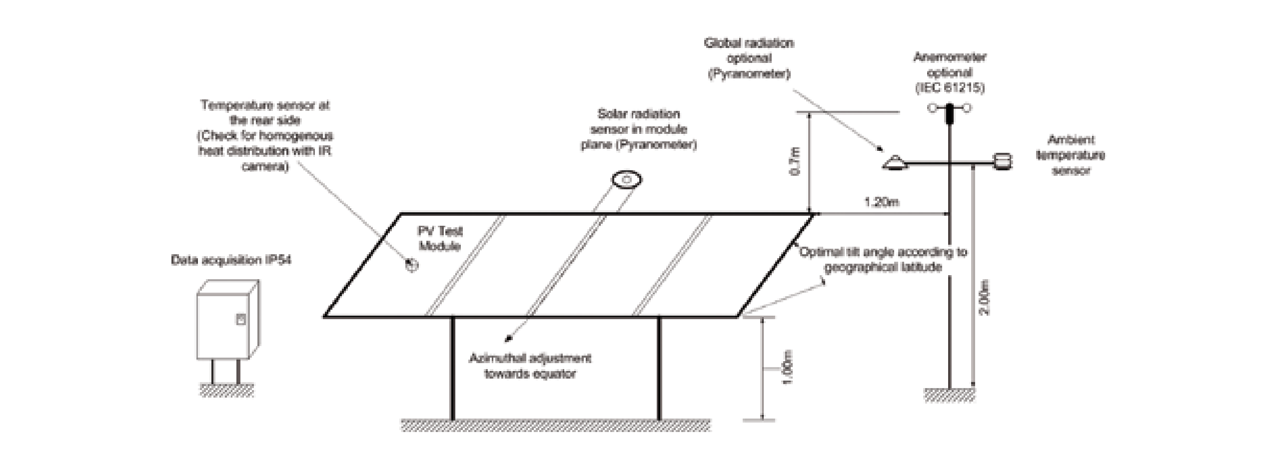

Figure 1. Typical plan of a standard testing setup [11].

the photovoltaic devices standards IEC 60904 Parts 1–10 [6].

As the procedures proposed in these standards are performed for various reasons, the requirements for measurement equipment and environmental conditions are specific to the performance of individual tests, and so the requirements can differ from test to test.

IEC 61853 provides guidelines on energy rating by calculating the energy yield on the basis of PV module characteristics and parameters, including irradiance, temperature, incident angle and spectral distribution. The calculations are performed using either given standard days or site-specific measured data. In the evaluation of site-specific data, the effort required of measurement equipment is enormous. In particular, the direct beam radiation G_{dir} and the solar spectrum $E(\lambda)$ have to be measured among many other parameters. Compared to real outdoor measurements, the energy rating according to IEC 61853 leads to reasonable results [7,8]. IEC 61853 Part 1 (of 4) was published in January 2011.

IEC 61724 provides measurement procedures for the overall performance of PV systems and suggests a data analysis presentation [9]. In contrast to this monitoring standard for PV systems, DERlab is focusing on test procedures for measuring the energy yield under various meteorological conditions for a specific PV technology, or under the same conditions for different PV technologies, without taking into account the performance of the power electronics.

The DERlab technical guidelines on long-term measurements

The common DERlab technical guidelines on long-term PV module outdoor tests were developed to harmonize outdoor testing procedures for energy yield measurements among different PV test laboratories. The document is meant to complement the above-mentioned standards by stipulating further criteria. It provides basic guidelines and procedures for the placement of measurement equipment and the requirements for the testing location as well as for the accuracy of the measurement equipment in measuring the energy yield of PV modules for at least one year. The DERlab technical guidelines do not address data evaluation and analysis.

Site-specific measurements imply natural influences on the tested modules and measurement equipment from flora and fauna, seasonal effects and regional climate. During the development of the test protocol, the maintenance of modules to remove impurities was (and still is) a controversial topic. As a justification for not cleaning the modules during the testing period, some laboratories suggest that the composition of the surface and framing of the module influences its self-cleaning mechanisms.

The DERlab document is clear in proposing a maintenance plan. It suggests that a general survey of the apparatus, and the cleaning actions of the measuring instruments and tested modules, as well as the calibration intervals for the various sensors used, should be noted for documentary and evaluation purposes.

The equipment for basic energy yield measurements records ambient temperature, module temperature, and irradiance in the module plane (plane of array); current and voltage measurements are taken at the maximum power point (MPP). The recording time interval is documented, with 15 seconds being a compromise between precision and applicability.

In accordance with ISO 9060 [10], irradiance is measured using a secondary standard pyranometer in the module plane. The sensitivity over a wide range of the solar spectrum allows a direct comparison of different module technologies to be made to a high accuracy. In the case of measurements of a single module technology, a reference cell of the same photovoltaic technology satisfying the IEC 60904-2 or IEC 60904-6 criteria is acceptable (see Fig. 1).

> "One important issue in the course of taking long-term energy yield measurements is the adequate operation availability of the transducers and data-logging apparatus."

Initial experiences with taking measurements in accordance with DERlab guidelines

An indicative data analysis and visualization graphs are now presented and briefly discussed. One important issue in the course of taking long-term energy yield measurements is the adequate operation availability of the transducers and data-logging apparatus to avoid gaps that increase the uncertainty of the annual energy yield. An availability of at least 98% to 99% of the potential operation time per year of the PV module should be aimed for.

Long-term measurements include the continuous recording of meteorological and electrical data for at least one year. These data are required for modelling and for checking the module performance and energy yield in different conditions, such as low light or oblique illumination. Information about seasonal and long-term effects such as degradation can be given on the basis of these measurements.

In the following figures the data originate from a polycrystalline silicon module with an STC nameplate power output of 220Wp. The PV module is installed facing south in an optimal inclination angle of 30° at the Centre for Renewable Energy Sources and Saving (CRES) facilities in Pikermi. Raw

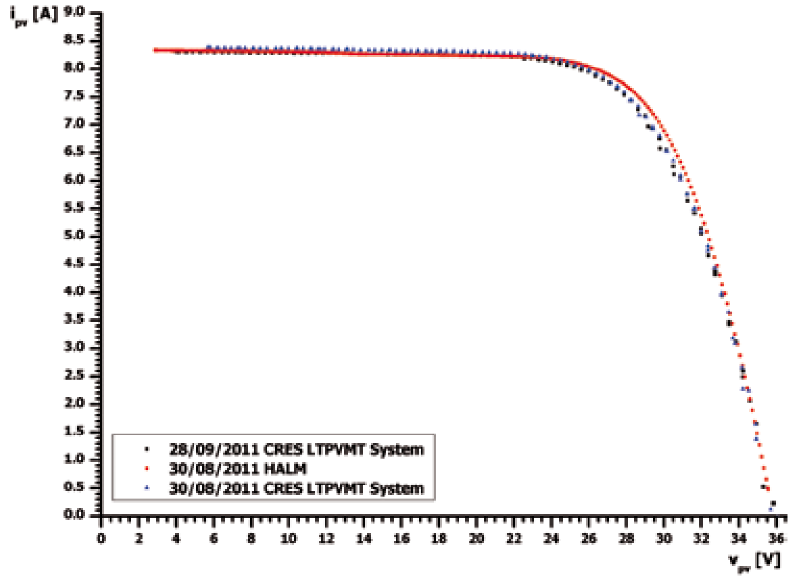

Figure 2. Polycrystalline PV module *I-V* curves, corrected for STC in accordance with IEC 60891.

	HALM PV-CT-F1 PV Curve Tracer (30/08/2011)	CRES LTPVMT System (30/08/2011)	CRES LTPVMT System (28/9/2011)
I_{sc} [A]	8.333	8.331	8.317
V_{oc} [V]	35.566	35.939	35.838
V_{mp} [V]	28.12	27.391	27.871
I_{mp} [A]	7.661	7.640	7.566
P_{mp} [W]	215.44	209.28	210.88
FF [%]	72.69	69.89	70.75
η [%]	13.21	12.83	12.93

Table 1. *I-V* curves of a polycrystalline Si PV module, corrected for STC using IEC 60891.

measurements taken every 15 seconds are averaged to 1-minute values. All parameters are calculated and presented for the time period between September 24th 2011 and October 8th 2011.

Once each month, a clear day with light wind is selected; the raw data of the *I-V* curve are retrieved and these data are then corrected for STC. The electrical output characteristics are determined in accordance with IEC 60891 [12]. This month-by-month analysis provides information about the module degradation over time.

Fig. 2 shows three *I-V* curves of the same polycrystalline Si PV module. Two *I-V* curves were taken on the first day of the test (August 30th 2011) using different photovoltaic curve tracers, with the objective of comparing the two outputs. The third *I-V* curve shown was taken one month later. All curves have been corrected for STC using the standard IEC 60891 to facilitate direct comparison.

More specifically, the *I-V* curves were taken on August 30th 2011 (at the beginning of the test) using: 1) a HALM PV-CT-F1 PhotoVoltaic Curve Tracer; and 2) an electronic load and analysis system that was designed and realized by CRES for long-term PV module testing. The third *I-V* curve was taken one month later, again using the CRES system, in order to investigate the PV module performance under the same conditions (STC). All the data were corrected to STC in accordance with the IEC 60891 procedure; the test results are summarized in Table 1.

Fig. 3 presents the PV module output power, as well as the field test meteorological conditions for a 15-day period (between September 24th 2011 and October 8th 2011), with 1-minute averaged

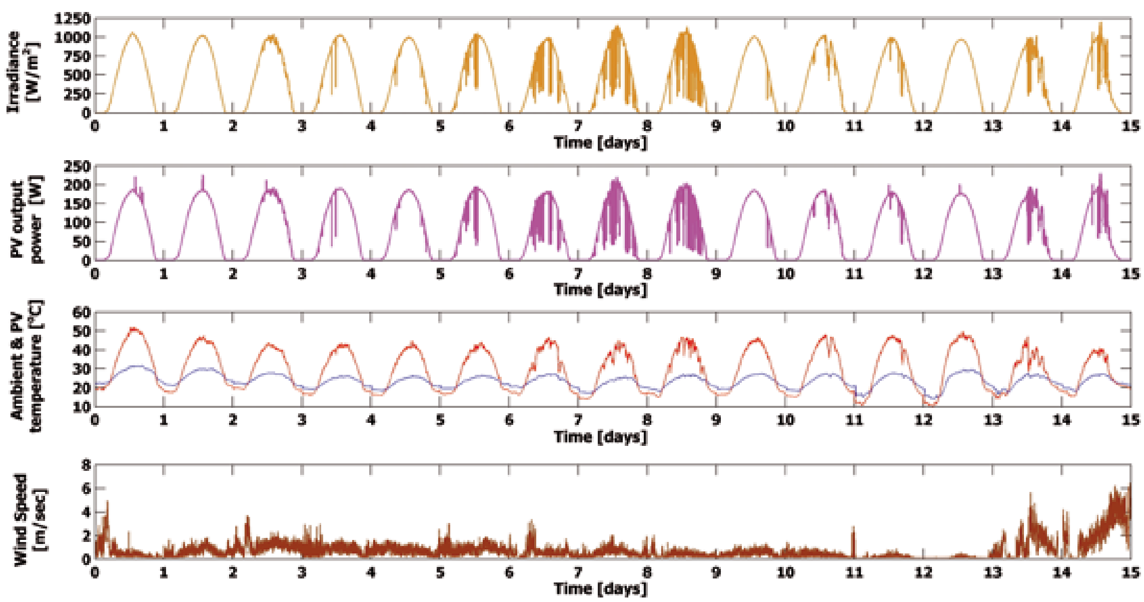

Figure 3. PV module output power and meteorological conditions analysis.

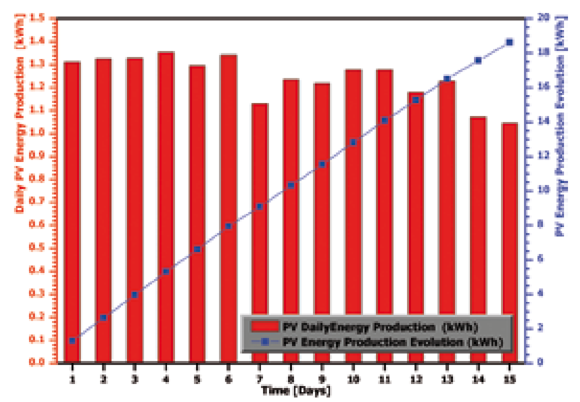

Figure 4. PV module daily and cumulative energy production.

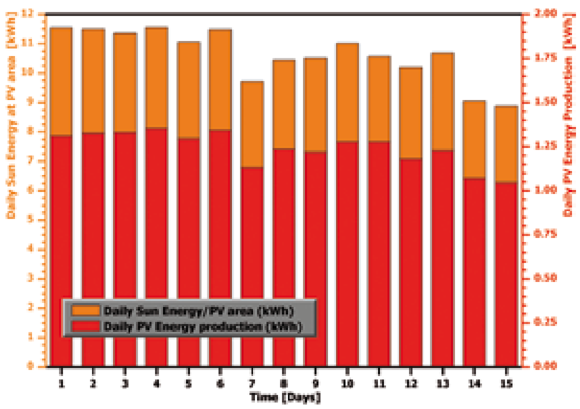

Figure 5. PV module daily energy production and average daily efficiency evolution.

recorded values and calculated parameters. A day is assumed to start at 05.00 and end at 21.00; the CRES electronic recorder system is shut down for the rest of the time.

The daily and cumulative energy production of the PV module is shown in Fig. 4; the module's daily energy production, relative to the available sun irradiation in the PV module plane, is shown in Fig. 5.

Fig. 6 illustrates the variation of the PV module efficiency during a 1-day period (day 13 in Fig. 3), with clear skies and light wind. The efficiency, as well as the PV module temperature, is plotted as a function of the irradiance for levels between 200W/m^2 and 1000W/m^2. Note how the PV module efficiency changes along the horizontal axis, going from left to right, corresponding to the morning, midday and afternoon hours.

Model validation – real-time analysis of modelled and measured performance

Performance monitoring should involve measuring the power and energy output of the PV module or system, as well as intermediate variables such as V_{mpp} and module temperature. Throughout the test period, it is recommended to regularly compare these data with the output of performance prediction tools used by industry and the financial community [1,2], given the observed weather and site conditions. An example of this approach for a system that performed well is shown in Fig. 7 in the form of a scatter plot of measured versus predicted DC power. Both approaches, either comparing modules with each other as outlined above or comparing the performance output with a model, allow performance problems to be identified. However, a comparison with an accurate model has the advantage of aiding in pinpointing the cause of the problem, which is valuable

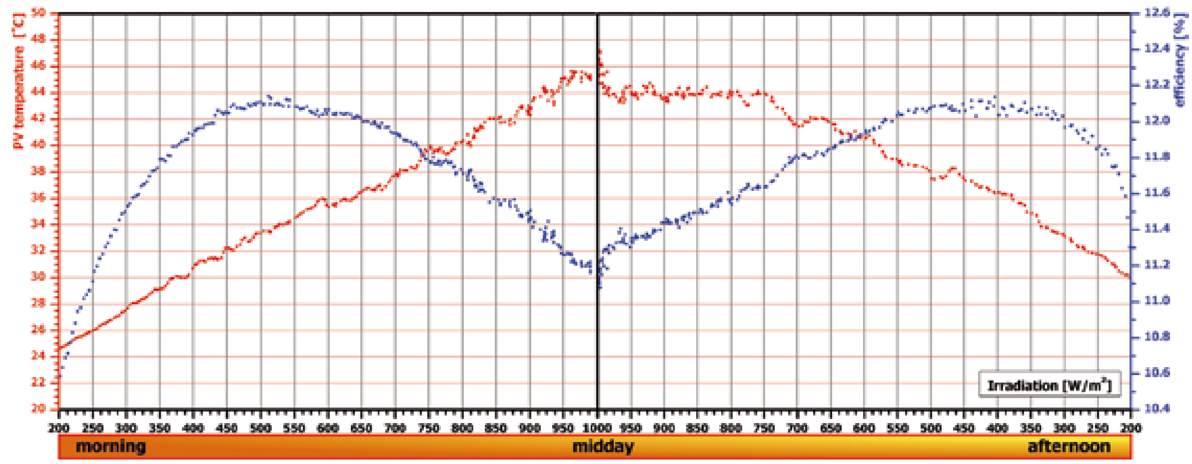

Figure 6. PV module efficiency variation during a clear day with light wind.

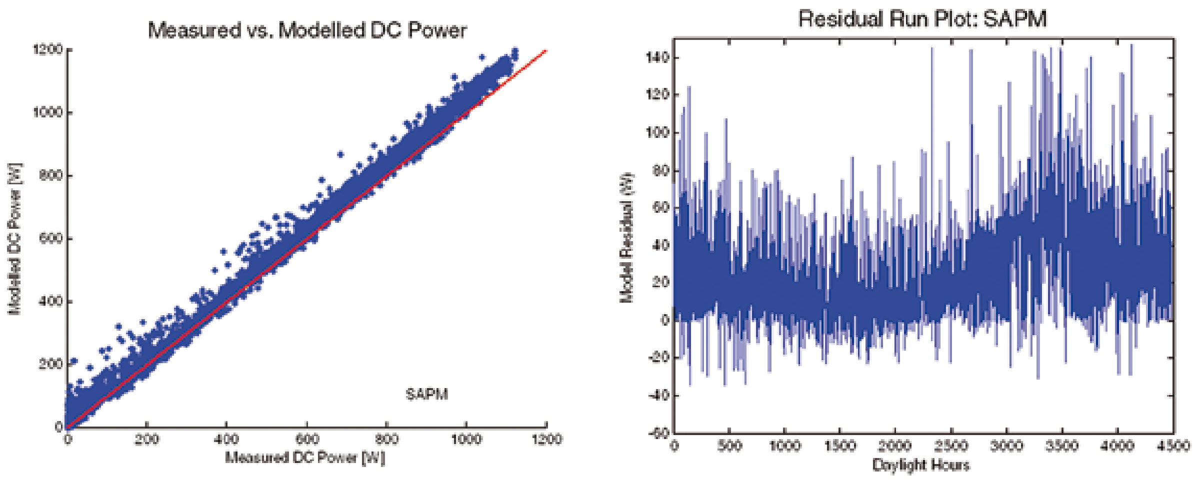

Figure 7. Left: a comparison of measured and modelled hourly power output from a PV system that is performing as expected. Right: a plot showing residuals (modelled – measured) as a function of time [3].

information for assessing overall system performance.

Module degradation

Long-term outdoor testing is necessary for measuring module degradation rates. There are many challenges associated with accurately measuring degradation rates, particularly over a short time period. Module P_{mpp} degradation rates of between 0.02%/year and 4%/year have been measured [13]. Most modules fall in the 0.5%/year to 1.5%/year range. Even with high-accuracy measurement equipment, it is a challenge to determine degradation rates over periods of less than three years. The DERlab approach can be used over multiple years (three or more) to measure module degradation, but in this case it is important to ensure that the modules and the irradiance equipment are cleaned prior to measuring *I-V* curves and that all the data are normalized to STC.

Conclusion

The DERlab technical guidelines on long-term photovoltaic module outdoor tests contribute to the harmonization of testing procedures between institutes performing photovoltaic outdoor tests. Outdoor tests that are currently running and being carried out according to the aforementioned guidelines within the DERlab members' laboratories will be evaluated after a one-year time period. The experience gained from these tests will then further contribute to the harmonization of photovoltaic long-term outdoor testing. This paper has presented some examples of data evaluation with regard to performance analysis and model validation. As these data evaluations require a highly accurate database, the DERlab approach aims at increasing data accuracy by establishing comprehensive and well-defined testing procedures. With 21 partner laboratories at the moment, DERlab is working on pre-normative research in the field of distributed energy resources (DER) with a focus on smart grids integration and testing of DER technologies.

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References

[1] Mermoud, A. & Lejeune, T. 2010, "Performance assessment of a simulation model for PV modules of any available technology", *Proc. 25th EU PVSEC*, Valencia, Spain.

[2] King, D.L. et al. 2004, *Photovoltaic array performance model*, Sandia National Laboratories SAND Report No. SAND2004-3535 [available online at http://www.sandia.gov/pv/docs/PDF/King%20SAND.pdf].

[3] Stein, J.S. et al. 2010, "A standardized approach to PV system performance model validation", *Proc. 35th IEEE PVSC*, Honolulu, Hawaii, USA.

[4] IEC 61646, 2008, Thin-film terrestrial photovoltaic (PV) modules – "Design qualification and type approval".
[5] IEC 61215, 2005, Crystalline silicon terrestrial photovoltaic (PV) modules – "Design qualification and type approval".
[6] IEC 60904 Parts 1–10, 1998–2011, Photovoltaic devices.
[7] IEC 61853-1, 2011, Photovoltaic (PV) module performance testing and energy rating – "Part 1: Irradiance and temperature performance measurements and power rating".
[8] Poissant, Y., Pelland, S. & Turcotte, D. 2008, "A comparison of energy rating methodologies using field test measurements", *Proc. 23rd EU PVSEC*, Valencia, Spain.
[9] IEC 61724, 1998, Photovoltaic system performance monitoring – "Guidelines for measurement, data exchange and analysis".
[10] ISO 9060, 1990, Solar energy – "Specification and classification of instruments for measuring hemispherical solar and direct solar radiation".
[11] DERlab 2011, "DERlab technical guidelines on long-term photovoltaic module outdoor tests", Reference No. 100-01.
[12] IEC 60891, 2009, Photovoltaic devices – "Procedures for temperature and irradiance corrections to measured I-V characteristics".
[13] Jordan, D.C. & Kurtz, S.R. 2011, "Photovoltaic degradation rates—an analytical review", *Prog. Photovolt: Res. Appl.*, doi: 10.1002/pip.1182.

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