HARMONISED PROCEDURES ON PHOTOVOLTAIC MODULES LONG-TERM ENERGY YIELD MEASUREMENTS AND PERFORMANCE EVALUATION UNDER OUTDOOR CONDITIONS

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ABSTRACT: Procedures on photovoltaic (PV) modules long-term tests under outdoor conditions have so far not been adopted by international standardisation committees. Notwithstanding the current practices applied within different laboratories with respect to PV outdoor tests, a commonly agreed and harmonised procedure has not been detailed so far. DERlab's approach to fill in standardisation activities gaps led to the development of technical guidelines providing specifications for PV modules energy yield measurement under outdoor conditions, related testing setup and measurement equipment accuracy requirements. DERlab recommendations offer consistent measurement procedures allowing direct comparison of PV modules energy yield under varying environmental conditions, as well as guidelines for module and measurement equipment maintenance. These guidelines complement recommendations contained in current international standards. This article describes the DERlab guidelines and also discusses options of data processing and key insights that can be derived from the measurements (e.g. module degradation, efficiency or energy yield).
Keywords: PV module, system performance, a-Si/µ-Si, energy yield.

1 INTRODUCTION

A parameter of interest related to the evaluation of PV modules technical qualification and reliability is the energy yield. Long-term PV module tests are carried out to support statements on site-specific PV module performance. Compared to the laboratory measurements, long-term outdoor measurements are not repeatable. Nevertheless they allow a direct comparison between the energy yields of different types of modules under varying environmental conditions. PV testing laboratories currently perform long-term outdoor tests according to internal rules derived from their own current practices. International standardization committees have not adopted guidelines on this topic so far. DERlab's approach to fill in the gaps of standardization activities led to the development of commonly agreed guidelines which provide requirements for performing PV outdoor tests for at least one year [1]. This paper presents recent results on long-term module performance testing using the DERlab technical guidelines.

The modelling of energy yield is an important aspect to be considered. There are numerous commercially available performance models and algorithms such as PVSyst [2] and the Sandia Array Performance Model [3]. The output of these models enables technical and financial decisions regarding the choice of modules to use within a system. Performance data from controlled outdoor module testing at the module level, as described in the DERlab technical guidelines, and at the system level are highly useful for validating modelling algorithms and energy yield predictions [4].

2 THE DERLAB TECHNICAL GUIDELINES

The DERlab technical guidelines on long-term photovoltaic module outdoor tests are developed to harmonise outdoor testing procedures for energy yield measurements among PV module testing laboratories.

The guidelines are complementary to and based on international standards and provide instructions on the test setup, requirements for the testing location, accuracy requirements for the measurement equipment, as well as instructions for modules and measurement equipment maintenance. Data evaluation and analysis are outside the scope of the DERlab technical guidelines.

Site specific measurements imply natural influences from flora and fauna, seasonal effects and regional climate on the tested modules and measurement equipment. During the development of the test protocol, maintenance of modules to remove dirt was and still is a controversial topic.

The DERlab guidelines offer a maintenance plan. The proposed protocol provides a general survey on the required equipment, cleaning actions for the measurement instruments and for the modules under test as well as calibration intervals for the various sensors.

The measurement equipment for energy yield measurements consists of ambient temperature, module temperature, irradiance in the module plane (plane of array) and current and voltage measurements at the Maximum Power Point (MPP). Optionally, global horizontal irradiance and wind speed can also be measured. The recommended recording time interval is 15 seconds, which is the best compromise between precision and applicability. Figure 1 shows the general test setup for long-term module performance. Note that the PV modules are installed in an optimal tilt angle related to the geographical latitude of the test site.

The irradiance on the PV array is measured with a thermopile secondary standard pyranometer according to ISO 9060 [5]. The sensitivity over a wide range of the solar spectrum enables a direct comparison of different module technologies with a high accuracy. In case of measurements of only one module technology, a reference cell of the same photovoltaic technology fulfilling the IEC 60904-2 or 60904-6 criteria is accepted.

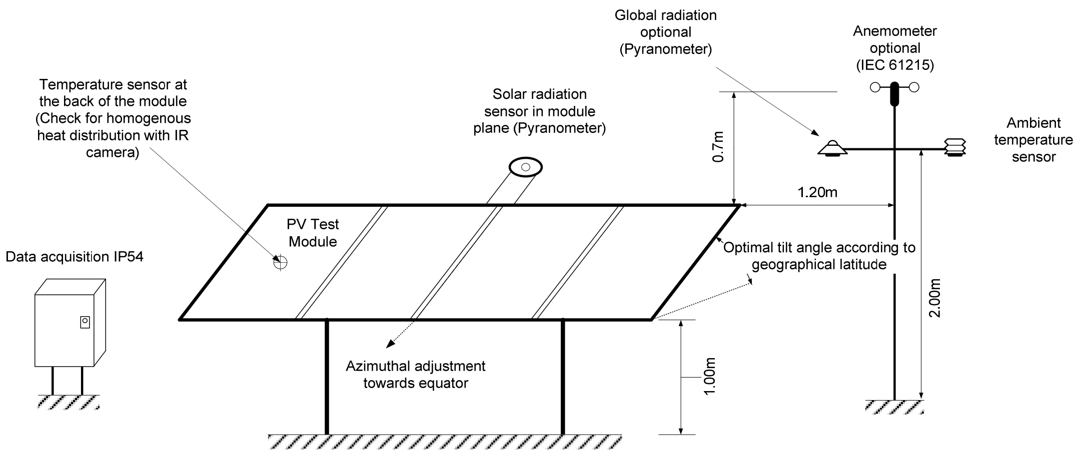


Figure 1: Exemplary setup of a standard testing location [1]

3 MEASUREMENT RESULTS ACCORDING TO DERLAB GUIDELINES OBTAINED AT CRES OUTDOOR FACILITIES (GREECE)

A poly-Si and a micromorph thin-film tandem technology module (a-Si/μ-Si) have been under test for one year according to the DERlab technical guidelines [1]. The data in the following figures originate from the month of June 2012, with label power output of 220Wp and 120Wp respectively. The PV modules are installed at CRES facilities in Pikermi-Greece (37°59.57’19’’N, 23°55.38’ 60’’E) in tilt angle close to latitude optimum of 30° facing south. The raw measurements are taken every 15 seconds and then they are averaged to 1 minute values. Both modules are stabilized. A once-a-month cleaning procedure was followed according to DERlab technical guidelines. Figure 2 presents the field test meteorological conditions (irradiance at PV modules plane, PV module temperature, ambient temperature, wind speed), as well as electrical data of the poly-Si module (such as the power at Maximum Power Point (P_{MP}), the short-circuit current (I_{SC}), and the open circuit voltage (V_{OC}), for three days in June: the coldest (01/06/2012), the hottest (13/06/2012) and the day which was characterized by the highest daily irradiance level (16/06/2012). The data recording period is starting at 05:00AM and ends at 21:00PM. For the remaining time interval of the day, the CRES electronic recorder system is shut down. Considering that the irradiance level is almost the same for the coldest and hottest days the differences between the electrical characteristics come from the different PV module temperature values. The shape of the irradiance and other parameters prior to 8:45 AM is due to shading from a building element and it is prominent during late spring, summer and early autumn months when the sun rises behind the plane defined by the PV modules.

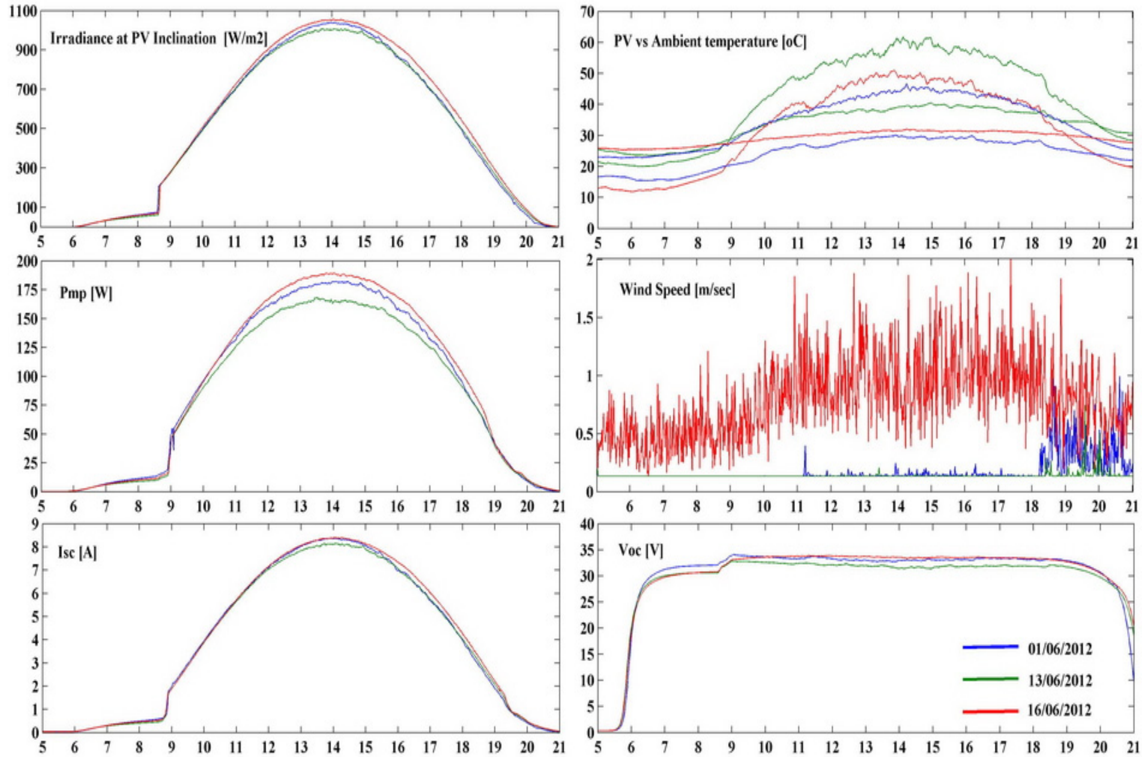


Figure 2: Poly-Si module electrical characteristics and meteorological conditions for 3 days in June at Pikermi, CRES.

In order to compare the poly-Si and a-Si/μ-Si modules energy production (during the specific summer month and the specific location), each modules' energy production is normalized to a DC PV array of $1kW_{p\text{-label}}$. In other words, the energy production values are independent of the inverter topology, the Maximum power point tracking (MPPT) accuracy and the balance of system characteristics (e.g. cable diameter or material). The P_{MP} values for each module are calculated by sweeping the PV modules I-V curves. More specifically, every 15 seconds the PV modules short-circuit current, open circuit voltage as well as the current and voltage at the MPP (I_{MP} and V_{MP} respectively) are measured and recorded. Thereafter the power at the MPP is calculated by multiplying the I_{MP} and V_{MP} values. Between two successive measurements the PV modules are forced to work near to the MPP for high irradiation levels, in order to allow the PV module to have a temperature profile and aging degradation similar to an actual system installation.

Table I summarizes the average daily production as well as the measured monthly production of each module for June 2012, while the last row presents the calculated monthly DC production for normalized $1kW_{p\text{-label}}$ PV arrays.

Table I: June 2012 Energy production statistics

	Poly-Si	α-Si/μ-Si
Average daily energy production (per single module) [kWh]	1,401	0,840
Monthly cumulative energy production (per module) [kWh]	42,03	25,2
Monthly cumulative energy production (for $1kW_{p\text{-label}}$ PV array) [kWh/kWp]	191	210

According to Table I, the a-Si/μ-Si module energy productivity is almost 10% higher compared to the corresponding poly-Si PV module (for the normalized DC PV array comparison) during the specific summer month, the specific location and the specific module manufactures.

Figure 3 shows the PV modules daily and cumulative energy production as well as the available sun irradiation at the PV module plane for a time period of one month (June 2012). It is worth mentioning that the irradiance level deviation is small for the majority of June days, while the normalized energy production of the a-Si/μ-Si module is higher than that of the poly-Si module every day of the month.

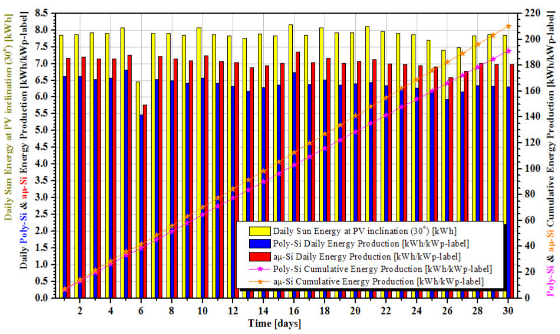


Figure 3: Normalized poly-Si and a-Si/μ-Si daily and cumulative energy production relative to the available sun irradiation at the PV module plane

It is also worth noticing that almost all days of the month of June are dominated by clear sky conditions. At this point it should be emphasized that the specific results obtained can be applied only for the aforementioned environmental meteorological conditions.

Additionally, Figure 4 illustrates the daily energy production ratio of the two different technology PV modules (poly-Si versus a-Si/μ-Si daily energy production ratio normalized on a kWp-label base), as well as the daily ambient average temperature and daily sun energy at the PV modules' plane. It has to be clarified that the average temperature values are calculated for 16 hours duration, according to the predefined testing day period. By studying this figure, we conclude that during the specific hot month the a-Si/μ-Si module energy production decreases less than the Poly-Si technology module. This trend is confirmed by the lower a-Si/μ-Si temperature coefficients (poly-Si P_{MP} temperature coefficient: -0.5%/K and a-Si/μ-Si P_{MP} temperature coefficient: -0.29%/K according to the module manufactures). The daily energy production variation tends to be limited for lower average ambient temperature days (days 1-5).

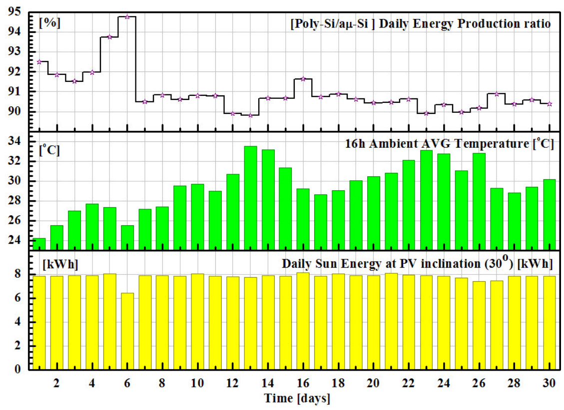


Figure 4: Poly-Si and a-Si/μ-Si modules daily energy production and meteorological conditions analysis for the month of June, 2012

Figure 5 presents the variation of the a-Si/μ-Si and poly-Si module temperatures with respect to the ambient temperature for June 6th, 2012. By studying this figure, it is clear that the temperature of a-Si/μ-Si module is lower compared to Poly-Si module, while the temperature difference becomes more pronounced in the first morning hours and in the afternoon.

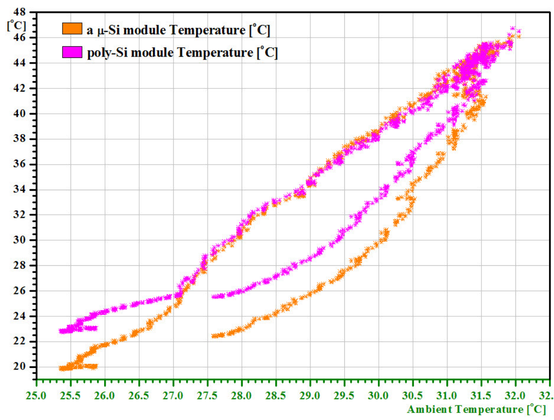


Figure 5: Poly-Si and a-Si/μ-Si module temperatures

compared to the ambient temperature for June 6th, 2012

The a-Si/μ-Si cells are encapsulated within a glass/glass structure without frame, while the poly-Si cells are laminated with glass only in the front side and have an aluminium frame. Effects which may result from the different module constructions have to be further analysed.

Figure 6 shows the average daily efficiency of both PV modules under test, with respect to the daily irradiation value at PV plane. According to this figure the poly-Si module average daily efficiency presents higher variation compared to the a-Si/μ-Si module for the same irradiance level. Beyond that, the real a-Si/μ-Si module average daily efficiency is closer to the module STC efficiency (8.28% calculated at STC), since the difference does not exceed 1%. In case of poly-Si module, the daily difference fluctuates between 1.39% and 2.14% from the 12.83% STC calculated value. The calculated STC efficiency for the poly-Si and a-Si/μ-Si module is based on the average value of six and ten month's continuous test period, respectively. In more details, a clear and low wind day is selected every month, and the raw data of the I-V curve (for irradiation level above 850W/m^2) are retrieved and corrected for Standard Test Conditions (irradiance of 1000 W/m², estimated solar spectrum of AM 1.5 global and PV module temperature of 25°C) according to IEC 60891. By using the above data, CRES estimated the PV module performance at STC.

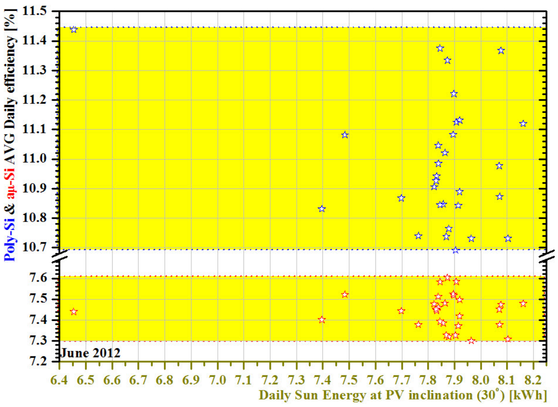


Figure 6: Poly-Si and a-Si/μ-Si modules average daily efficiency evolution for the month of July, 2012

Finally, by using the raw measurements of June 2012, Figure 7 illustrates the a-Si/μ-Si module temperature and P_{MP} values with respect to the corresponding solar irradiance at the PV module plane.

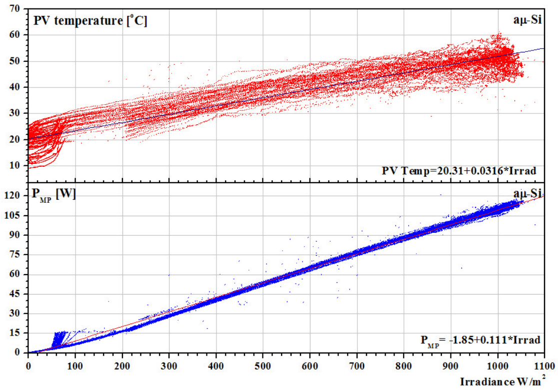


Figure 7: a-Si/μ-Si module temperature and P_{MP} values with respect to the corresponding sun irradiation at PV module plane

The above figures, as well as more statistics results can be used to model the PV module productivity and efficiency under various meteorological conditions, to examine the module behaviour under low irradiance conditions, to identify performance problems, to identify the NOCT (Nominal Operating Cell Temperature), and to monitor temperature coefficients and module performance changes over time.

4 LONG-TERM MEASUREMENT RESULTS ACCORDING TO DERLAB GUIDELINES OBTAINED AT NTUA OUTDOOR TESTING FACILITIES (GREECE)

Long-term performance tests were performed on two polycrystalline silicone (poly-Si) modules in order to verify their performance on a specific location and under varying weather conditions and states of operation. The tests were performed during the period of the 1st of August 2011 to the 31st of July 2012 in the facilities of NTUA in the Electrical Energy Systems Laboratory in Athens-Greece. The modules were obtained from the same manufacturer and from the same production line, with nameplate peak power output of 220Wp and 13.4% efficiency at STC. The modules where installed facing south and at the optimal angle of 30 degrees, on the grey gravel cement roof of the laboratory, with minimal obstructions from buildings and vegetation. The module bottom edge is 0.5 meters from the ground. Especially during the summer months, dust developed on the modules' surface. A once-a-month cleaning procedure was followed which kept the surface of the modules at a relatively clean state throughout the year. The meteorological and electrical data were measured using a data acquisition system developed by Papendorf Software Engineering, namely the 'SOL.Connect' cabinet, which uses an ISET-mpp meter measuring card for each module. Meteorological measured data consisted of the irradiance at the PV module plane, the PV module temperature in the centre of the module and at a top corner, and the ambient temperature. Electrical measured data consisted of the power at the Maximum Power Point (MPP), the short-circuit current and the open circuit voltage. Raw data was recorded every 15 seconds and averaged over 1 minute.

In order to measure the power output of the modules and their efficiency at STC within outdoor field tests, two methods are applied: the "standard" method and the "northern" method suggested in [6] according to the availability of data. In the standard method a bin of values of irradiance close to 1000W/m^2, namely 995 to 1005 W/m^2 is selected and values of output power at the Maximum Power Point (MPP) and respective values of module temperature are recorded throughout the year. By determining the trend line, an estimation of the output power at conditions close to STC can be calculated, as seen in Figure 8. With the use of this method, the calculated power output for the module was 217.0Wp, with a 1.43% difference from the 220Wp label power output at STC.

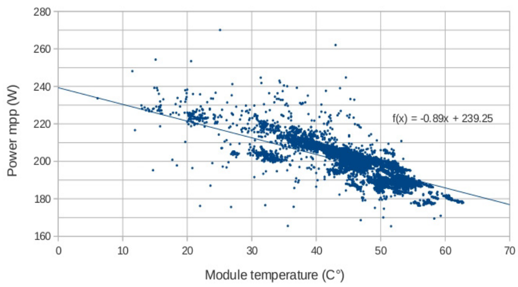


Figure 8: Derivation of peak power output at STC with interpolation of power at MPP vs. module temperature at irradiance values close to 1000W/m^2

In the "northern" method, a bin of values for the module temperature close to 25°C is recorded, namely a temperature interval between 24°C to 26°C, and values of output power at the Maximum Power Point and respective values of irradiance at module plane are recorded throughout the year. By determining the trend line, an estimation of the output power at conditions close to STC can be calculated as shown in Figure 9. With the use of this method, the calculated power output for the module is 220.23Wp, with a 0.04% difference from the 220Wp label power output STC.

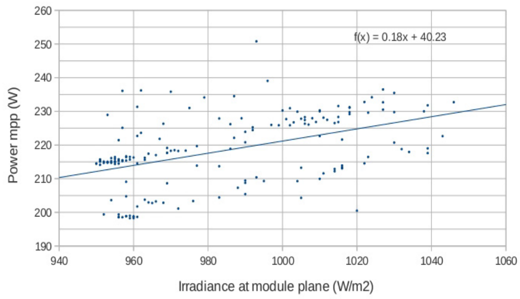


Figure 9: Derivation of peak power output at STC with interpolation of power at MPP vs. irradiance at module temperatures close to 25°C

An estimation of the PV module's efficiency at STC can also be measured by collecting data in a bin of 24°C to 26°C of the module temperature and by calculating the efficiency through related values of irradiance close to 1000W/m^2 and of power at MPP, as seen in Figure 10. The module efficiency value of 13.4% was calculated with the use of the interpolated trend line, with a 0.22% difference from the 13.4% label efficiency of the manufacturer at STC.

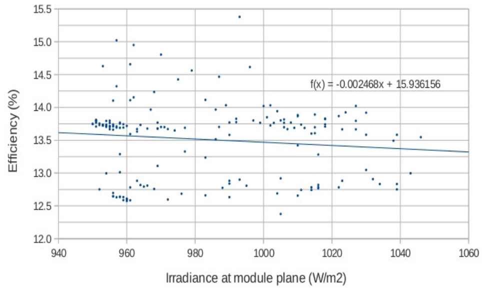


Figure 10: Derivation of module efficiency at STC using values close to 1000W/m^2 and module temperatures close to 25°C

Furthermore, the annual energy yield of the poly-Si module was measured at the location of Athens-Greece, using the PV.Analyzer software tool of Papendorf Software Engineering GmbH and the related database where data had been stored for the time period from August 2011 to July 2012. The resulting annual energy yield is 398.78 kWh and the annual normalized power output is 1.812 kWh/kWp for the "standard" method and 1.837 kWh/kWp for the "northern" method.

The monthly variation of the energy yield and of the specific module output is shown in Figure 11.

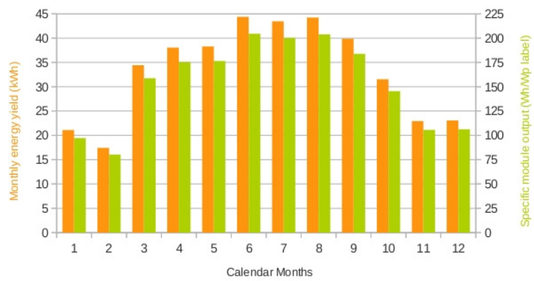


Figure 11: Energy yield and specific module output for every calendar month from August 2011 to July 2012

In conclusion, the efficiency of the poly-Si module under different weather conditions was investigated, namely during a sunny winter day (January 13, 2012), a sunny summer day (July 20, 2012) and a partly cloudy summer day (August 19, 2012). As seen in Figure 12, during the sunny winter day the module's efficiency is much closer to that stated by the manufacturer at STC since the module is operating at lower temperatures, closer to 25°C.

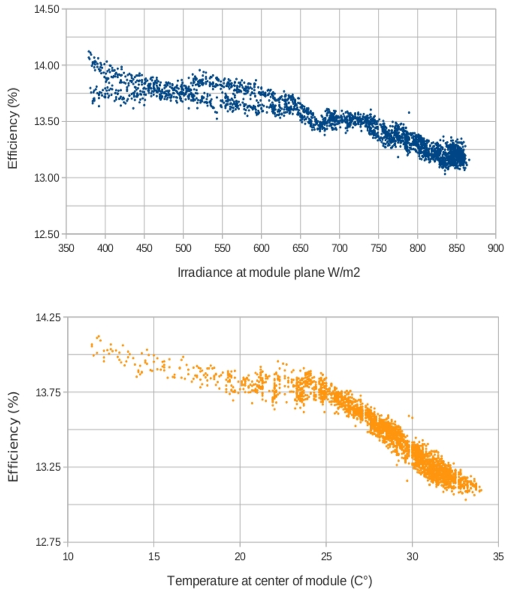


Figure 12: Efficiency vs. irradiance and module temperature during a sunny winter day

On the other hand, during a sunny summer day, Figure 13, the module's efficiency is lower than that stated by the manufacturer at STC since the module is operating at higher temperatures. As it can be observed, the module's efficiency increases with rising irradiance levels until late morning (e.g. 9:30) and then varies close to a constant value with respect to variations in the module's temperature. This occurs until early evening (e.g. 17:30) when irradiance levels start to drop again and the module's efficiency decreases. These variations in efficiency during the morning and evening hours are due to the fixed positioning of the PV modules in relation to the position of the sun which result in high differences in air mass (AM) values in comparison to the rest of the day. The module temperature has a reduced influence on the efficiency of the PV module during these times of the day, and mostly follows the power production during the day in combination with the ambient temperature.

On the other hand, the variations of efficiency during the early morning hours occur less during the sunny winter day of Figure 12, due to an obstruction from a nearby mountain, which does not allow their effect to be recorded**.** These shadings have a minimum effect on the measurements and occur during 20 minutes in the early morning of winter days (mainly December, January and February). The mountain is located on the east side of the station, has a height of 500m and its peak is at distance of 3.35 km from the measurement station. This gives an angle of 8.5 degrees to the horizon.

Finally, during a partly cloudy summer day the module's efficiency is retained at levels close to those stated for STC conditions since module temperatures are lower than in a sunny summer day, Figure 14. High scattering of single measurements can be observed in Figure 14 due to the difference in time response between the pyranometer and the power output of the PV module, under rapidly changing irradiance conditions, such as those observed during a partly cloudy day.

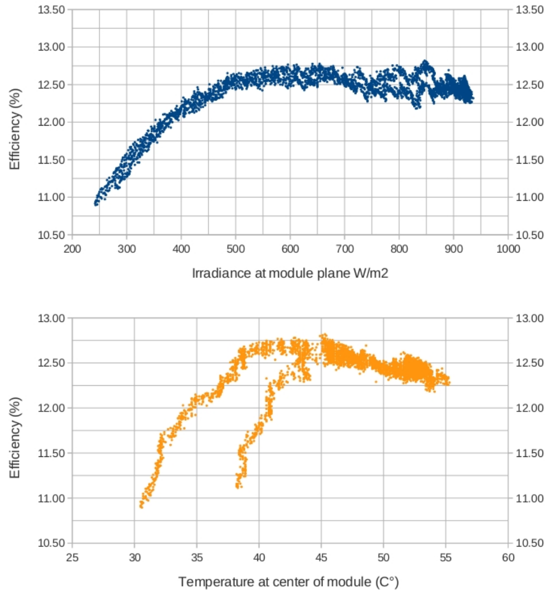


Figure 13: Efficiency vs. irradiance and module temperature during a sunny summer day

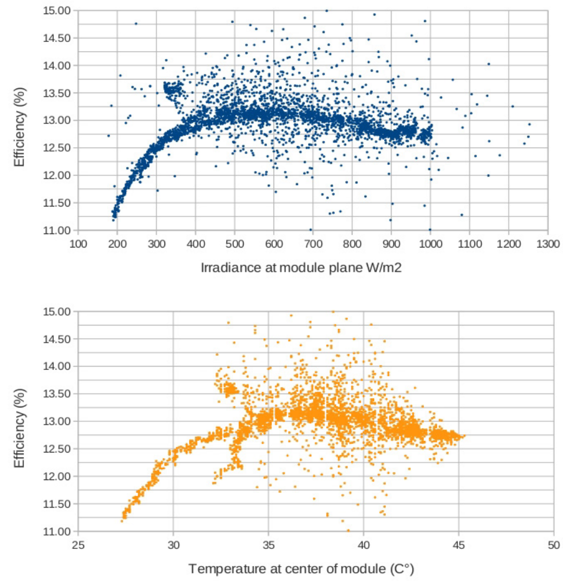


Figure 14: Efficiency vs. irradiance and module temperature during a partly cloudy summer day

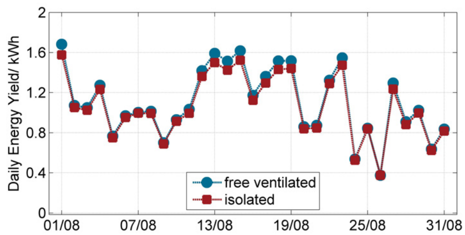
5 LONG-TERM OUTDOOR MEASURMENT RESULTS ACCORDING TO DERLAB GUIDELINES OBTAINED AT IWES - SYSTEC TESTING FACILITIES (GERMANY)

The long-term outdoor measurement was performed at IWES since 2011. The testing setup is located in Kassel, Germany (51°18'N, 09°26'E). For the PV module performance evaluation, two identical mono-crystalline modules (mono-Si) have been taken into account with different module configurations:

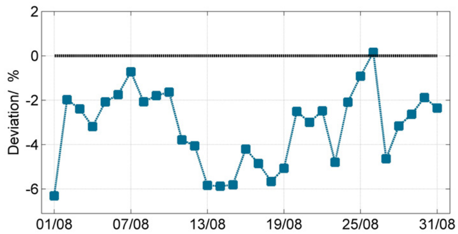
- free ventilated PV glass-backsheet module
- isolated PV glass-backsheet module with thermal insulation on the backside.

Extruded rigid polystyrene foam, so called XPS, has been used as thermal insulation. This isolated PV module configuration is one outcome of the research activity in the FP7 European project – SOPHIA, so called Insulated Test Condition (ITC) [7]. It describes the worst-case scenarios of the PV modules in Building Integrated Photovoltaic (BIPV) applications. In the evaluation process, the free-ventilated and isolated PV modules will be considered at best and worst case scenarios of BIPV module applications, respectively. The evaluation was carried out based on measurements from 1st August 2012 to 31st August 2012. The modules' specifications are as follows: power output of 245W with temperature coefficient of power output (α-P_{MPP}) at -0.45%/K. For the electrical data measurement, the ISET-mpp meter is used to measure the IV-curves of both modules. All meteorological and electrical data together with the module temperature were recorded every 1 minute.

Figure 15 represents the daily energy yields (a) and corresponding deviations (b) between both module configurations over one month. At higher daily energy yields, representing sunny day, the deviations are also higher. At lower daily energy yields, representing cloudy day, the deviations are lower. Therefore, it can be evaluated that the higher the energy yield is, the higher the obtained deviation.



(a)



(b)

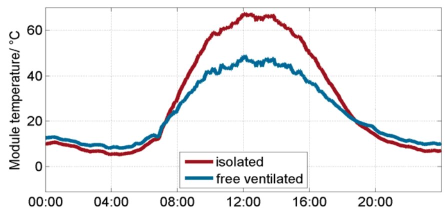
Figure 15: Daily energy yields (a) and daily deviations (b) between free-ventilated and isolated PV modules

Table 2 gives the maximum daily energy yield on the 1st August a minimum daily energy yield on the 26th August together with monthly energy yield. At the same time, it describes the deviation of maximum and minimum daily energy yield together with monthly energy yield between both module configurations. It can be seen that the maximum deviation could be reached over 6.31% at maximum daily energy yield day, while it is only 0.15% at minimum daily energy yield day. The deviation of monthly energy yield is 3.66%. Therefore, it can be further evaluated that the deviation of both module configuration becomes higher for the location with higher solar irradiation.

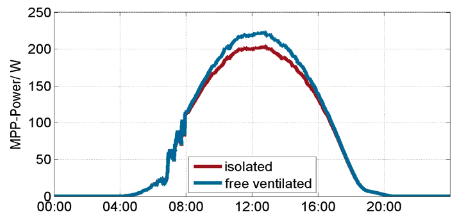
Table II: Maximum daily energy yield and monthly energy yields together with the related deviations of free-ventilated and isolated PV modules

Energy yield (kWh)	Free-ventilated	Isolated	Deviation (%)
max–daily	1,6821	1,579	-6,31
min-daily	0,3759	0,3753	-0,15
monthly	34,26	33,01	-3,66

In order to evaluate the PV module performance, Figure 16 gives measurement results on a full sunny day of both module configurations on May 25th 2012: the operating temperature (a) and the power output (b). The operating temperatures and the temperature difference of both module configurations are correlated to the solar irradiation. At noon, the operating temperatures are nearly 70°C and 50°C with related power outputs of 200 Wp and 225 Wp for isolated and free-ventilated PV modules, respectively. This represents a maximum deviation of power output of about 11%.



(a)



(b)

Figure 16: Operating temperature (a) and power output (b) of free-ventilated and isolated PV modules on a sunny day (May 25th 2012)

Figure 17 (a) depicts the plot of the operating temperatures of both PV module configurations over solar irradiation. It can be seen that they increase with the increase of solar irradiation and reduce with the lowering of the solar irradiation. The temperature difference of increased and reduced operating temperature of the isolated PV module is higher compared to free-ventilated PV module at certain solar irradiation due to its higher thermal capacity. Moreover, for the free-ventilated PV module the gradient of the operating temperature becomes nearly saturated at a solar irradiation higher than 800 W/m², while the gradient of the operating temperature becomes flatter for the isolated PV module at solar irradiations higher than 900 W/m². These effects are the results of the equilibrium of power input and power dissipation (via conduction, radiation and convection) of each PV module. These results can also be seen in the power output curves over solar irradiation in Figure 17 (b). For the free-ventilated PV module, the gradient of power output becomes flatter at the solar irradiation higher than 800 W/m², while for isolated PV modules it becomes flatter at solar irradiation higher than 900 W/m².

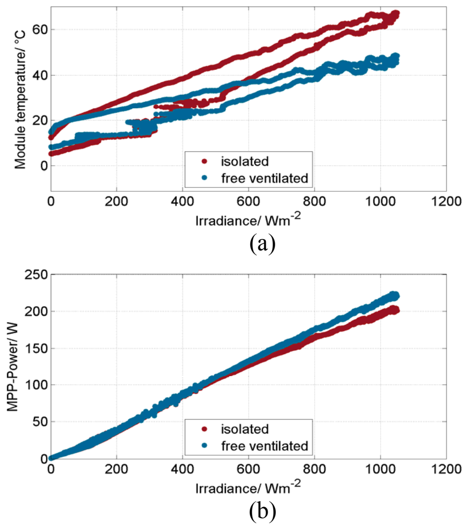


Figure 17: Operating temperature (a) and power output (b) over solar irradiation of free-ventilated and isolated PV modules

6 CONCLUSION

The DERlab technical guidelines on long-term PV module outdoor tests contribute to the harmonisation of testing procedures within PV testing laboratories. Outdoor tests results performed recently according to the aforementioned guidelines at three DERlab members' laboratories have been shown in the previous chapters, as well as exemplary types of analyses which have been derived from the measured data. The experience achieved during the tests will further contribute to the harmonisation of photovoltaic long-term outdoor testing.

This article shows examples of data evaluation concerning performance analysis and module characteristics. As these data evaluations require a database of high accuracy, the DERlab approach aims at increasing the data accuracy by setting comprehensive testing procedures and related measurements equipment accuracy.

With currently 20 member institutes, DERlab works on pre-normative research in the field of distributed energy resources (DER) with focus on grid integration and testing of DER technologies.

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