FIELD TESTING OF PORTABLE LED FLASHER FOR NOMINAL POWER MEASUREMENTS OF PV-MODULES ON-SITE

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ABSTRACT: Nominal power measurements of individual PV modules are needed to quantify the critical modules of PV plants offering lower energy production than expected. Today's state of the art procedure of shipping a small number of modules to a laboratory is time- and cost intensive and it bears the chance of accidental damage. The Portable LED Flasher (PLF) was developed to require no dismounting of the modules. The quality of the PLF was tested on three PV plants in Switzerland. Additionally, ten PV modules of each plant were measured in the certified indoor laboratory of SUPSI, resulting in a maximum deviation of 3% of the STC values. Furthermore, a round robin test on a single crystalline silicon reference module at 25°C was performed at the JRC's ESTI laboratory, the Swiss Mobile Flasher Bus and SUPSI resulting in a maximum deviation of the mean values below 1% compared to the PLF. A throughput of up to 150 modules or 500 modules respectively per day is expected and the total measurement costs are estimated to be about a tenth of the costs compared to an indoor laboratory. Module temperature measurement is crucial for a low total uncertainty. Thus, methods such as pre-shadowing of the module and approximation of cell temperature are the current focus of further improvement of the PLF measurement method.
Keywords: PV Module, Electrical Properties, Qualification and Testing, Cost reduction, Degradation

1 Motivation and Market Needs

The measurement of nominal power of PV modules is essential for the quality control of PV plants and its benefit depends highly on the costs for the measurement. Operators or owners of the plant have to apply economically feasible methods to prove insufficient STC power of module(s) for the purpose of further negotiations with the module manufacturer.

If these measurements are too expensive they may not be performed. The current state of the art procedure is to take a very small number of modules which will be measured indoors by a certified test laboratory. For these tests, the PV modules have to be dismounted from the PV plant and shipped to the laboratory, which is time- and cost-intensive and it bears the chance of accidental damage during transport or dismounting. Today, a required sample number can only be assessed if the measurement costs of each PV module are below the cost of a new PV module. This is not the case for the traditional approach of demounting a few samples and shipping them to a stationary, certified laboratory. The ZHAW developed an alternative approach by the use of the Portable LED Flasher (PLF). It is designed to measure PV modules directly on-site without the need to dismount them [1]. The PLF comprises a light engine with over 5000 LEDs to simulate the sun spectrum.

This paper reports the findings and experience of this new STC performance measurement method applied to a large set of PV modules on three different PV plants in Switzerland.

Table I: Four methods of nominal power measurements of PV modules and their dis-/advantages [1].

Measurement Method	Advantage	Disadvantage
Field Measurements under sunlight with reference cell 	• Inexpensive measurement device • No dismounting damage • Instantaneous result	• Uncertainty >5% • High fix costs at sub-optimal irradiance conditions • Temperature correction
Stationary measurement in certified laboratory 	• Low uncertainty of 1.3–3.5%	• High costs • Dismounting, Transport • Low sample number
Field measurement with light engine in car 	• Uncertainty 3–4% • Instantaneous result	• Dismounting • Temperature correction
Field measurement with Portable LED Flasher 	• Uncertainty 3–4% • Instantaneous result • No dismounting damage	• Temperature correction

2 SPECIFICATIONS OF IMPROVED PROTOTYPE

ZHAW invented the first functional model of the PLF in 2014 [2]. In a consecutive joint project, together with Electrosuisse an optimised device has been engineered. The optimised parameters and overall technical details of the new version of the PLF are shown in Table II. The major improvements compared to the first functional model comprise the weight reduction of the light engine of 40%, better spectral characteristics (Class A), higher measurement rates and flexibility due to the power autonomy (battery pack).

Table II: Technical specifications of the optimized Portable LED Flasher

Specification	**Value**
Outer dimension	2.0 m (with wheels: 2.6 m) × 1.1 m
Active optical area	2.0 m × 1.1 m
Transport dimension	1.1 m × 0.7 m × 0.6 m
Weight light engine	30 kg, with wheels: 38 kg
Spectrum	11 LED wavelengths, Class A
Illumination time	Typ. 130 ms – adjustable
Illuminance	20% higher than STC
Minimum theoretical measurement rate	10 Seconds
Power Supply	Lithium battery for 750 flashes
Temperature measurement	Either Platinum RTD or Thermocouple
Acquisition serial number	Barcode scanner
Handling and data storage	Tablet, instantaneous display of measurement result

The light engine of the PLF is divided into 18 equal LED boards comprising of 272 LEDs each. The intensity of the LEDs can be controlled individually for each sector containing approximately 32 LEDs. The spatial non-uniformity of the PLF has been determined using a crystalline reference cell and amount to 1.73%. According to IEC60904-9 the non-uniformity thus satisfies Class A.

983	993	1000	994	991	1007
982	989	1006	999	988	1000
977	1004	996	979	983	981
976	986	990	978	986	995
990	992	1001	990	987	982
985	997	1005	982	979	988
982	984	984	1003	983	989
979	986	981	990	987	991
986	999	981	1001	985	984
975	995	988	990	991	991
981	989	1005	1005	1007	1006
977	977	1006	1009	995	1009

Figure 1: Normalized irradiance of the PLF in W/m^2.

LEDs with central wavelengths of 430 nm to 940 nm are used to reflect the STC spectrum AM1.5G most precisely. The spectral mismatch is below the limit of Class A in all intervals of the spectrum.

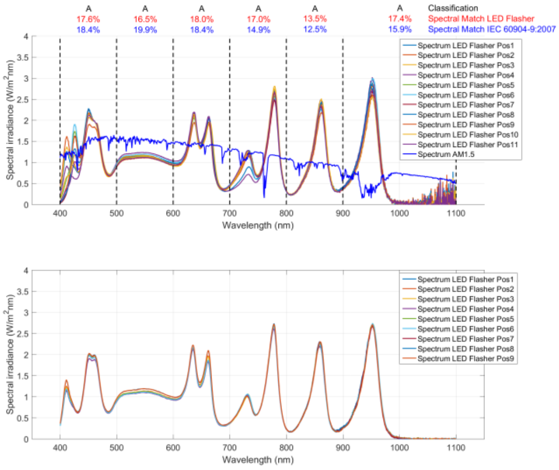

Figure 2: The spectral irradiance of AM1.5G (top, blue) and the measurements on the PLF with an Avantes AvaSpec-ULS2048 of ZHAW (top) in eleven different lateral positions in the intervals of IEC 60904-9. Bottom picture shows the spectral measurements performed with an Ocean Optics HR2000+ by ESTI in nine different lateral positions.

A major upgrade of the new version of the PLF is its flexibility regarding transport. Its light engine can be disassembled into three autonomously functional parts (See Figure 3). The possibility to transport the PLF with a station wagon has been proven in the field tests.

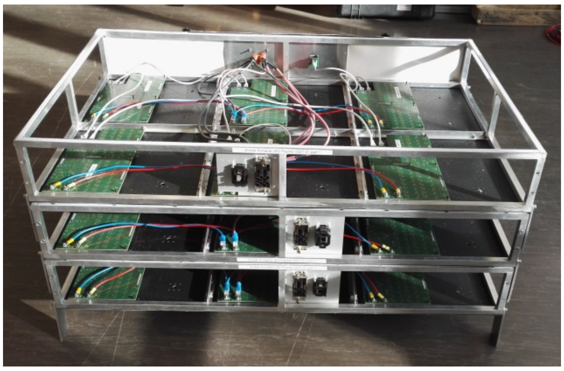

Figure 3: The light engine of the PLF disassembled and stacked ready for transport or storage.

3 ROUND ROBIN TEST WITH CERTIFIED LABORATORIES

In order to classify the uncertainty of the measurements with the PLF a round robin test with a reference module was performed. The same module was measured at the certified laboratory of SUPSI, at the certified laboratory of EU-JRC ESTI and with the Swiss Mobile Flasher Bus (SMFB) [3]. Furthermore, as part of the publicly funded project of Swiss Federal Bureau of Energy, samples of modules of three PV plants were measured by the PLF under outdoor conditions. Additionally, ten modules of each sample were shipped to the Swiss laboratory of SUPSI to compare with the results of the PLF.

To eliminate the uncertainty of temperature measurement, the PLF was installed in the indoor laboratories of ESTI during the round robin test. Immediately after measuring the reference module with the certified infrastructure of ESTI (Uncertainty P_{mpp} of 1.3%, k=2 [4]), the PLF performed the measurements on the same module. It could be shown that the difference of the averaged measurements with the PLF to ESTI, SUPSI and SMFB is below 1%, see Figure 4.

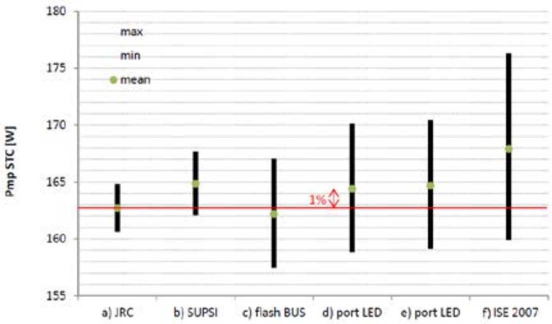

Figure 4: Results of the round robin test on the crystalline reference module (95% confidence interval). a) EU-JRC ESTI (combined uncertainty of 1.3%). b) SUPSI (combined uncertainty of 1.7%). c) SMFB. d) & e) PLF. f) ISE measurement in 2007

4 RESULTS OF FIELD MEASUREMENTS

The aforementioned field test of three PV plants lasted two consecutive days each. To estimate the uncertainty of the PLF under field conditions ten modules of each plant were measured by the certified laboratory of SUPSI. The measurement conditions of outdoor measurements entail module temperatures with mostly large discrepancies with respect to the STC of 25°C. The temperature measurement is crucial for the overall uncertainty. The maximum deviation of the individual measurement with the PLF is 3% compared to the measurements of the SUPSI laboratory. It has been observed that this deviation is lower in times of low solar irradiance, which can be explained by the lower temperature transients (see Chapter 5). This higher accuracy of nominal power measurement can also be achieved during night time measurements with the additional advantage of omitted yield losses to the system

Table III: Deviation of the outdoor measurement with the PLF to the indoor measurement in the certified laboratory of SUPSI. The values are averaged over ten PV modules per site.

PV Plant	Deviation of the PLF to SUPSI (k=2)
Die Werke, Wallisellen	(1.2 ± 1.81)%
AXA, Winterthur	(0.96 ± 0.74)%
LKW, Schaan FL	(1.51 ± 0.47)%

Figure 5: The PLF during the outdoor measurements at the PV Plant “Die Werke, Wallisellen”.

The experiences during these first outdoor tests revealed throughput rates of up to 130 modules per day. Estimations expect a setup time of one hour and they promise a measurement throughput of at least 150 modules per day. The measurement costs per module are expected to be about a tenth compared to the costs of the common measurement in a certified laboratory.

The lion’s share of the measurement time depends on the ease of handling since the actual electrical IV-measurement has a cadence of six measurements per minute. Thus, further investigations on how to reduce the time for roll on of the light engine, positioning on the module and temperature acquisition are being conducted by ZHAW.

The field measurements of the PV plants, after being in service since two, six and seven years respectively, revealed that no measured power of the modules were beyond its warranty boundaries. In Figure 6, the measured nominal power of the 180 modules are sorted in bins of 5 W power range. The nominal power according to the datasheet is 180 W. No measurement showed significant discrepancy compared to the lower power boundary of 164.7 W (95% of power warranty after 5 years and estimated uncertainty of PLF of 3.5% results in lower boundary of 91.5% which is equal to 164.7 W).

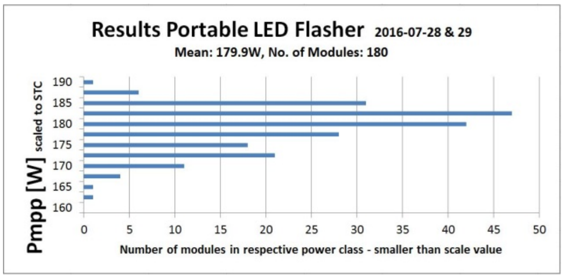

Figure 6: Number of modules with nominal power in classes of 5 W, as measured with the PLF on the PV plant “die werke, Wallisellen” on July 28th and 29th 2016.

With this new method it is possible to achieve a larger number of samples and thus, it enables the rearranging of PV plants into new strings with similar nominal power. This retrofit promises an increase in energy yield.

In order to identify modules with possible low nominal power compared to the datasheet value a thermal imaging of the plant can be conducted. The thermal imaging together with the visual inspection enables a pre-selection resulting in more significant samples of the whole array and plant.

5 IMPROVEMENTS OF TEMPERATURE MEASUREMENT AND UNCERTAINTY

The intended throughput of 150 modules per day requires a measurement time of about two minutes per module. In this short period the module will not reach thermal equilibrium with the ambient air and thus, it is difficult to extract the cell temperature within the PV module.

During the field testing an increased uncertainty has been observed during times of high solar irradiance. It has been found that this error was based on the uncertainty in the estimation of the module temperature due to the exponentially decreasing module temperature after shadowing of the module. The deviation between the measured temperature and the real cell temperature together with the inhomogeneous shadowing led to high uncertainties of the temperature corrected P_{mpp} value. Therefore, the ZHAW established an approach for improved cell temperature estimation leading to an improved temperature correction of P_{mpp}.

In order to determine the appropriate temperature acquisition method a 60-cell polycrystalline reference module was equipped with two PT100 RTDs. One of the RTDs was attached to the backsheet of the module and the other one to the front glass. Then, the electrical characteristics of the reference module were determined with the PLF at constant room temperature of 25±0.3 °C in the indoor lab of the ZHAW.

Table IV: Selected electrical data of the polycrystalline reference module as stated in the datasheet and as measured with the PLF at the ZHAW indoor laboratory (25±0.3 °C). *Estimated temperature coefficient, valid for this module and measurement setup

Electrical Quantity	Datasheet	Measured
P_{mpp} [W]	250.00	248.95
V_{oc} [V]	37.70	37.52
TC P_{mpp} [%/K]	-0.45	-0.53*
TC V_{oc} [%/K]	-0.33	-0.32*

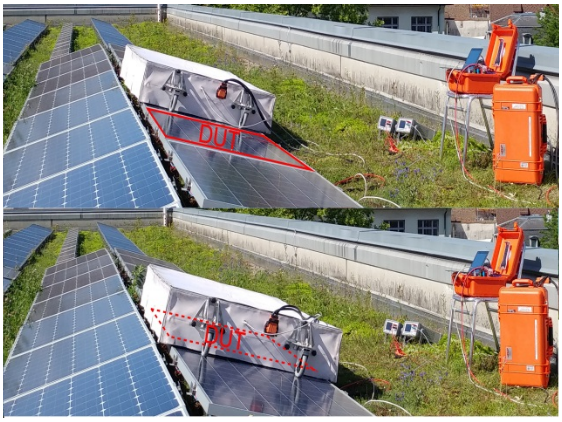

Figure 7: Pictures of the outdoor measurement setup. The top picture shows the PLF on a neighbouring module while the reference module is exposed to the sunlight. The bottom picture depicts the setup during shading and measuring the reference module. On the right hand side the battery and the measurement electronics are shown.

The reference module was thereafter mounted to the PV array of the ZHAW PV outdoor lab and exposed to solar irradiance of around 800 W/m^2 (Figure 7 top) before being shadowed for half an hour by the PLF (Figure 7 bottom). During the period of shadowing the IV characteristic was measured in ten second intervals with the PLF. The aim of the measurement series was to find an optimised method to measure a constant temperature corrected P_{mpp} near its STC value over a large temperature range.

The decrease in measured temperature over time due to shadowing is depicted in Figure 8. The cell temperature was estimated using the measured V_{oc} value (Figure 10) and the temperature coefficient of V_{oc} (see Table IV). Consequently, the P_{mpp} was temperature corrected using the estimated cell temperature and the temperature coefficient of P_{mpp} (see Figure 11).

Newton's Law of Cooling fits the approximated cell temperature:

$$T(t) = T_{amb} + (T_{start} - T_{amb}) \times e^{\frac{-0.0063}{s} \times t}$$

The residuals of the curve fitting are shown in Figure 8 bottom.

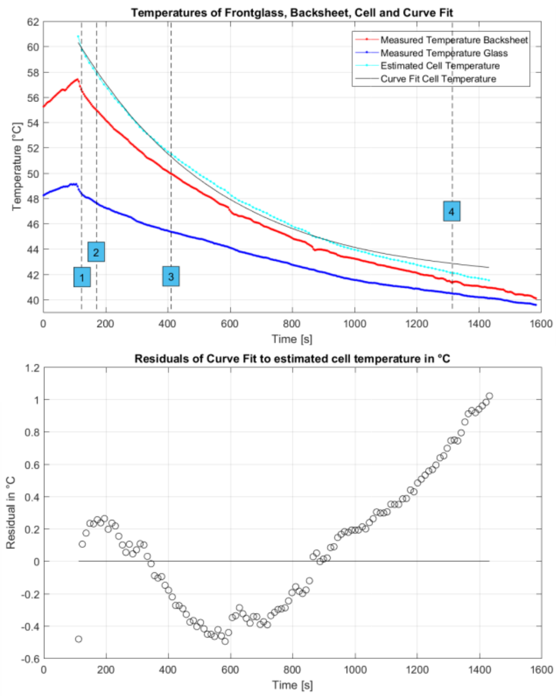

Figure 8: Top: Measurement results of two RTDs mounted on the backsheet (red line) and on the front glass (blue line) of the reference module. The cell temperature (cyan line) was estimated using the V_{oc} values and temperature coefficient of V_{oc}. Vertically dashed lines for 1) ten seconds, 2) one minute, 3) five minutes, and 4) 20 minutes after shadowing of the module. Bottom: Residuals (black circles) of the curve fit (top, black line) of the estimated cell temperature in degree celsius.

Figure 9 illustrates the problem of temperature measurement with a cross section of a PV module. The temperatures at the time steps 1-4 as indicated and explained in Figure 8 are shown as gradients over the layers of the PV module. The different thermal resistances and thicknesses of the different layers lead to temperature gradients with different slopes resulting in different temperatures at the front glass and at the backsheet. These temperatures differ from the cell temperature except in thermal equilibrium. During the first few seconds after shadowing, the difference in temperature between the cell and the glass/backsheet is relatively large (Figure 9, top red dashed line). This divergence decreases as the module approaches thermal equilibrium (Figure 9, bottom red dashed line).

Figure 8 shows that the estimated cell temperature is 4.4 °C higher than the measured backsheet temperature, which is caused by the thermal resistance of the encapsulation material and backsheet. This observation correlates to figures in literature [5]. Misinterpretation of the backsheet temperature for the actual cell temperature then could lead to an underestimation of P_{mpp} of up to 2.3% or 5.8 W.

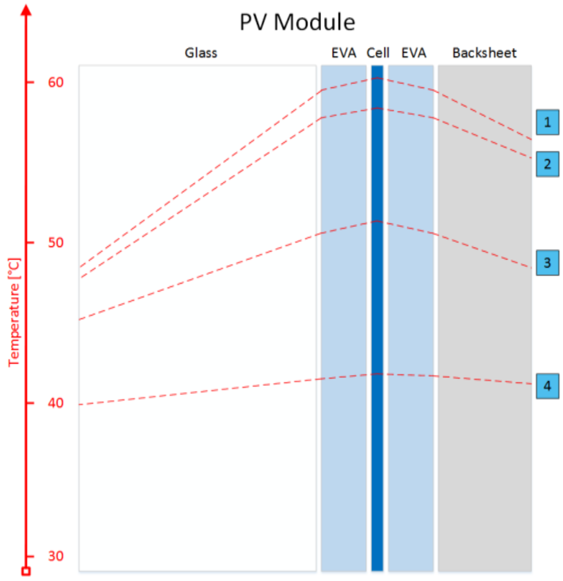

Figure 9: Temperature profile along the cross section of a PV module with the PV cell in the middle, encapsulated by EVA and front glass and backshee t (proportions in the lateral dimension are not to scale). Numbers 1 to 4 describe the lateral temperature characteristics after 10 seconds, 1, 5 and 20 minutes respectively.

The open-circuit voltage was corrected using the measured backsheet temperature (Figure 10, red) and the estimated cell temperature (Figure 10, cyan). It can be seen that the correction with the estimated cell temperature matches the STC value of V_{oc} as measured indoors at 25°C (Figure 10, black).

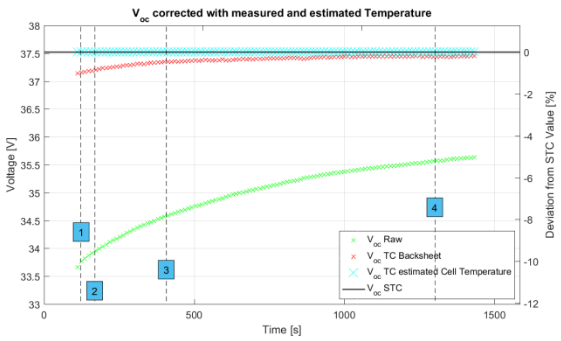

Figure 10: Raw data (green) and temperature corrected values of V_{oc} of the reference module during the same measurement as in Figure 8. The vertical lines indicate the temperatures after 10 s, 1, 5 and 20 min after shadowing of the PV module.

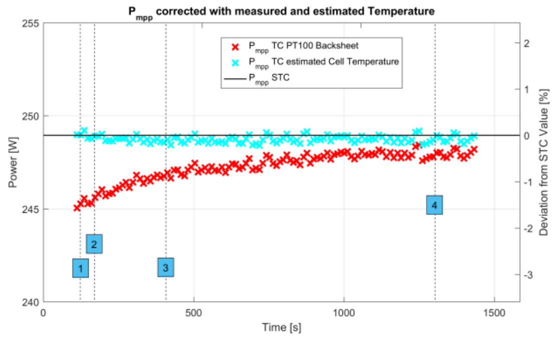

Figure 11: Temperature corrected values of P_{mpp} of the reference module during the same measurement as in Figure 8.

The maximum power was corrected using the measured backsheet temperature (Figure 11, red) and the estimated cell temperature (Figure 11, cyan). Again, the correction with the estimated cell temperature matches the STC value of P_{mpp} as measured indoors at 25°C (Figure 11, black) with very small deviation.

The RMSE of the P_{mpp} value estimated with the cell temperature is 0.1% while the RMSE of the P_{mpp} value corrected with the backsheet temperature is 0.83%. The uncertainty of the temperature measurement could be reduced considerably with this measurement setup resulting in a lower uncertainty of the nominal power measurement.

In order to alleviate the underestimation of P_{mpp} several measures are proposed:

I. Shadowing the next modules in line with a blanket ten minutes before the measurement in order to measure the electrical properties of the module nearer to thermal equilibrium. Homogenous shadowing leads to a homogenous temperature of the module.

II. Approximation of the cell temperature by measurement of front glass temperature and ambient temperature. To ensure a constant time delay between start of shadowing and measurement the measurement will be automatically started after a fixed time.

III. For large batches and lower uncertainty a calibration of temperature coefficients of the modules can be done on site.

As part of further research work, the ZHAW is establishing a tool to automatically determine the temperature coefficients of a module during a measurement series of roughly 15 minutes. This procedure is done on site of the PV plant and will contribute to the reduction of uncertainty in nominal power measurement with the PLF.

6 CONCLUSION

The new version of the Portable LED Flasher is superior compared to predominant nominal power measurement methods regarding the flexibility and costs. Due to elimination of demounting and shipping to a stationary laboratory, the costs for measurements can be reduced to one tenth. Thus, a higher number of modules for the same price can be evaluated which increases the significance of the sample and allow a more accurate assessment of the current economic value of the PV plant in question. The energy autonomy and mechanical structure of the light engine allow the transport to the site with a station wagon and measurements without mains connection for one day.

A round robin test confirmed the low uncertainty of <1% of the PLF in laboratory conditions (25°C). As a result of field tests the uncertainty was found to be below 3% in outdoor conditions. Further analysis of outdoor measurements led to a proposal of several measures that increase the accuracy of the critical temperature measurement. The temperature transient due to shadowing of the module by the light engine of the PLF can be alleviated by pre-shadowing the modules for at least 10 minutes before the measurement.

Furthermore, the actual cell temperature, which is relevant for the temperature compensation, can be estimated by measuring the ambient temperature and time between shadowing and IV-measurement. Successive research and development is done at the ZHAW to further reduce the uncertainty of the PLF.

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