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Final report

MARIE

Reduction of measurement uncertainties of PV modules and systems in the field

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Summary

The measurement of the STC power is one of the core tests within the inspection of PV systems. Most of the measurement uncertainties declared for field testing are based on rough estimations and are mostly not certified by an independent body. This makes a performance claim very difficult. On the other hand, the testing in an accredited test laboratory with high and certified measurement accuracies requires the shipment of modules to the lab site, which generally limits the number of tested modules and increases the risk of transport damages. The project MARIE aims to reduce the gap between laboratory and field testing by introducing a test procedure which traces the field measurements back to the laboratory. SUPSI and SPF will therefore share their know-how and test infrastructure to improve the accuracy and reliability of power measurements in the field and demonstrate its effectiveness through some real case studies. The project results will flow into: (1) New high-precision PV power verification service packages for Swiss system operators, module distributors, insurance companies etc., (2) International best practice guidelines: IEA PVPS Task 13 technical report ‘Good Practice Recommendations to qualify PV Power Plants using Mobile Devices’ and (3) Training courses on PV system failure diagnostic.

Zusammenfassung

Die Messung der STC-Leistung ist einer der Kerntests bei der Inspektion von PV-Anlagen. Die meisten der für Feldmessungen angegebenen Messunsicherheiten basieren auf groben Schätzungen und sind meist nicht von einer unabhängigen Stelle zertifiziert. Dies macht einen Leistungsanspruch sehr schwierig. Andererseits erfordert die Prüfung in einem akkreditierten Prüflabor mit hohen und zertifizierten Messgenauigkeiten den Versand von Modulen zum Laborstandort, was in der Regel die Anzahl der geprüften Module begrenzt und das Risiko von Transportschäden erhöht. Das Projekt MARIE zielt darauf ab, die Lücke zwischen Labor- und Feldmessungen zu schliessen, indem ein neues Prüfverfahren eingeführt wird, dass Feldmessungen bis ins Labor zurückverfolgt. SUPSI und SPF werden daher ihr Know-how und ihre Testinfrastruktur teilen, um die Genauigkeit und Zuverlässigkeit von Leistungsmessungen im Feld zu verbessern und ihre Wirksamkeit anhand einiger realer Fallstudien zu demonstrieren. Die Projektergebnisse fließen ein in: (1) Neue Servicepakete mit hochpräzisen PV-Leistungsmessungen für Schweizer Anlagenbetreiber, Distributoren, Versicherungen etc., (2) Internationale Best Practice-Richtlinien: IEA PVPS Task 13 technischer Bericht " Good Practice Recommendations to qualify PV Power Plants using Mobile Devices" und (3) Schulungen zur Fehlerdiagnose bei PV-Systemen.

Résumé

La mesure de la puissance STC est l'un des tests clés de l'inspection des installations photovoltaïques. La plupart des incertitudes de mesure indiquées pour les mesures sur le terrain sont basées sur des estimations approximatives et ne sont généralement pas certifiées par un organisme indépendant. Cela rend toute revendication de performance très difficile. D'autre part, le contrôle dans un laboratoire d'essai accrédité avec des précisions de mesure élevées et certifiées nécessite l'envoi de modules sur le site du laboratoire, ce qui limite généralement le nombre de modules contrôlés et augmente le risque de dommages pendant le transport. Le projet MARIE vise à combler le fossé entre les mesures en laboratoire et les mesures sur le terrain en introduisant une nouvelle procédure de test qui permette de retracer les mesures sur le terrain jusqu'au laboratoire. La SUPSI et le SPF partagent donc leur savoir-faire et leur infrastructure de test afin d'améliorer la précision et la fiabilité des mesures de performance sur le terrain et de démontrer leur efficacité à l'aide de quelques études de cas réelles. Les résultats du projet seront intégrés dans : (1) de nouveaux ensembles de services comprenant des mesures de puissance PV de haute précision pour les exploitants d'installations suisses, les distributeurs, les compagnies d'assurance, etc., (2) des directives internationales sur les meilleures pratiques : IEA PVPS Task 13 Technical Report " Good Practice Recommendations to qualify PV Power Plants using Mobile Devices " et (3) Formation au diagnostic des pannes des systèmes PV.

Contents

1 Introduction

1.1 Motivation

The measurement of the STC power is one of the core tests for the assessment of the performance of a PV system. Most of the measurement uncertainties declared for field-testing are based on rough estimations and are mostly not certified by an independent body. This makes a performance claim very difficult. On the other hand, the testing in an accredited test laboratory with high and certified measurement accuracies requires the shipment of modules to the lab site, which generally limits the number of tested modules and increases the risk of transport damages.

1.2 Objective

The project aimed to reduce the gap between laboratory and field-testing by introducing new test procedures which traces the field measurements back to the laboratory. SUPSI and SPF shared therefore its know-how and test infrastructure to improve the accuracy and reliability of power measurements in the field and demonstrate its effectiveness. Therefore, two different field-testing methods were investigated: (1) testing of single modules with a mobile flasher and (2) string testing with mobile I-V tracers. For both approaches, the best and standard case measurement uncertainties were determined and a validation performed.

1.3 State of the art

SUPSI offers the measurement of the STC power of modules in its laboratory with an ISO17025 certified uncertainty of ±2.6% (u%;k=2) without spectral mismatch correction and ±1.6% (u%;k=2) with spectral mismatch correction. The measurements are performed under controlled test conditions with a stationary class A+A+A+ solar simulator. The SUPSI PVLab is today the only laboratory in Switzerland offering ISO 17025 accredited high precision STC power measurements for PV modules. For field testing SUPSI owns 2 different portable I-V tracers which can be used for failure detection or power claims of PV systems in the field. The uncertainty of the STC measurement in the field is generally estimated to be in the range of ±2.5 and ±5.0% (u%;k=2).

On the other hand, SPF offers the measurement of the STC power of single modules in the field with a mobile flasher with an estimated uncertainty of ±3.0% (u%;k=2). Large numbers of modules can be measured without shipping the modules to the laboratory. The measurement uncertainty has been confirmed through single measurements at SUPSI, but a full validation of the test procedure in the praxis and for all different technologies were still missing. SPF is today the only laboratory in Switzerland offering testing services with a MBJ mobile test laboratory, which permits to combine directly in the field the electrical performance tests with other tests like: electroluminescence, insulation resistance and bypass diode testing.

2 PV system testing with mobile flasher

2.1 Introduction to the MBJ solar simulator

SPF owns a mobile PV test centre from MBJ Solutions GmbH. All test equipment is built inside a trailer in a compact way so that measurements can be done on-site. The tests include I-V curve measurement, electroluminescence and infrared imaging as well as HiPot, grounding, and diode tests. Table 1 shows the main characteristics for I-V curve measurement.

Table 1: Technical specifications of the mobile flasher used at SPF

Product name	MBJ Mobile PV-Testcenter 2.0
Technology	LED, 6 colours
Simulator class according to IEC 60904-9	A+ (Spectrum) A (Uniformity) A+ (Stability)
Illuminated area / homogenous area	1'280mm x 2'140mm / 1'020mm x 1'940mm
Irradiance range	200-1'200 W/m²
Pulse duration	200 ms
Irradiance measurement	Reference cell (Fraunhofer ISE)
Temperature measurement	Infrared sensor
I/V range	20 A / 250 V

2.2 Irradiance adjustment

Up to now, irradiance adjustment is done by MBJ during yearly calibration of the mobile lab. The used reference module is a mono n-type Yingli Panda YL265C-30b. The module is measured by TÜV Rheinland with a stated measurement uncertainty for P_{max} of ±1.5 % (k = 2). As described in the best practice guideline of IEA PVPS TASK 13 [2], the adjustment is done for P_{max}.

As one result of the tests to be performed, a reference module shall be chosen with an average spectral response as best fit for the mobile flasher. For the single measurement, the additional use of a spectrally matched reference module can further minimise the spectral mismatch, most suitable is a module of the same type as the device under test.

2.3 Temperature measurement

For the mobile lab, temperature measurement of the module is done with an infrared sensor that measures at the lower part of the backside of the module (Figure 1). The manufacturer specifies the measurement accuracy with ±1 °C. To verify this indication for different materials (backside foil or glass) and to determine temperature inhomogeneities within the tested module during measurement, four contact sensors were used. The sensors were first calibrated to a measurement accuracy of ±0.1 % and two sensors each installed in the upper and lower part of the module. The two lower sensors are at the same height at each side of the built in infrared sensor.

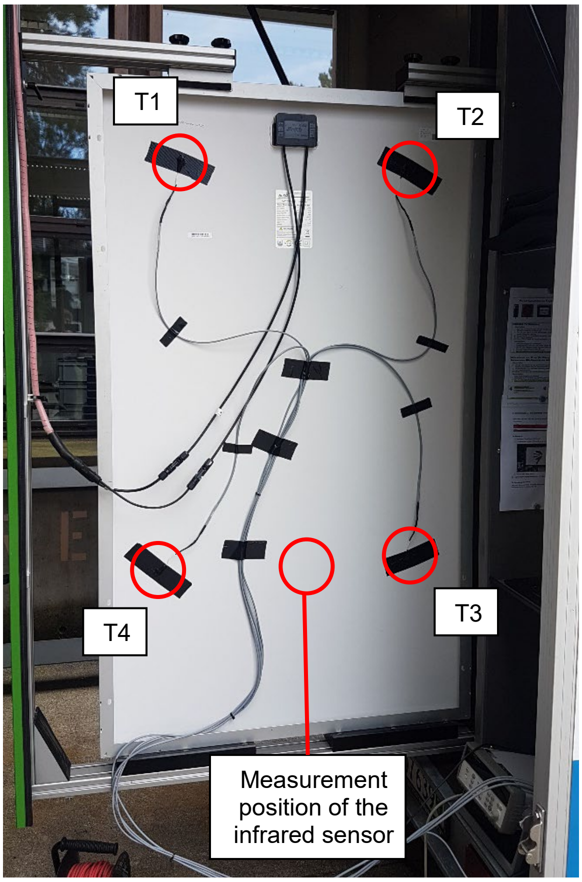


Figure 1: Test setup for temperature measurement verification, T1-T4: contact sensors

Different test conditions were considered with different temperature conditions of the mobile lab (outside temperature, 25 °C non-stabilized, 25 °C stabilized) and the temperature of the module (outside temperature, module heat-up with a reverse current to 25 °C, 25 °C stabilized) in different combinations. With this test setup, a glass-foil module (Jinko JKM260P, P1) and a glass-glass module (Meyer Burger Bifacial 365, P2) were measured in the following situations with the measurements M1-M7 and M8-12 carried out at different test days:

- M1: Mobile lab not conditioned / module not conditioned, immediate measurement
- M2: Mobile lab not conditioned / module not conditioned, measurement 5 min after tray closure
- M3: Mobile lab at 25 °C, not stabilized / module not conditioned, immediate measurement
- M4: measurement after 5 min stabilization (i.e. 5 min after M3)
- M5: measurement after 20 min stabilization
- M6: measurement after 30 min stabilization
- M7: measurement directly after M6 (repeatability)
- M8: Mobile lab stabilized at 25 °C / module not conditioned, immediate measurement
- M9: Mobile lab stabilized at 25 °C / module heat-up to 25 °C with reverse current
- M10: measurement after 12 min (P1) or 6 min (P2) stabilization
- M11-12: measurements directly after M10 (repeatability)

The measurements M1 to M7 were done on 01/10/2020 with outside temperatures between 15 and 19 C, the measurements M8 to M12 on 14/10/2020 with outside temperatures between 14 and 17 °C respectively.

2.3.1 Temperature deviation within the modules

The temperature deviation within the module is mainly caused by the installation position of the air conditioning system inside the lab in the upper rear part of the trailer, i.e. the hot (or cold) air hits the module next to T2. This leads to a temperature deviation especially during warm up phases with a highly active air conditioning of up to 4.3 K (M4). In a stabilized situation, this deviation can be reduced to approx. 1.5 K (M5-M7, Figure 2). In the case of the glass-glass module, six minutes are not enough for stabilization, the temperature deviation is still 3 K (M10-M12).

In a stabilized situation (M5-M7), the temperature measurement of the infrared sensor and T3 and T4 fits very well with a maximum deviation of 0.2 K. As the contact sensors have a higher inertia, they show especially after a rapid module heat-up with reverse current still lower temperatures of the former measurement (M8 to M9).

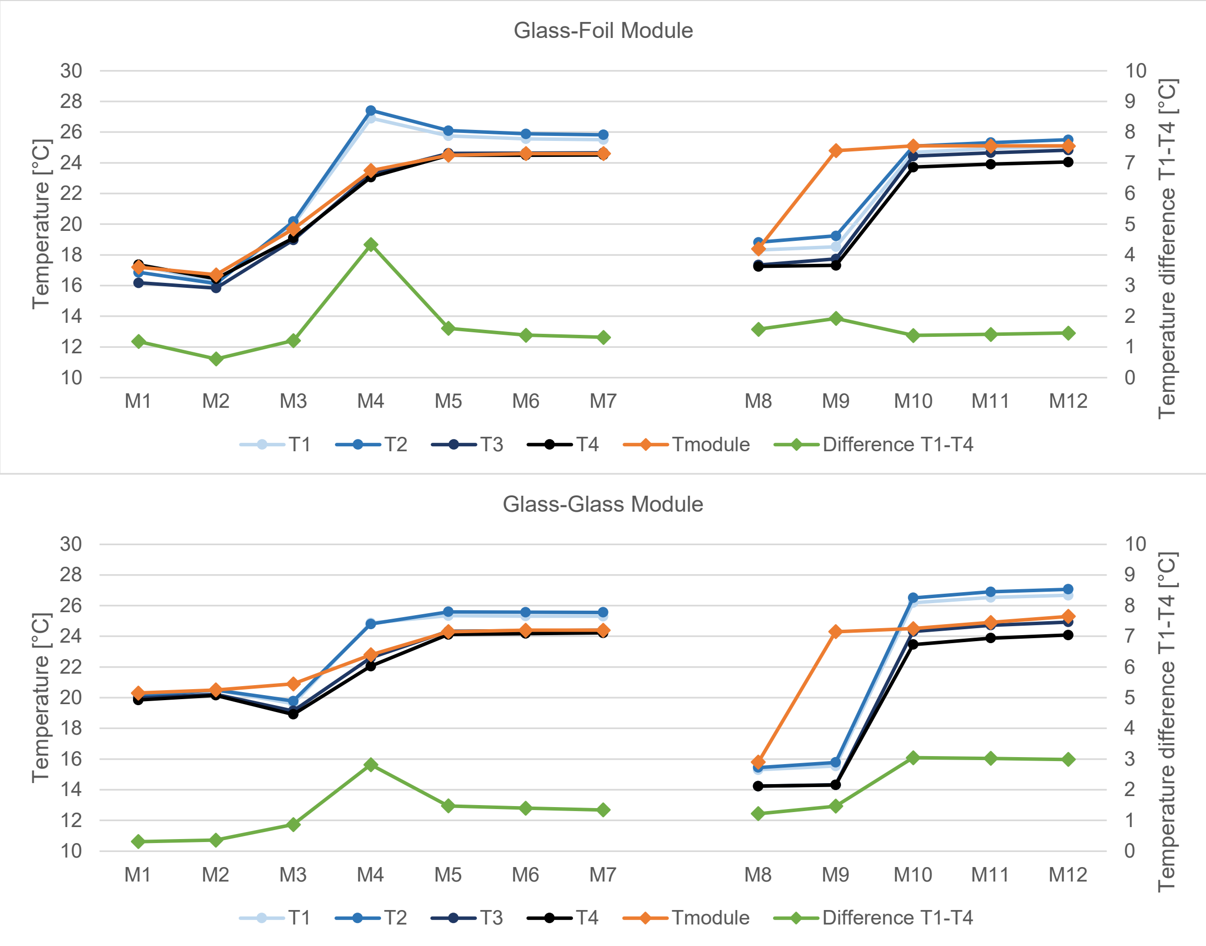
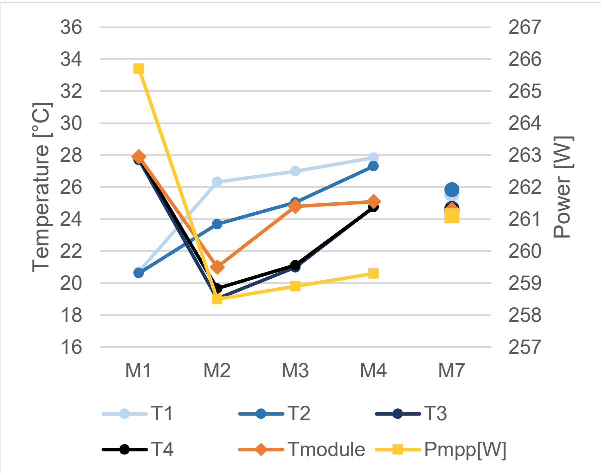


Figure 2: Temperature measurement of the contact sensors T1-T4, the build in infrared sensor (Tmodule) and the maximum temperature difference between the four contact sensors for the glass-foil and the glass-glass module

2.3.2 Measurement of modules with inhomogeneous temperature distribution

In the field because of partly sunny and partly shadowed parts of the modules, greater temperature inhomogeneities may arise. To simulate such a situation, the former used glass-foil and glass-glass modules were installed in the lab with temperature sensors as shown in Figure 1. First, the lower half of the module was in the sun and the upper half shadowed, afterwards vice versa.

The temperature deviation reached between the shadowed and the not shadowed part of the module was between 6 and 11 K. The maximum power measurement deviation of the temperature corrected value compared to the stabilized situation is 2.7% (Figure 3).



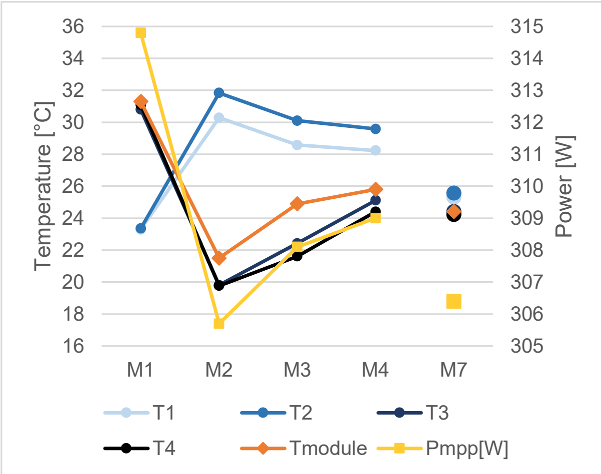


Figure 3: Temperature and power measurement of partly shadowed modules, left: glass-foil, right: glass-glass module

2.3.3 Power measurement at different temperature conditions

For 14 modules of five different module types from four manufacturers, power measurements at different temperature conditions were carried out. Temperature correction is done according to IEC 60891:2009 (Ed. 2) method 2 with the respective data sheet's temperature coefficients. Analogous to the previous measurements M8-M12 the following tests were performed:

- M1: Mobile lab stabilized at 25 °C / module not conditioned, immediate measurement (module temperatures between 11 and 18 °C)
- M2: module heat-up to 25 °C with reverse current until time-out (25 °C may not be reached)
- M3: module heat-up to 25 °C with reverse current (starting from M2)
- M4-M6: follow-up measurements after few minutes' stabilization

The maximum measured power deviation between the not conditioned modules and the temperature-stabilized condition is up to 2.9% whereas the maximum deviation between the measurements after heat up with reverse current compared to the stabilized condition is not more than 0.2% (Figure 4). The deviation using the data sheet's temperature coefficients is supposed to be even higher at lower temperatures than the module temperatures that occurred during the tests performed here, or at very high temperatures. It has to be noted that the used modules are not fabric new and a potential current induced degradation through the module heat up with a reverse current can be neglected.

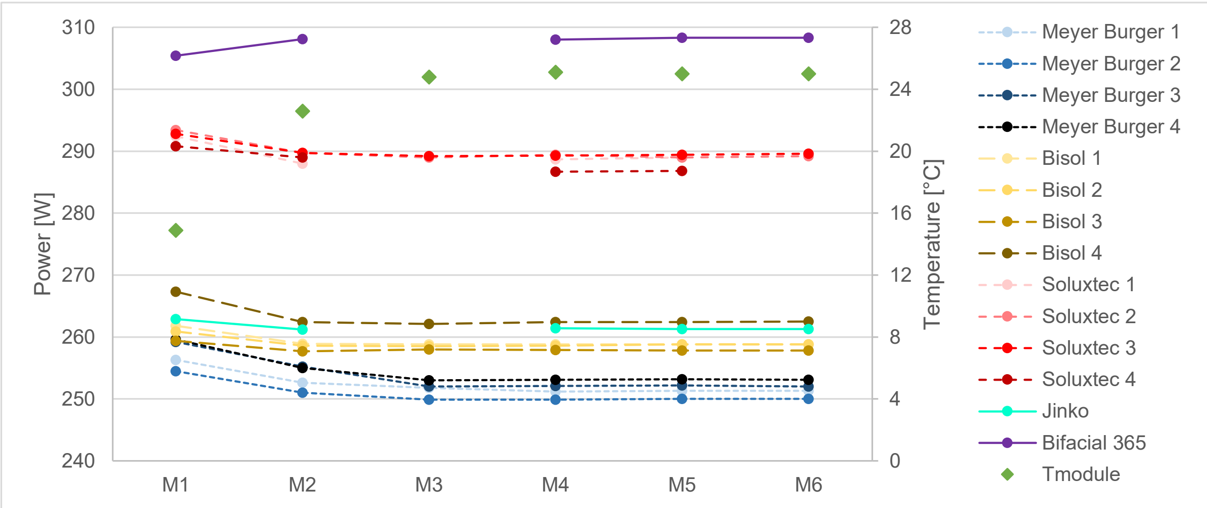


Figure 4: Power measurement of 14 modules under different temperature conditions (Tmodule: module temperature of Meyer Burger 1, similar for all modules)

Figure 5 illustrates measurement results of a different set of five module types. The deviation of P_{max} for a temperature corrected measurement at different module temperatures compared to the measurement at 25 °C is shown, using the data sheet's temperature coefficients. At 20 °C the maximum deviation is 0.6 %, at 23 °C about 0.4 %.

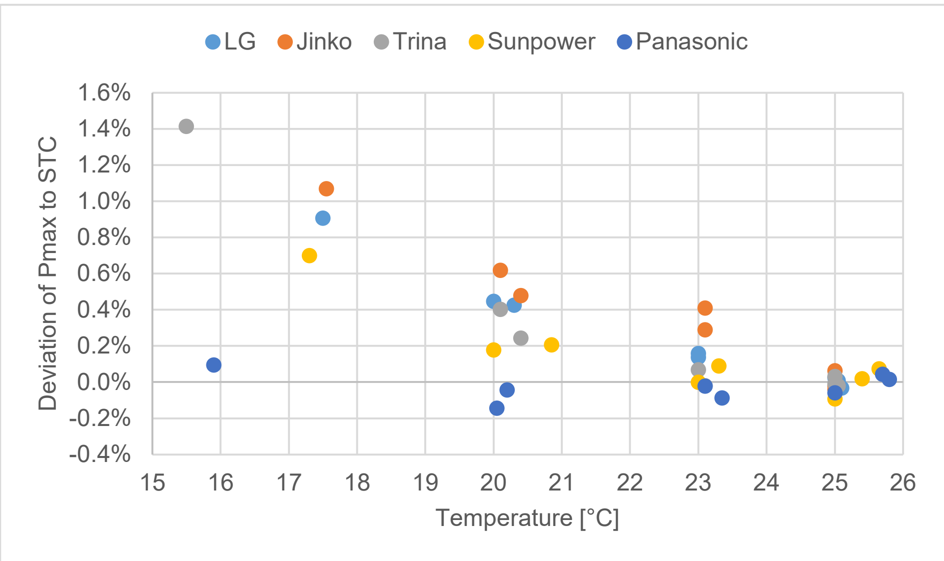


Figure 5: Deviation of temperature corrected P_{max} to the measurement result at standard test conditions for different temperatures.

2.3.4 Base module usage for temperature correction

Besides using the data sheet's temperature coefficients, another possible procedure is using a base module for measurements of several modules of the same type at a temperature other than 25 °C. One module is measured at the not conditioned temperature and afterwards brought to 25 °C stabilized temperature. If all other modules have the same temperature as this base module (+/-2 K), the measurement data from the base module can be used as temperature correction for the rest of the modules. For the Bisol, Meyer Burger and Soluxtec modules, one module each is selected as base module and the procedure applied to the cold measurement results (M1) of the three other modules as shown in Figure 4. The four modules of one module series are of the same type, but with some of the modules several load tests as well as temperature cycles and humidity freeze tests were carried out, which have led to module aging and micro-cracks. Other modules were simply stored. With the described correction procedure a maximum power deviation from the 25 °C stabilized value of 0.8 % is reached. The calculated value is in each single case closer to the stabilized value than using the data sheet's temperature coefficients. This correction procedure is suitable for P_{max}, but not for the correction of I_{sc}, V_{oc} or other parameters of the I-V curve.

2.4 Measurement of capacitive modules

Thanks to the relatively long sweep time of approx. 150 ms of the MBJ LED flasher, no capacitive effects occur measuring standard modules. However, with new module generations (especially HJT and IBC), this sweep time may not be sufficient. With the present measurement infrastructure, the I-V curve can only be measured forward, i.e. from I_{sc} to V_{oc}, so that it cannot be determined whether capacitive effects occur or not.

Therefore, a new IV curve box provided by MBJ was procured and installed in the mobile lab. With this box, despite the so far used forward measurements of the I-V curve, also backward measurements are possible, so that the capacitive effect can be calculated. In the case of capacitive modules, stepwise measurement can be carried out, holding voltage at a certain level for each step, with the step width being adjustable (Figure 6).

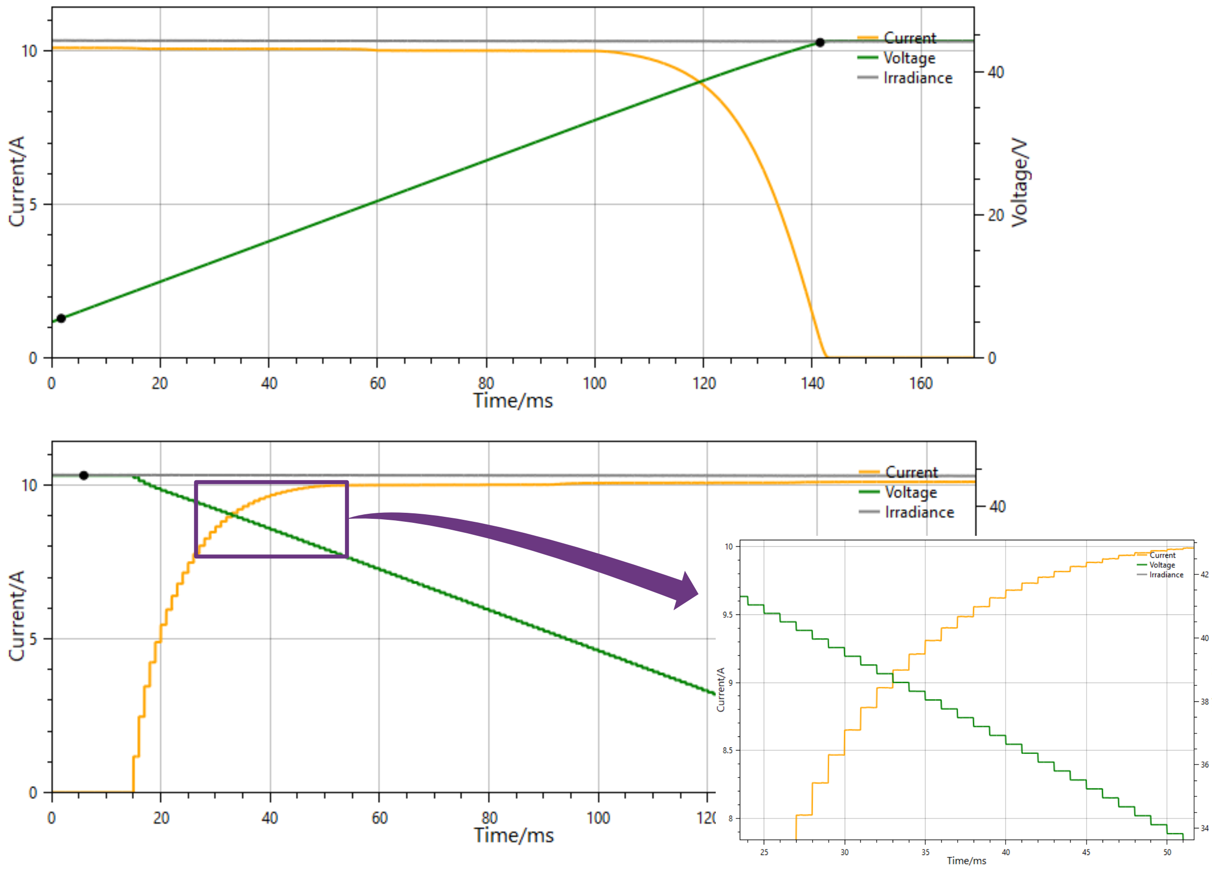


Figure 6: Time based curves for voltage and current, above: standard measurement (forward, continuous), below: backward measurement stepwise with detail of the same measurement.

Figure 7 shows the forward and backward continuous and stepwise measured I-V curves of a Panasonic n-type HTJ module. Table 2 contains the measurement results of several modules. Some of those modules were also used as reference modules for test procedure validation (compare chapter 5.1). The deviation of P_{max} between forward and backward measurement for the two HJT modules is between 2 and 2.3 %, for the IBC modules approx. 1.7 %. For all other modules the deviation is less than 0.1 %, which is lower than stated repeatability of measurement. With a stepwise I-V curve measurement capacitive effects for all modules can be avoided, the difference between forward and backward measurement being less than 0.1 %. A step width of 1 ms proofed to be suitable.

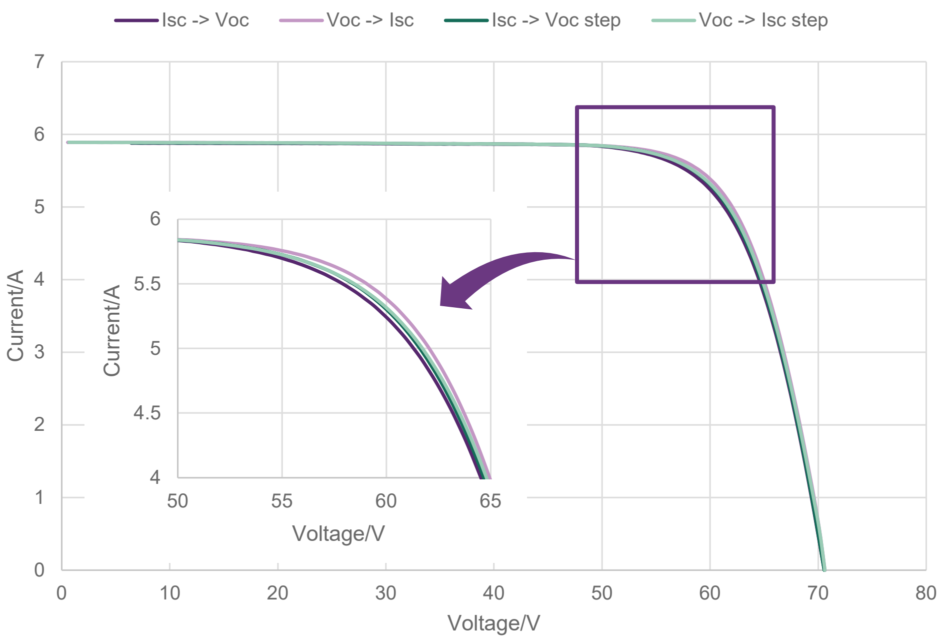


Figure 7: Forward and backward continuous as well as stepwise I-V curve measurement of a Panasonic n-type HTJ module.

Table 2: Measurement results of forward and backward continuous and stepwise measurement for a set of modules with different cell technologies.

Cell technology	Pm forward continous [W]	Pm backw. continous [W]	ΔPm forw/ backw	Pm forward stepwise [W]	Pm backw. stepwise [W]	ΔPm forw/ backw
Mono n-type HJT	317.3	323.9	2.07%	320.8	320.8	0.02%
Mono n-type HJT half-cut	352.7	360.7	2.26%	355.8	355.8	0.00%
Mono n-type IBC	384.7	391.5	1.77%	388.1	388.0	-0.03%
Mono n-type IBC	348.0	353.8	1.66%	349.7	349.6	-0.02%
Mono n-type PERL	319.7	319.7	-0.01%			
Mono p-type PERC half-cut	354.3	354.6	0.09%			
Mono p-type PERC	291.2	291.0	-0.04%			
Poly p-type	258.0	257.9	-0.03%			

3 PV system testing under natural sunlight

3.1 STC correction procedure

When measuring in the field STC (Standard Test Conditions), corresponding to 25 °C of module temperature, 1000 W/m² in-plane irradiance and an AM1.5 spectrum, are rarely achieved. A correction of the measured I-V curve from real to standard conditions is therefore required. The principles of the translation are defined in the standard IEC 60891 [1]. A review of the operating manuals of commercial I-V curve analysers performed in the framework of the IEA PVPS TASK 13 [2] has shown that in most cases the recommended translation procedures are not well implemented or not controllable. This leads to a high uncertainty, which makes a warranty claim almost impossible. SUPSI implemented therefore an own tool for the processing of the measured I-V curves.

The translation procedure implemented there is based on a simplified one-diode model, which was improved by Monokroussos et al. [3] and integrated as procedure 2 into the latest version of the IEC 60891 standard [1]. It is the most appropriate procedure for the purpose of field testing, as it can be used over a large range of irradiance levels and it takes into account non-linearities of the open-circuit voltage and temperature dependence of series resistance, which are typical for new generation modules based on PERC technology. The correction procedure is described by the following two equations for current and voltage:

$$I_2 = \frac{G_2}{G_1} \cdot I_1 \cdot \frac{\left(1 + \alpha_{rel} \cdot (T_2 - 25°C)\right)}{\left(1 + \alpha_{rel} \cdot (T_1 - 25°C)\right)} \qquad [1]$$

$$V_2 = V_1 + V_{oc,stc} \cdot \left[\beta_{rel} \cdot \left(f(G_2) \cdot (T_2 - 25°C) - f(G_1) \cdot (T_1 - 25°C)\right) + \frac{1}{f(G_2)} - \frac{1}{f(G_1)}\right] - R'_{s1} \cdot (I_2 - I_1) - k' \cdot I_2 \cdot (T_2 - T_1) \qquad [2]$$

where, $$f(G) = \frac{V_{oc,stc}}{V_{oc}(G)} = 1 + B_1 \cdot ln\left(\frac{1000 Wm^{-2}}{G}\right) + B_2 \cdot ln^2\left(\frac{1000 Wm^{-2}}{G}\right) \qquad [3]$$

and $$R'_{s1} = R'_s + k' \cdot (T_1 - 25°C) \qquad [4]$$

I_1, V_1	current and voltage of the measured I-V curve;
I_2, V_2	current and voltage of the target I-V curve;
G_1	measured irradiance;
G_2	target irradiance;
T_1	measured temperature of the DUT;
T_2	target temperature of the DUT;
$V_{oc,stc}$	open-circuit voltage at STC;
V_{oc1}	measured open-circuit voltage;
α_{rel}	relative short-circuit current temperature coefficients, of the DUT measured at 1000 W/m^2;
β_{rel}	relative open-circuit voltage temperature coefficients, of the DUT measured at 1000 W/m^2;
B_1	irradiance correction factor for open-circuit voltage;
B_2	irradiance correction factor for open-circuit voltage which accounts for non-linearity of V_{OC} with irradiance scaling;
R'_S	internal series resistance of the DUT;
R'_{S1}	internal series resistance at temperature T_1;
k'	temperature coefficient of the internal series resistance R'_s.

The semi-empirical translation equations contain six correction parameters: Besides the relative temperature coefficients for short-circuit current (α_{rel}) and open-circuit voltage (β_{rel}) an additional temperature coefficient (κ′) is considered, which accounts for changes of the internal series resistance (R'_S) with temperature. The two parameters B_1 and B_2 describe the irradiance dependency and correct the open-circuit voltage. B_1 is linked with the diode thermal voltage D of the p-n junction and the number of cells n_s serially connected in the DUT, whereas B_2 takes into account non-linearities of V_{OC} which can occur at lower irradiances. In the case of linearity, B_2 can be set equal 0.

3.2 Determination of IEC 60891 correction parameters

To get the highest precision for the STC correction, a reference module, selected from the system to be tested, is measured with a class A+A+A+ solar simulator. The IEC 60891 correction parameters described in section 3.2.1 are determined from a set of 5 I-V curves measured at 25°C and different irradiances in the range of 100-1100 W/m² and another set of 5 I-V curves measured at 1000 W/m² and different temperatures in the range of 15-65°C.

Figure 8 shows the developed software for the extrapolation of the needed correction parameters with an example of the reference module of the MARIE test facility presented in section 5.2.

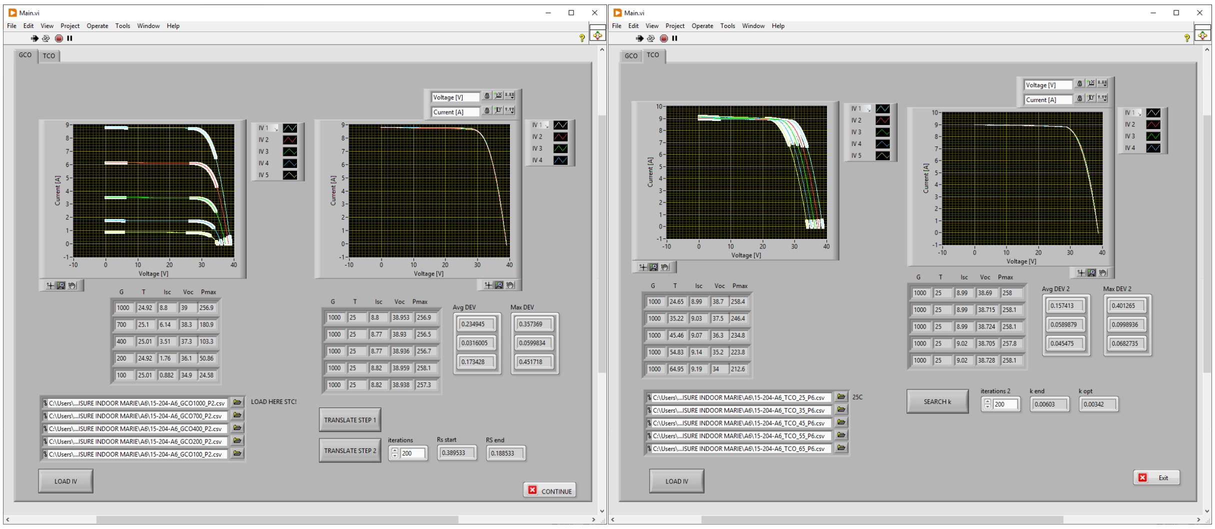


Figure 8: Tool for the extrapolation of the module parameters for the I-V curve translation procedure described in the standard IEC 60891:2021 ed. 3.0 paragraph 5-7.

The deviation of the STC corrected I-V curves respect to the measured I-V curve lays typically within ±0.5% over the whole range of irradiances and temperatures and below ±0.1% when considering only irradiances above 600 W/m². A detailed analysis of the translation uncertainties was published in chapter 4.3 of the open source Report IEA-PVPS T13-20:2020 [2].

3.3 Current-voltage measurement in the field

Once the correction parameters are defined and the reference STC parameters (P_{max}, V_{oc} and I_{sc}) of the strings or modules to be measured in the field are set field testing can be performed.

SUPSI owns two I-V tracers (cetisPV-CTM-F1 and TRIKA) for the measurement of PV modules and strings. Depending on the size of the string (see Table 3) one or the other I-V tracer system has to be chosen. Compared to the pure capacitive load of TRITEC the h.a.l.m electronic load cetisPV-CTM-F1 allows to manually adapt the voltage ramp parameters (start voltage, end voltage and sweep speed) to the device under test. High efficiency modules, characterised by a large module capacitance, can be so measured with lower sweep speeds, avoiding any measurement artefacts. The cetisPV-CTM-F1 is the first choice for high precision measurements and measurements of high efficiency modules, whereas the TRI-KA due to its user-friendliness is the first choice for relative measurements of systems with standard modules (low cell capacitance).

Table 3: I-V curve testers used at SUPSI for the measurement in the field.

PRODUCT NAME / MANUFACTURER	
cetisPV-CTM-F1 / h.a.l.m	**TRI-KA / Tritec**
	
max. current-voltage range	
250 V / 20 A (electronic load)	1000 V / 15 A (capacitive load)
1000 V / 100 A (electronic load + capacitive load booster)	

3.4 Irradiance and temperature measurement in the field

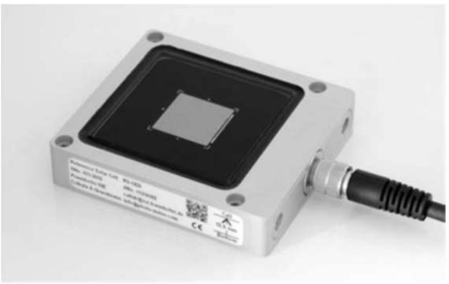
The plane-of-array solar irradiance (G_{poa}) and PV module temperature (T_{mod}) measured together with the I-V curve sets the test conditions to be corrected to STC. An error in the measurement of irradiance and/or temperature or unstable conditions during the I-V measurement has a direct impact on the uncertainty of the translated STC power. To avoid thermal instability or I-V curve distortions due to passing clouds the measurements are generally performed at clear sky and windless conditions. A separate datalogger for the continuous monitoring of irradiance and temperature is run in parallel to identify the best time to test and to have a back-up to the measurements performed with the I-V tracer equipment. Due to the higher uncertainty of the TRI-KA sensors and the difficulty to calibrate them, the datalogger data can be used in alternative to improve its accuracy.

Some of the most important aspects related to the irradiance and temperature measurement are here summarised.

Irradiance measurement

To minimize the uncertainty of the plane-of-array irradiance (G_{poa}) measurement only traceable calibrated reference cells with the lowest possible uncertainty should be used. SUPSI uses therefore in-house calibrated reference cells traceable to PTB. Depending on the irradiance sensor and applied test procedure (with or without spectral mismatch correction) uncertainties between ±0.8% and ±2.4% are achieved. Table 4 shows the different irradiance sensors available at SUPSI for the outdoor use together with its measurement uncertainty. As the temperature of the reference cells in the field deviates from the 25°C for which they are calibrated, a temperature correction has to be applied. The reference cell temperature is measured with an integrated temperature sensor. The temperature coefficient of the reference cell can be measured in the laboratory.

Table 4: Examples of irradiance sensors used at SUPSI for the measurement in the field together with some characteristics and its calibration uncertainty.

		
ISET SENSOL poly-Si with integrated shunt resistor and temperature sensor (PT1000)	ISET SENSOL mono-Si with integrated shunt resistor and temperature sensor (PT1000)	FhG-ISE mono-Si (PERC) with external shunt resistor and integrated temperature sensor (PT100)
u[%,k=2]= ±2.4%	u[%,k=2] = ±2.4%	u[%,k=2] = ±0.8%

The used reference cell should be as much as possible spectrally and optically matched to the device under test. SUPSI can therefore choose between reference cells with different cell technologies (mono, poly and high efficiency cells) and different filters for thin film modules like for e.g CdTe. For crystalline silicon modules the deviation of the spectral response (SR) of the reference cell from the SR of the module/string under test, even if low, leads to a spectral mismatch error in the range of up to ±1% when measuring during a clear sky day and irradiances above 600W/m^2. The deviation of the Angle of incidence (AOI) dependency of the reference cell from the modules under tests are negligible, as measurements are generally carried out under high irradiances with small AOIs.

To reduce to a minimum the spectral and optical mismatch error, the parameters ($I_{sc,stc}$ and α_{rel}) of the previously measured reference module can be used to calculate an effective irradiance $G_{Isc,ref}$ (see equation 5). This approach is not applicable for degraded modules where a high variability in I_{sc} is to be expected (e.g modules affected by yellowing, soiling, glass corrosion, delamination or LeTid). An inter-comparison of G_{poa} and $G_{Isc,ref}$ is in any case useful when analysing outdoor data.

$$G_{Isc,ref} = 1000 \cdot \frac{I_{sc}\left(1 + \alpha_{rel} \cdot (25°C - T)\right)}{I_{sc,stc}} \qquad [5]$$

To further support the data analysis, a minimum of two reference cells are measured. One of the reference cell is connected to an independent datalogger which continuously monitors the environmental conditions to identify unstable conditions. The datalogger is synchronised with the irradiance measurement of the I-V tracer. All sensors are placed with the same inclination and orientation as the modules and as close as possible to the array being measured. If not possible a separate tripod is mounted close to the test equipment. The alignment of the sensors with the plane-of-array is verified with a goniometer.

Temperature measurement

To minimize the uncertainty of the module temperature measurement (T_{mod}) different methods are combined. The standard approach is to attach a PT100 sensor to the back of the module. To determine the non-uniformity and the best position of the temperature sensors corresponding to the average module temperature, multiple measurements, IR sensors and/or IR imaging are used. The measured value (T_{bom}) is always compared with the equivalent cell temperature (ECT) calculated according equation 6. The equation is derived from the formulas in paragraph 3.1 and it requires the real time measured open circuit voltage (V_{oc}) of the DUT, the STC open circuit voltage ($V_{oc,stc}$) and the respective temperature coefficient β_{rel} of the reference module REF.

$$\mathrm{ECT} = 25°\mathrm{C} + \frac{1}{\beta_{rel} \cdot f^2(G)} \cdot \left(\frac{V_{oc}}{V_{oc,stc}} \cdot f(G) - 1 \right) \qquad [6]$$

The ECT approach has the advantage to deliver the real average temperature of the PV cells of a module or string. This is particularly important when measuring systems showing large thermal differences over the strings, modules (e.g. glass-glass) where the difference between back of module and cell temperature isn't negligible or building integrated modules which temperature can't be measured from the back. However, it has to be considered that the ECT approach works only for modules with similar V_{oc}. It can be so applied only to modules without evident deviations in V_{oc} due to the manufacturing process or degradation modes affecting V_{oc} (e.g PID, bypass diode failures).

3.5 Data processing

Figure 9 shows the tool developed by SUPSI for the processing of the outdoor measured I-V curves. The SW is compatible with both I-V tracer formats and allows to save all relevant information (date time of measurement, measured and corrected I-V curves/parameters, correction parameters, measured/calculated/manual irradiances and temperature values).

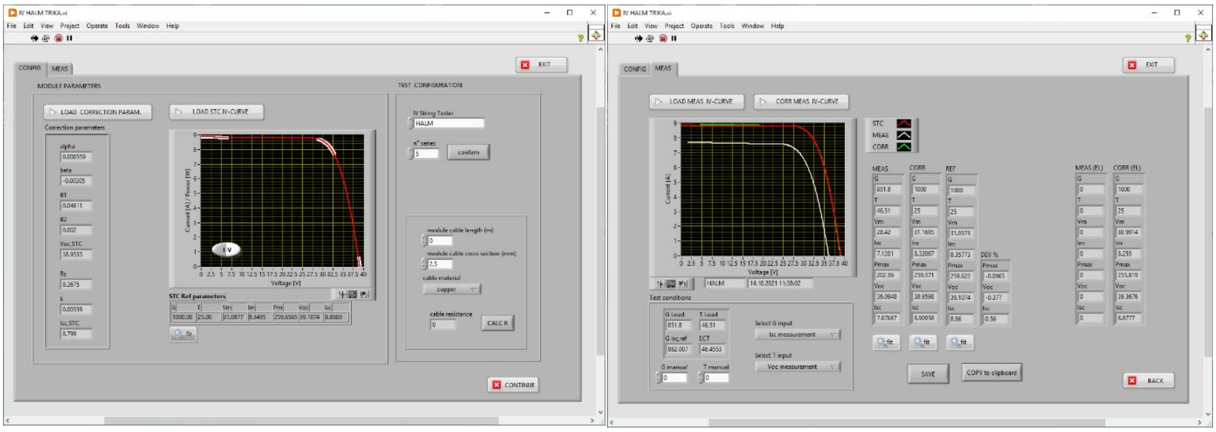


Figure 9: Tool for the translation of outdoor measured I-V curves to STC. Left: configuration window. Right: Translation window.

In the first window the SW allows to upload the measured correction parameters required for the translation of the measured I-V curves to standard test conditions (STC), as well as the to be used reference I-V curve. After this the I-V tracer type and number of modules in series are inserted. Additionally cable lengths, cable cross section and its specific resistance can be configured for the calculation of eventual cable losses.

In the second window the measured I-V curve can be uploaded and translated to STC. The SW allows to select between 3 different irradiance and temperature inputs: (1) measured irradiance G_{poa}, (2) calculated effective irradiance $G_{Isc,ref}$, (3) a manual irradiance (e.g. datalogger value can be here inserted), (4) measured temperature T_{bom}, (5) calculated equivalent cell temperature ECT and (6) a manual temperature (e.g. value from a IR thermometer).

4 Measurement uncertainties

On-site I-V measurements are affected by higher uncertainties compared to measurements in a controlled test environment (solar simulator in a climatized dark room) as present in an accredited test laboratory. The difference is mainly caused by the reference sensors or modules used for the irradiance measurement or adjustment of the mobile solar simulator and the higher deviations from standard test conditions (STC). A larger correction to STC is therefore required introducing a further error source.

Beside the general recommendations described in the IEA-PVPS Report 'Qualification of Photovoltaic (PV) Power Plants using Mobile Test Equipment' [2] the gap between laboratory and field-testing is significantly reduced by using a reference module with low calibration uncertainties of the same type (spectrally and optically matched) with the device under test. Following actions were introduced by SUPSI and SPF to improve their measurement uncertainties in the field.

1) Calibration at SUPSI PV-Lab of a reference module of the same type as tested in the field (same size, front layer and spectral response).
2) Measurement of the reference module I-V curve correction parameters needed for the STC correction according IEC 60891.
3) Implementation of mitigation measures for modules with high cell capacitance to avoid any measurement artefacts (e.g lower sweep speeds or voltage step ramps).

For the measurement with the mobile solar simulator following additional best practice recommendations are observed:

- The irradiance adjustment is done to P_{max}.
- The mobile laboratory is stabilised at 25 °C (approx. 15 min).
- The device and reference cell temperature is regularly checked.
- Correct positioning of the module inside the test frame (at the front of the frame and at the marked middle position).
- Modules with non-uniform temperatures (e.g. due to partial shadowing) are stabilised for a low temperature deviation within the module.
- Measurements are performed at 25 °C ±5 °C module temperature (If module parameters are well known a higher deviation is possible).

For the daylight I-V measurements with a portable I-V tracer following additional best practice recommendations are followed:

- Calculation of ECT according equation 6 and inter-comparison with T_{bom} (if measured).
- Calculation of $G_{Isc,ref}$ according equation 6 and inter-comparison with G_{poa}.

A differentiation is done between the best case based on the preliminary calibration of a device under test in the laboratory and the fulfilment of the before described recommendations, and the worst case based on a calibrated reference device closely matched to the device under test and some alternative temperature measurements and/or correction procedures.

With the mobile solar simulator the temperature measurement remains the same, but the temperature correction is made with the simplified procedure described in 2.3.4, whereas for the daylight I-V measurement the correction procedure and parameters remain the same, but the temperature is measured with a PT100 attached to the back of the module.

Table 5 lists the final best and worst case $P_{max,stc}$ measurement uncertainties together with the major contributions for a crystalline silicon module/string achieved in the field with the mobile solar simulator or the daylight I-V tracer used at SUPSI and SPF in comparison to the high precision measurement at SUPSI PV-Lab.

Compared to the laboratory best P_{max} uncertainty of ±1.6% (u%[k=2]) with the MBJ solar simulator an uncertainty of **±2.0%** to **±3.4%** is reached and **±2.4%** to **±3.1%** with a daylight I-V measurement.

In dependence of the availability of a calibrated reference module from the system, its representativeness or practical limitations in the field (e.g. time restrictions, temperatures, accessibility) the uncertainty calculation has to be adapted.

Table 5: Pmax@STC combined uncertainty and contributions (for a c-Si module) achievable in the field either with a mobile solar simulator or a mobile daylight I-V tracer in comparison to the one achieved with a stationary class A+A+A+ solar simulator.

Contributions	**Stationary solar simulator (SUPSI PVLab)**	**Mobile solar simulator (MBJ gen 2.0)**		**Daylight I-V measurements of a PV string**	
		best case	**worst case**	**best case**	**worst case**
Irradiance (G) uncertainties					
Calibration reference device	0.5% (primary ref cell)	1.6% (reference module)	1.6% (reference module)	1.6% (reference module)	1.2% (secondary ref cell)
Spatial non-uniformity	1%	NA	1.09%	0.5%	0.5%
Spectral mismatch	0.5%	0.1%	3%	0.1%	1%
Positioning	0.17%	0.15%	0.37%	NA	2%
Temperature (T) uncertainties					
Temperature sensor	0.18°C (RTD)	1°C (IR)	1°C (IR)	1°C (ECT)	0.18°C (RTD)
Temperature uniformity	0.5°C	1°C	1°C	NA	4°C
STC correction uncertainty					
G/T correction	NA	0.65%	0.8%	0.5%	0.5%
Combined expanded P_{max} uncertainty (k=2, >95%)	**±1.6%**	**±2.0%**	**±3.4%**	**±2.4%**	**±3.1%**

Note: Only temperature and optical uncertainty contributions are here listed, being the main source of differences between laboratory and field inspections. The other contributions e.g. data acquisition uncertainties are not shown.

5 Validation of test procedures

5.1 Mobile solar simulator measurements versus laboratory measurements

Three mono c-Si modules were chosen for validation of the test procedure. To cover a wide range of current c-Si module technologies with different spectral response and cell capacitance, a p-type PERC half-cut, an n-type IBC, and an n-type HJT half-cut module have been selected. The modules were first stabilised (indoor light soaking accord. IEC 61215) and measured at SUPSI with an uncertainty of ± 1.6 % (k = 2) and sent to SPF. There the measurements were repeated in the mobile lab for module temperatures of 25 °C ±1 °C. The standard n-type reference module (see 2.2) is used and no spectral mismatch correction applied. The procedure insofar differs from the one described in chapter 4.

Table 6 shows the measurement results for the different module parameters of the three reference modules at SUPSI and SPF. The last column includes the deviation of P_{max} measured with the respective standard test procedure to the measurement method of P_{max} for capacitive modules. This is for SUPSI I-V curve measurement with a sweep time of 10 ms versus steady state measurements (multiple flashes at constant voltage) and for SPF I-V curve measurement with a sweep time of approx. 150 ms versus stepwise measurement as described in chapter 2.4.

The results show a good match. For the PERC and the IBC module the difference in P_{max} is less than 0.5 %, only the HJT shows a slightly higher deviation of 1.3 % (compare Table 6 and Figure 10). It can be concluded, that the spectral response of the first two matches well with the reference module, while the spectral mismatch for the HJT in combination with the MBJ Flasher seems to be higher.

Table 6: Comparison of the measurement results of the three reference modules at SUPSI and SPF.

Cell technology		Pmax [W]	Uoc [V]	Isc [A]	Umpp [V]	Impp [A]	ΔPm cap/standard
Mono n-type HJT half-cut	SUPSI	360.62	44.30	10.24	37.44	9.63	8.94%
	SPF	355.78	44.23	10.10	37.31	9.54	0.88%
	ΔSPF/SUPSI	-1.34%	-0.16%	-1.29%	-0.34%	-1.01%	
Mono n-type IBC	SUPSI	388.60	75.88	6.34	65.15	5.97	11.26%
	SPF	388.10	75.82	6.32	64.93	5.98	0.89%
	ΔSPF/SUPSI	-0.13%	-0.07%	-0.36%	-0.34%	0.20%	
Mono p-type PERC half-cut	SUPSI	355.94	40.88	10.94	34.17	10.42	0.51%
	SPF	354.27	40.80	10.86	34.06	10.40	0.25%
	ΔSPF/SUPSI	-0.47%	-0.20%	-0.80%	-0.30%	-0.17%	

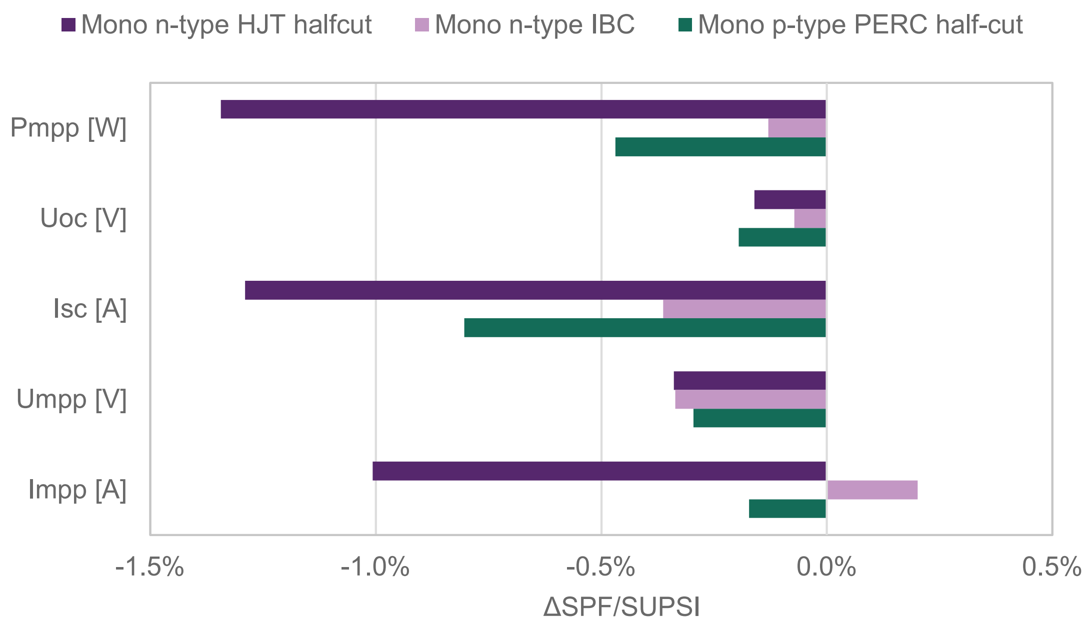


Figure 10: Deviation of measurement results at SPF compared to the results at SUPSI of the three reference modules.

5.2 Daylight I-V measurements versus laboratory measurements

5.2.1 PV test facility

To validate the uncertainty of string measurements in the field a small open-rack mounted reference system was built at SUPSI composed of 2 strings with five PV modules each with a nominal power of respectively 265 Wp and 270 Wp and a third string with eight 245 Wp modules. The system is oriented south/south-west and the inclination is 30°. The modules of the last string have power optimizers, which can be bypassed for the purpose of testing. The system was designed with a special interconnection box which allows to change string configurations and cable resistances to simulate different system configuration and the possibility to insert modules with failures for the validation of field diagnostic tools.

Figure 11: Picture of the PV string test facility installed at SUPSI (Campus Mendrisio).

5.2.2 Laboratory testing

The modules, taken from a former R&D project, underwent different test sequences and periods of outdoor exposure over its lifetime, leading to a mismatch between the modules. To have a clear picture of their actual performance all modules were re-tested indoor before being installed on the new test facility. Table 7 shows the measured STC parameters of the 5 modules of string 1 (M1-M5) selected for the purpose of this validation and the indoor stored reference module (REF), together with the standard deviation of the string modules.

Table 7: Measured P_{max}, I_{sc} and V_{oc} at STC.

Lable	Pmax [W]	Voc [V]	Isc [A]
REF	257.03	38.96	8.80
M1	259.62	39.11	8.86
M2	256.62	38.88	8.82
M3	252.53	38.57	8.77
M4	257.74	38.98	8.87
M5	255.40	38.66	8.85
StDev (M1-M5)	**1.04%**	**0.53%**	**0.46%**

To get a better idea about the variability of the modules also the relative efficiency at different irradiances was measured. Figure 12 shows a zoom of I_{sc} and V_{oc} and the irradiance dependency of each module compared to the reference module, whereas Figure 13 shows the respective electroluminescence images.

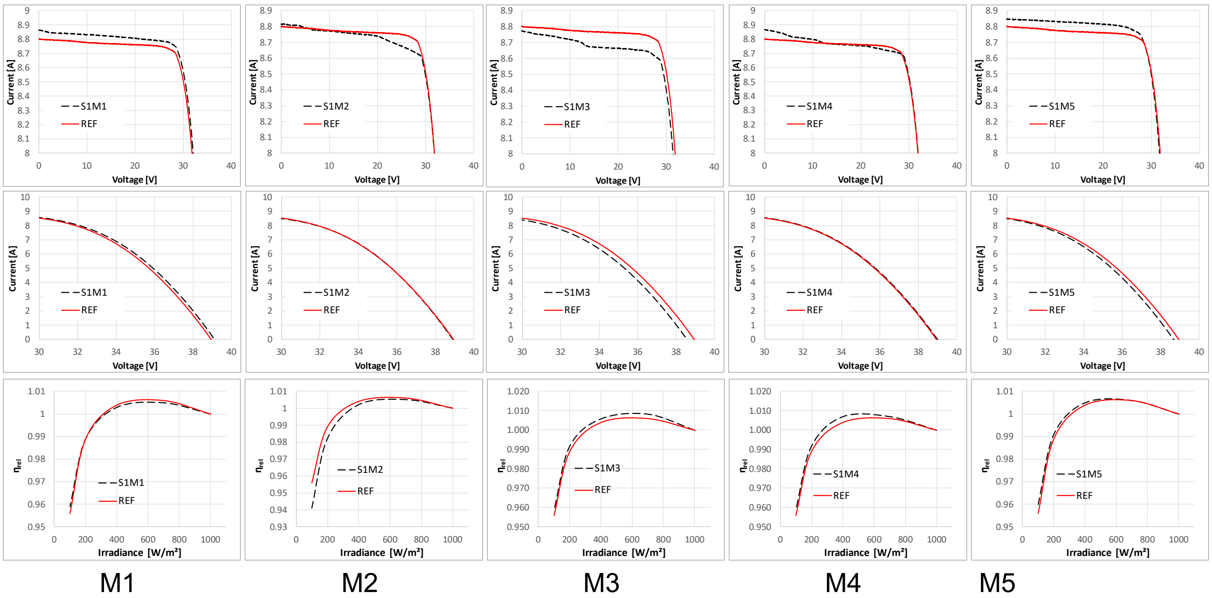


Figure 12: Indoor characterisation of the 5 modules under test compared to the reference module. Line 1: Zoom of I_{sc}@STC; Line 2: Zoom of V_{oc}@STC; Line 3: relative efficiency in dependence of irradiance.

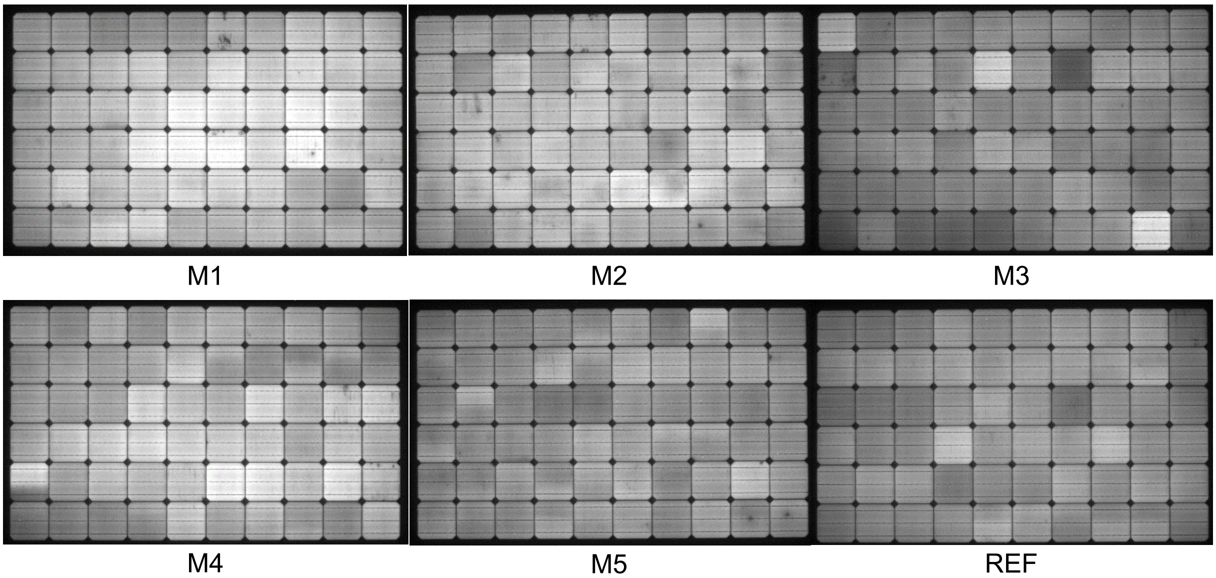


Figure 13: Electroluminescence images of the 5 modules under test and the reference module.

The module characterisation highlighted some cell mismatch and micro-cracks. These differences will have a direct impact on the accuracy of the STC performance measurement performed in the field. The deviations in low light performance are relatively low.

5.2.3 Calibration of reference module

For the purpose of the STC correction of the field measurements a reference module was characterised according IEC 60891:2021 and the correction parameters were determined with the tool described in section 3.5. The so obtained parameters, are shown in Table 8.

Table 8: IEC 60891 ed.3 (method 2) correction parameters.

Correction parameters	description	value
alpha	rel. short-circuit current temperature coefficient	0.0559 %/ºC
beta	rel. open-circuit voltage temperature coefficient	-0.3053 %/ºC
B1	linear VOC irradiance correction factor	0.046109
B2	non-linear VOC irradiance correction factor	0.001998
Rs	internal series resistance	0.3675
k	Rs temperature coefficient	0.00339
Isc,stc	short-circuit current @STC	8.799
Voc,stc	open-circuit voltage @STC	38.953

5.2.4 Field testing and STC correction

A step by step approach was followed for the validation of the field measurements with the two I-V curve tracers (see chapter 3.3). In the first run (run 1) each single module was measured with the h.a.l.m and immediately after with the Tritec system followed by the consecutive connection of an additional module until the full string lengths of 5 modules was achieved. The sequence was then repeated the other way around (run 2). The measurements were performed before noon during a clear sky day in October with small irradiance variations. The irradiance was in the range of 700-900 W/m² and module temperatures in the range of 29-38°C.

For the STC correction three different scenarios, using different Irradiance (G) and temperature (T) inputs were analysed:

- **Scenario 1:** G and T correction based on the DUT $I_{sc,stc}$ and $V_{oc,stc}$
- **Scenario 2 (best case):** G and T correction based on the REF $I_{sc,stc}$ and $V_{oc,stc}$
- **Scenario 3 (worst case):** G and T correction based on sensor data (reference cell and PT100)

The analysis of the STC measurement accuracy in the field with different scenarios is here separated into module and string measurements.

<u>STC correction of single module measurements</u>

The **scenario 1** is never occurring in a real inspection, where the $I_{sc,stc}$ and $V_{oc,stc}$ of the DUT is unknown. This analysis is however important to get an idea about the accuracy of the STC correction with the best available irradiance and temperature values. On one hand the equivalent cell temperature (ECT) calculated with $I_{sc,stc}$ and $V_{oc,stc}$ of the DUT gives the real average cell temperature of the module, and on the other hand the calculated effective irradiance ($G_{Isc,ref}$) avoids the spectral mismatch error one has with a not perfectly matched reference cell.

Figure 14 a) gives on the left the results for the single modules measured with the h.a.l.m system and on the right with the Tritec system. For the h.a.l.m system the deviations between outdoor STC corrected and indoor measured values are within ±0.1% for I_{sc} and V_{oc} and ±0.5% for P_{max}. For the Tritec system the deviations reach slightly higher values up to ±0.5% for I_{sc} and ±1.5% for P_{max}. The increase for the TRI-KA is mainly due to differences in the quality of the I-V curves when measuring a single module (e.g less data points, higher start voltage, higher sweep speed) which leads to a less accurate measurement or interpolation of the final I_{sc} and P_{max} values.

The **best case (scenario 2)** is the one where one or more reference modules are calibrated in the laboratory before going into the field and the measured $I_{sc,stc}$ and $V_{oc,stc}$ values are used to calculate the effective irradiance $G_{Isc,ref}$ and equivalent cell temperature ECT.

Figure 14 b) shows the deviations between the outdoor STC corrected and indoor measured values. Due to the variability in I_{sc} and V_{oc} within the modules, described in paragraph 5.2.2 and represented by the standard deviation in Table x, the deviation in Figure x b) is increasing in accordance. The error caused by the deviating I_{sc} and V_{oc} adds up to the P_{max} error observed in the best case scenario. For the h.a.l.m system the deviations between outdoor STC corrected and indoor measured values reach up to ±1.0% for I_{sc} and V_{oc} and ±2.0% for P_{max}. For the Tritec system the deviations reach slightly higher values up to ±1.1% for I_{sc} and V_{oc} and ±2.5% for P_{max}.

The **worst case (scenario 3)** is when the irradiance and temperature is measured with a reference cell and a temperature sensor attached to the back of the module. This method is the standard approach when the modules are easily accessible. An inter-comparison of measured (sensor based) and calculated G and T (I_{sc} and V_{oc} based) values is always recommended to identify any problems in the measurement or system quality.

In this case the standard approach leads, as shown in Figure 14 c), to a systematic overestimation of the I_{sc} value. The deviation is caused by the spectral mismatch between the reference cell and the DUT and the calibration uncertainty of the reference cell. The mono SENSOL sensor depicted in Figure x was here used. The open circuit voltage V_{oc} is instead mostly underestimated due to the fact that the on the back side measured temperature is always 1-3 °C lower than the internal cell temperature. Positive deviations are imputable to the non-uniformity of the module temperature in combination with the positioning of the sensor on a hotter cell with respect to the average cell temperature. A central position was here maintained for all modules. For both systems, the deviations between outdoor STC corrected and indoor measured P_{max} were in the range of ±2.0%.

a) Scenario 1

b) Scenario 2 (best case)

c) Scenario 3 (worst case)

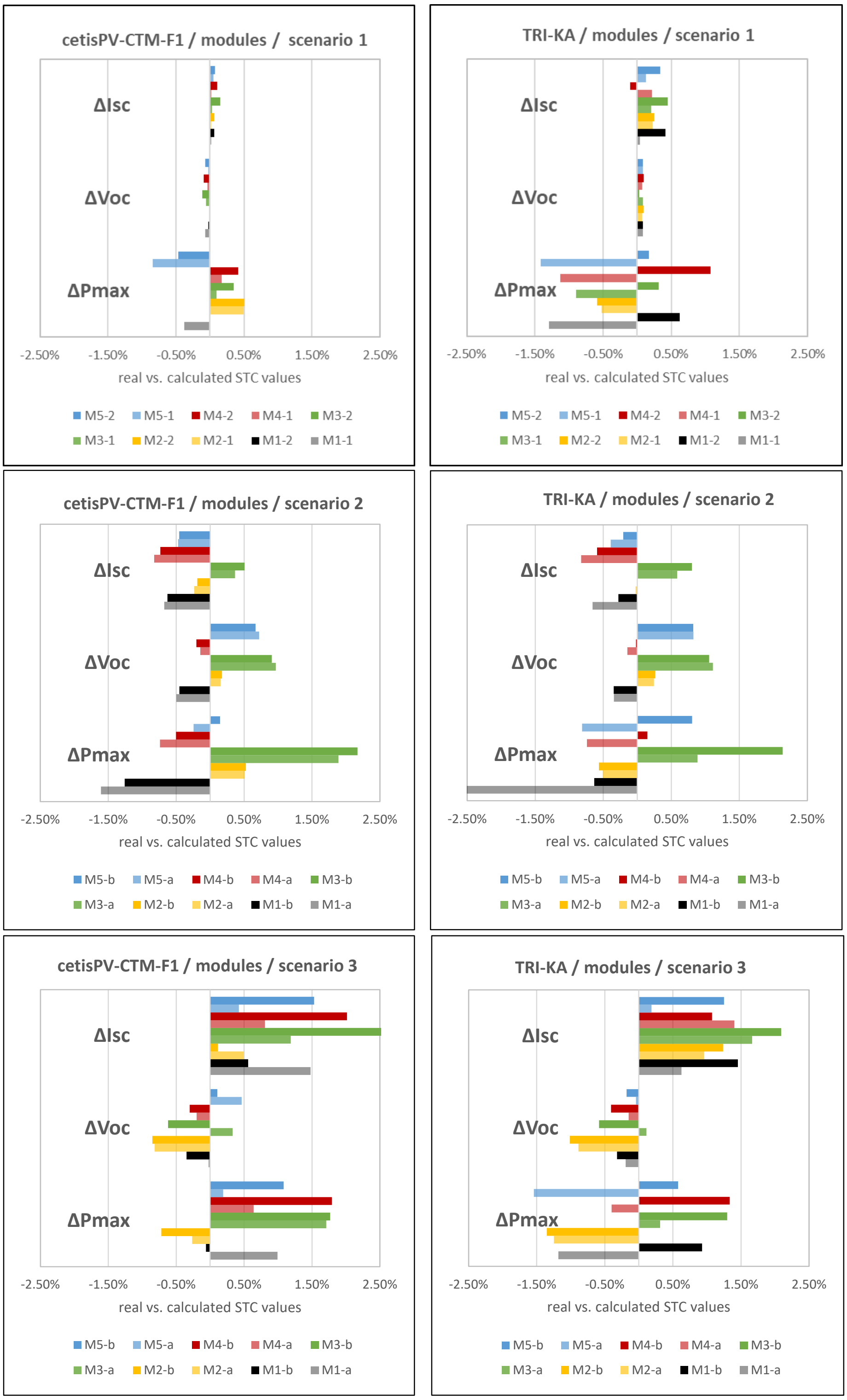


Figure 14: Deviation between the STC corrected outdoor and indoor measured values (I_{sc}, V_{oc} and P_{max}) for each module (M1 to M5) for the 3 scenarios. For each module two measurements made at different times (run1 and run2) are depicted (e.g. M1-a in light grey and M1-b in black). The left figure shows the results obtained with the h.a.l.m I-V tracer and the right with the Tritec I-V tracer.

STC correction of in series connected modules

In the case of serially connected PV modules the measurement allows only statements about the average performance of the PV modules, which results from the measured quantities of P_{max}, V_{oc} and I_{sc} divided by the number of modules in series. Usually, these values are compared to the data sheet values. For the purpose of this validation, the outdoor STC corrected values of n in series connected modules were compared to the calculated values of each string. The indoor measured I-V curves (see Table 7) have been combined to get the theoretical I-V curve of each string (Sn). Cable losses are here neglected.

Figure 15 a) shows the deviations for respectively 2, 3, 4 and 5 in series connected modules and by taking ECT and $G_{Isc,stc}$ as input (**best case**), whereas Figure 15 b) shows the deviations achieved when taking the measured (sensor based) irradiance and temperature as input (**worst case**).

a) Scenario 2 (best case)

b) Scenario 3 (worst case)

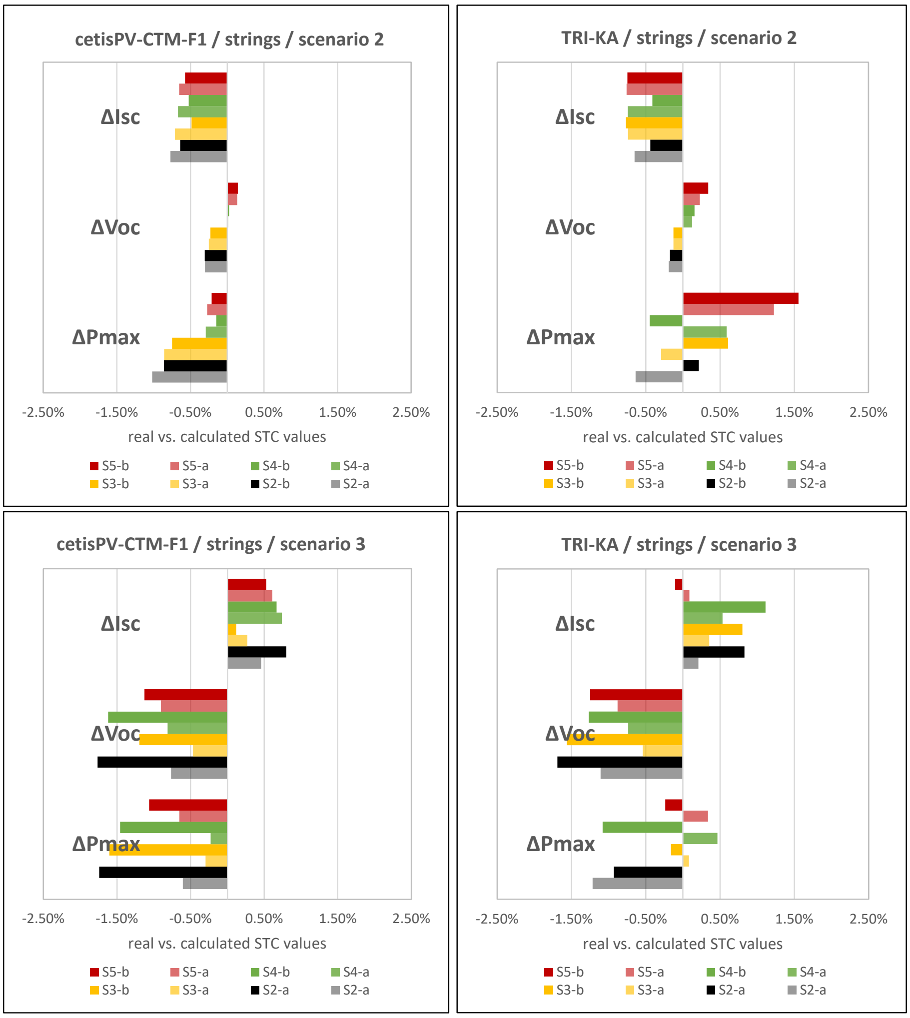


Figure 15: Deviation between the STC corrected outdoor and calculated reference values (I_{sc}, V_{oc} and P_{max}) for n (2, 3, 4 and 5) in series connected modules (Sn) for two different scenarios. For each string configuration two measurements at different times (run1 and run2) have been done (e.g. S2-a in light grey and S2-b in black). The left figure shows the results obtained with the h.a.l.m I-V tracer and the right with the Tritec I-V tracer.

In the **best case** both measurement systems lead to V_{oc} values which remains within ±0.35% and I_{sc} within ±0.8% respect to the expected value. With the h.a.l.m system a slight under-estimation of P_{max} of up to 1.0% is observed, whereas for the Tritec system deviations are slightly higher with a maximum over estimation of 1.6%.

In the **worst case**, the deviations for V_{oc} increases up to 1.6% due to the larger uncertainty in the determination of the string temperature. Due to the spectral mismatch of the DUT respect to the reference cell the I_{sc} is instead overestimated. Both systems lead to a deviation in P_{max} of maximum -1.8%.

6 Conclusions

SUPSI improved its test procedure for the STC measurement of PV modules and strings in the field achieving a measurement uncertainty of ±2.4 % (u % [k = 2]) when using a calibrated reference module for the determination of the correction parameters, as well as for the determination of the effective irradiance and equivalent cell temperature of the system.

Thanks to the implementation of a new I-V curve box, modules with high cell capacitance like HTJ or IBC modules can now be measured with SPF's mobile flasher without any measurement artefacts. With the set up best practice recommendations, the measurement uncertainty for the mobile flasher could be reduced to ±2.0 % (u % [k = 2]) when using a calibrated and spectrally matched reference module.

7 Dissemination

The know-how collected in the framework of this project was implemented into the IEA PVPS Task 13 technical report 'Good Practice Recommendations to qualify PV Power Plants using Mobile Devices' [2], presented also at the IEA PVPS Task 13 parallel Event of the 38th EU PVSEC.

8 References

[1] IEC 60891 edition 3.0, Photovoltaic (PV) devices - Procedures for temperature and irradiance corrections to measured I-V characteristics, International Electrotechnical Commission, 2021.

[2] Report IEA-PVPS T13-24:2021 'Qualification of Photovoltaic (PV) Power Plants using Mobile Test Equipment', ISBN 978-3-907281-12-3, 2021.

[3] C. Monokroussos, H. Müllejans, Q. Gao, and W. Herrmann, "I-V translation procedure for higher accuracy and compliance with PERC cell technology requirements," 38th EUPVSEC, 2020.