# Actual issues on power measurement of photovoltaic modules

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ABSTRACT

Power measurements of PV reference modules can, at standard testing conditions (STC), show tolerance deviations of up to ±3%, greatly affecting the maximum power output and thereby lowering the overall energy yield of the installation. Despite some existing technical problems, there is an urgent need on the part of the photovoltaic community to achieve more accuracy in power measurements in respect to the ever-growing production volumes. Some approaches being undertaken to carry out high-quality power measurements are addressed in this paper. The deviation from an ideal simulator performance are shown and discussed for two types of simulators, with reference to the most relevant parameters: irradiance level, deviation from homogeneity, spectral mismatch and temporal stability.

## Introduction

Maximum power output $P_{max}$ at standard testing conditions is directly related to the commercial value of photovoltaic modules (€/$W_p$). Its actual deviation from the nameplate value is a hot topic as it is the most obvious reason for reduced energy yields in the field. Other common explanations for low yields are factors such as bad system design or installation issues and/or poor performance ratios, instabilities or failures of the modules in the field. Deviations from $P_{max}$ are the result of a combination of the width of the sorting classes used by the manufacturer, the uncertainty of the measurement by their sun simulator, and the tolerances of the reference module used for calibration. The reference modules are provided by independent institutes, which perform precision measurements in accordance with given international standards. Actual round-robin comparison tests demonstrate that the tolerances on STC power outputs show a deviation of ±3% for c-Si single-junction reference modules and even more for multi-junction cell modules.

$$\text{Non-uniformity}\,[\%] = \left[\frac{\max irradiance - \min irradiance}{\max irradiance + \min irradiance}\right] \times 100\%$$

Equation 1.

## Deviation from homogeneity of irradiance

The definition for deviation from homogeneity or relative non-uniformity is given in IEC 60904-9:2007, Ed.2 as shown in Equation 1 below.

Figs. 1 and 2 show the measured deviation from uniformity of irradiance distribution for two different solar simulators.

According to IEC 60904-9:2007 Ed.2, the maximum deviation in uniformity for a class A sun simulator is ±2%. The measured uniformity of ±0.3% on a Pasan SSIIIb achieved that requirement very easily. Uniformity of a simple light-soaking test bench (class C) is given in Fig. 2. The standard states that the maximum non-uniformity is ±10%, which is 33 times higher than that of the Pasan simulator. The resulting effect of non-uniformity on the I-V characteristics of a PV module is shown in Fig. 3.

A uniformity of 2% – the permitted limit for a class A sun simulator – leads to an underestimation of up to 1.7% of STC power output ($P_{max}$) as shown in Fig. 3. The actual deviation depends on the mismatch of the short-circuit currents of the cells or balance of currents in the module.

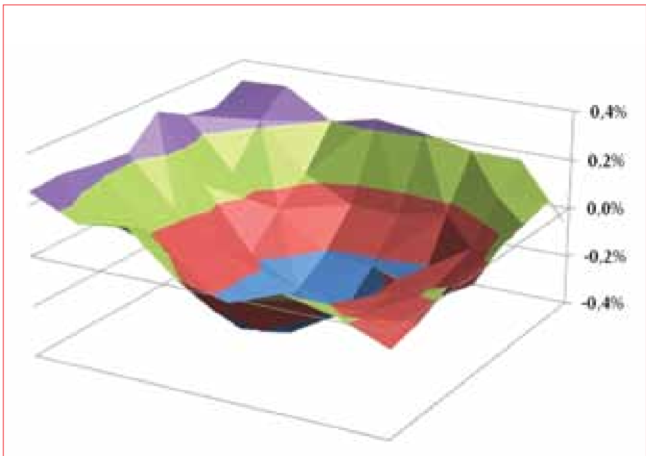


Figure 1. Deviation from uniformity distribution of irradiance on a 3.0m × 3.0m plane of measurement for a class A sun simulator (Pasan SSIIIb).

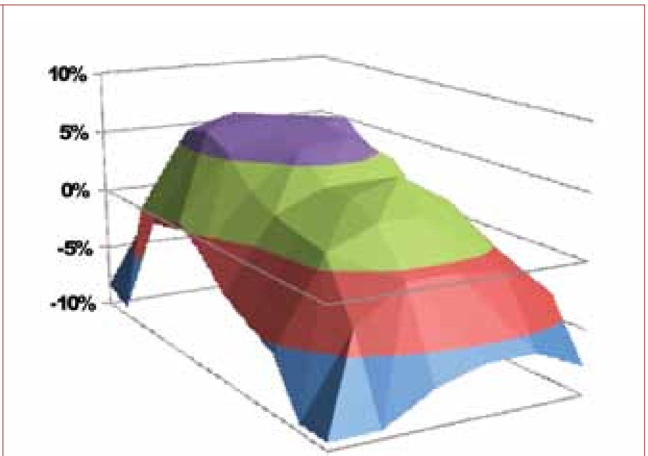


Figure 2. Deviation from uniformity distribution of irradiance of a class C sun simulator (PI light soaker using 8 HQI lamps at PI Berlin) on a 2.2m × 1.3m plane.

For the most relevant characteristics of a module ($I_{sc}$, $P_{max}$, FF, $V_{oc}$), the effects brought about by the deviation of irradiance from uniformity on the change power output measurement are demonstrated in Fig. 4.

As can be observed in Fig. 4, the decrease in uniformity leads to a slight increase in FF, but an overall drop of $P_{max}$ as a result of the dominating decrease of $I_{sc}$. We must conclude that uniformity of irradiance is quite relevant for the correct measurement of $P_{max}$. It is usually not possible to correct the measurement by a simple factor for compensation, but the Pasan IIIb sun simulator showed a minimal error due to this effect.

## Spectral mismatch of the simulator spectrum

The IEC 60904-9:2007 Ed.2 standard states that a class A simulator is allowed to deviate less than ±25% from the AM $1.5_G$ spectrum (as defined in IEC60904-3 Ed.1). It also says that a class B simulator should deviate less than ±40% and a class C sun simulator less than -60%/+100%.

In order to overcome the problems posed by different spectra, a correction factor for the current depending on the spectrum of the sun simulator – the Mismatch Factor (MMF) – is introduced. The MMF is a correction of the current of a test specimen according to IEC 60904-7:1998 Ed.2, as shown in Equations 2 and 3. MMF is essentially a function of the relative spectral response of the specimen and the reference cell, and of the mismatch between the reference spectrum (AM $1.5_G$) and the spectrum of the sun simulator. Only the current is affected by this correction, and, as a consequence, the current $P_{max}$.

$e_{STC}(\lambda)$ relative reference spectrum AM$1.5_G$
$e_{sim}(\lambda)$ relative simulator spectrum
$s_{TC}(\lambda)$ relative spectral response of the Test Cell
$s_{RC}(\lambda)$ relative spectral response of the reference cell (e.g. WPVS)

$$I_{SC}^{AM1.5} = \frac{1}{MMF} \cdot I_{SC}^{Simulator}$$

Equation 2.

$$MMF = \frac{\int_{\lambda_{01}}^{\lambda_{e1}} e_{STC}(\lambda) s_{RC}(\lambda) d\lambda}{\int_{\lambda_{01}}^{\lambda_{e1}} e_{sim}(\lambda) s_{RC}(\lambda) d\lambda} \cdot \frac{\int_{\lambda_{00}}^{\lambda_{e0}} e_{sim}(\lambda) s_{TC}(\lambda) d\lambda}{\int_{\lambda_{00}}^{\lambda_{e0}} e_{STC}(\lambda) s_{TC}(\lambda) d\lambda}$$

Equation 3.

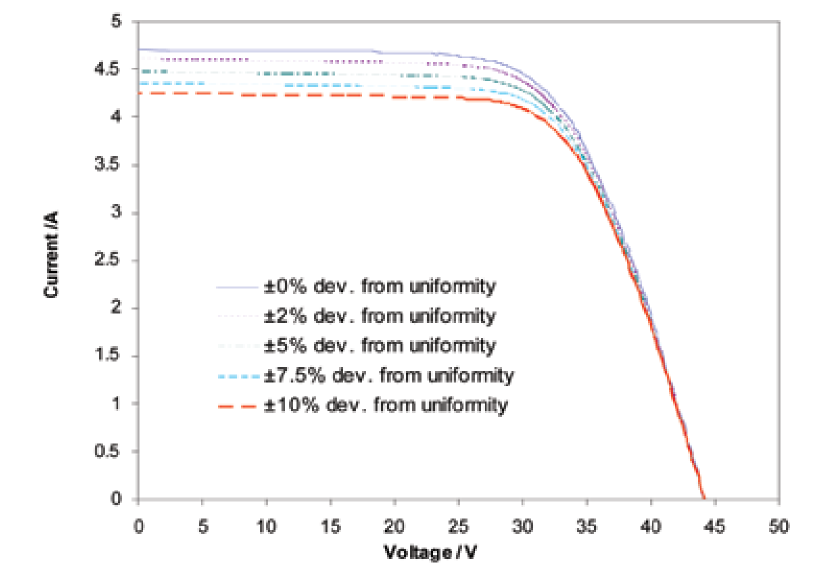


Figure 3. Change of I-V characteristics using the deviation from uniformity of a sun simulator as a parameter. The curve of this module has been calculated by summing up the voltages at equivalent currents of the single cell curves involved. The currents were then modified with the deviation from uniformity of irradiance in the plane of measurement as described in [1].

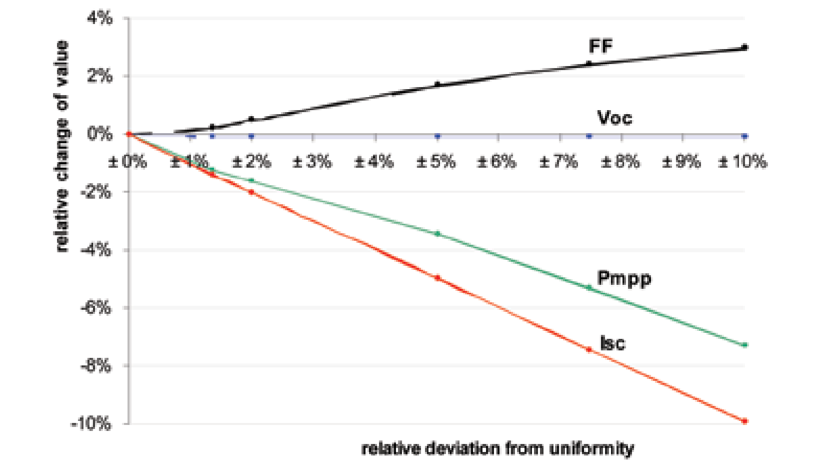


Figure 4. Change of curve parameters FF, $V_{oc}$, $P_{max}$ and $I_{sc}$ as a function of the simulator's deviation from uniform irradiance on the test plane (as shown in Fig. 1). Graph shows a slight increase in FF and a strong decrease in $I_{sc}$, leading to a decrease in $P_{max}$ ($P_{mpp}$). Test conducted on a module comprised of 60 crystalline silicon cells.

Fig. 5 shows the measured spectral deviation of the Pasan class A sun simulator from the AM $1.5_G$ spectrum and of the aforementioned light-soaking test bench. As expected, the class C simulators will produce larger scattering in $P_{max}$ than the class A simulator. The larger spectral deviation from AM $1.5_G$ results in larger spectral mismatch correction factors for the modules and therefore in an increased uncertainty of $P_{max}$. The uncertainty of $P_{max}$ is caused by the uncertainty of the spectral response of each test specimen.

Modern class A simulators (as the Pasan SSIIIb) show spectral mismatches of less than ±6% for all spectral intervals over the whole time interval of the flash duration, as demonstrated in Fig. 6 (measurement by PI, Pasan and TÜV Rheinland). Due to the increasing bulb temperature during the measuring period of 8ms, the blue part of the spectrum increases at the final part of the measurement and therefore the mismatch factor MMF changes slightly (by less than 0.001). This leads to a change of less than 0.1% in $P_{max}$ for single-junction cells.

The Pasan SSIIIb sun simulator at PI Berlin saw an MMF variance of ±0.4% for all single-junction cell technologies (relative to a MMF of 1.007 for single-crystalline silicon). The 'secondary reference' is provided by PTB (German National Institute for Scientific and Technical services), which is referred to their primary reference in cooperation with NREL (National Renewable Energy Laboratory) in the USA, JQA (Japan Quality Assurance Organization) in Japan and TIPS (Tianjin Institute of Power Sources) in China. Fig. 7 shows the MMF for different single-junction cell technologies.

For single-junction-celled modules the MMF is a simple function of the spectral response and the spectrum of the sun simulator. The deviations from true $P_{max}$ are caused by variation of spectral response within the technologies. The current mismatch between top and bottom for tandem cells is even more sensitive to the simulator spectrum than single-junction cells, as shown in Fig. 8.

Fig. 9 shows the spectral responses of a tandem cell. The top cell absorbs the bluish, and the bottom cell the reddish part of the irradiance. The current mismatch of both cells depends on the spectrum, thickness, and absorption coefficient of both layers. As the mismatch between the top and the bottom cell at AM $1.5_G$ lowers $P_{max}$ at STC, it also needs to be minimized for AM$1.5_G$. Optimizing the energy yield per module also accounts for the degradation in-field and real sky spectra at a certain location.

The standards currently propose mismatch correction using outdoor data at clear sky conditions close to AM $1.5_G$ (diffuse share <30%). Though spectral mismatch corrections for these cells is not feasible within a straightforward correction algorithm, the spectrum of the simulator needs to match AM $1.5_G$ (IEC 60904-3 Ed.2) as closely as possible.

The class A simulator being used in this experiment differs by 3% to AM $1.5_G$ in terms of current mismatch between the top and bottom cell for three different tandem cells under test, as shown in Fig. 8. In accordance with the difference in uniformity effect of $P_{max}$ and $I_{sc}$, an additional error of ±1% was estimated for $P_{max}$ due to the actual spectrum of the Pasan SSIIIb simulator at PI Berlin.

## Transient effects

The time taken to trace through and measure a whole I-V curve of a PV module in a sun simulator is known as sweep time. For modules with transient effects (such as CIGS, CdTe, CIS, and high-efficiency single-crystalline Si modules) the sweep time affects the measured $P_{max}$. In a simple model this effect can be described as a capacity in parallel to the generator, which has to be charged and discharged during the I-V tracing and the corresponding measurements. In order to avoid deviation in $P_{max}$ brought about by transient effects,



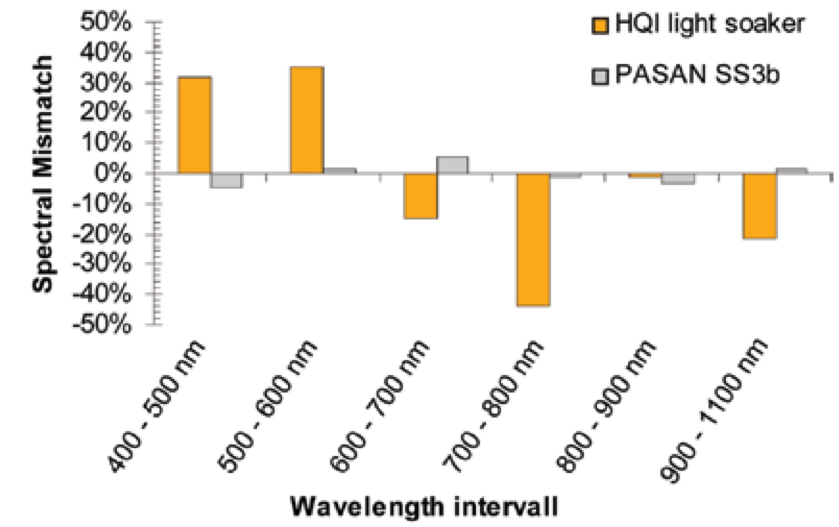


**Figure 5. Deviation from AM $1.5_G$ of two different solar simulators. Class C simulators will produce even larger scattering of $P_{max}$, because their spectral deviation from AM $1.5_G$ results in larger spectral mismatch factors for the modules under test.**

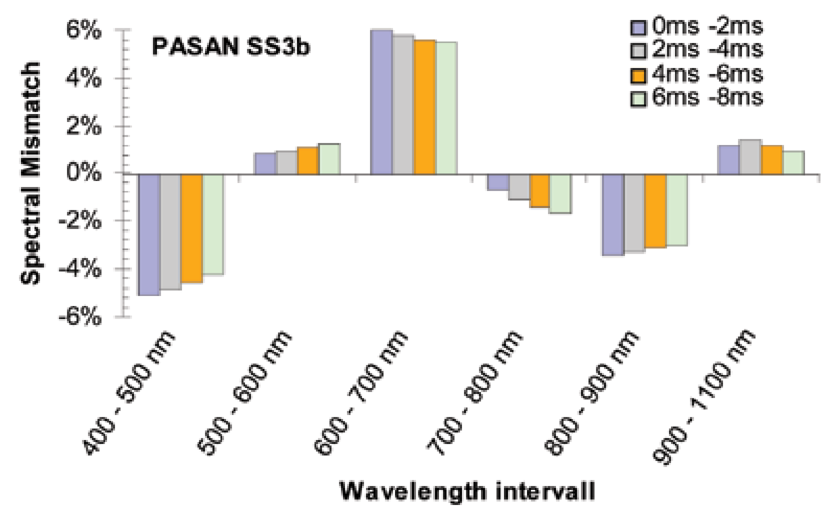


**Figure 6. Relative spectral mismatch compared to the AM $1.5_G$ reference spectrum as a function of flash duration of the Pasan SSIIIb sun simulator (measurements by TÜV Rheinland).**

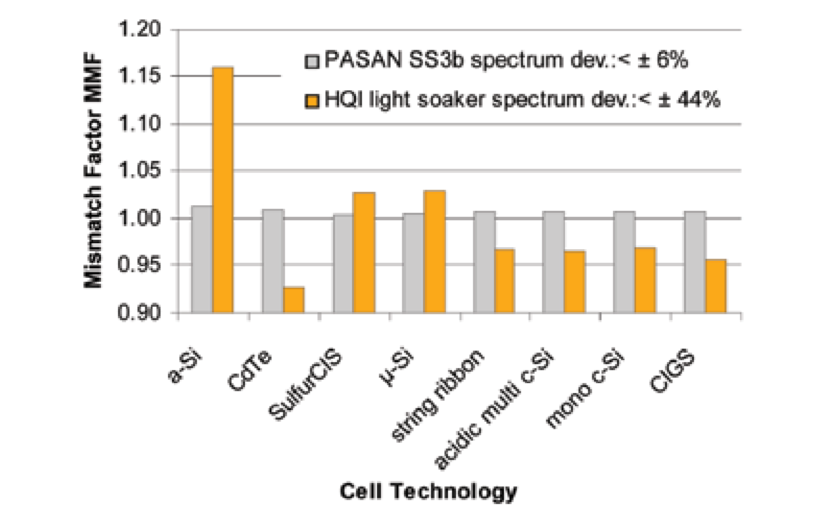


**Figure 7. Spectral mismatch factor for different solar cell technologies at two different solar simulators.**

it is necessary to sweep through the I-V curve using an appropriate time to allow charging of that capacity.

The graph in Fig. 10 shows the I-V curves resulting from the use of different sweep times for a CIGS module. The effects on the resulting $P_{max}$ for different technologies are shown in Fig. 11.

The maximum sweep time of the Pasan SSIIIb is 8ms, which proved to be sufficient for standard a-Si, mc-Si, and sc-Si modules (max. deviation of 0.5%). For the technologies shown in Fig. 11, a partial trace trough the I-V curve during the sweep time of 8ms is recommended in order to reduce measurement errors.

## Conclusion & outlook

In our experience, energy rating is most critical for thin-film technologies. For tandem-junction structures of e.g. µ-Si/a-Si, prediction of energy yield is complicated because of the interdependence of degradation and spectral effects. The main factors of uncertainty for STC measurements are given in Fig. 12.

The uncertainty of the $P_{max}$ measurement with a secondary reference from PTB in WPVS design leads to a combined expanded uncertainty of $P_{max}$ at ± 2.2% for U95 (coverage factor k = 2) for single-junction modules.

> "For modules with transient effects, the sweep time affects the measured $P_{max}$."

The error bars are garnered from c-Si modules measured at PI Berlin with their individual deviations from average values for the temperature coefficients $\beta = -0.33\%/K$; $\alpha = 0.06\%/K$; curve correction factor $\kappa = 6.7 \cdot 10^{-4} \Omega/K$ and the spectral mismatch of MMF = 1.007 with the Pasan SSIIIb sun simulator at PI Berlin, broken down as follows:

1. Spectrum deviation from AM $1.5_G$, IEC 60904-3 Ed. 2

   400–500nm: -5%;

   500–600nm: 1%

   600–700nm: 6%

   700–800nm: -1%

   800–900nm: -3%

   900–1100nm: 1%
2. Deviation from uniformity: ± 0.3% on 3m × 3m plane
3. Temporal stability (deviation 0.5%).

The combined expanded uncertainty of $P_{max}$ for tandem cell modules is 2.9% (k = 2) including an additional error of ±1.1% for the current mismatch experienced with that simulator spectrum.

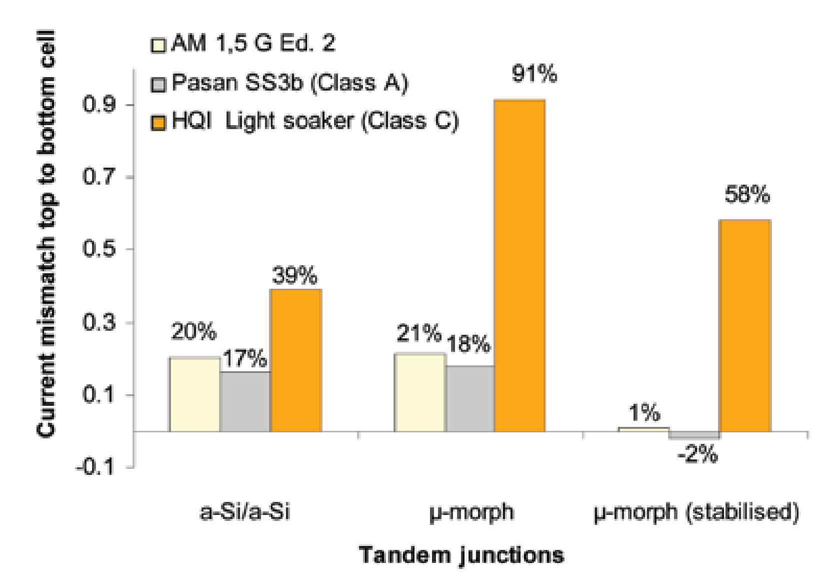


Figure 8. Mismatch of electrical currents between top and bottom cell for different spectra and tandem cell technologies (always in combination with a-Si as top cell). Although the cells are connected in series, the cell with the lowest current determines the performance.

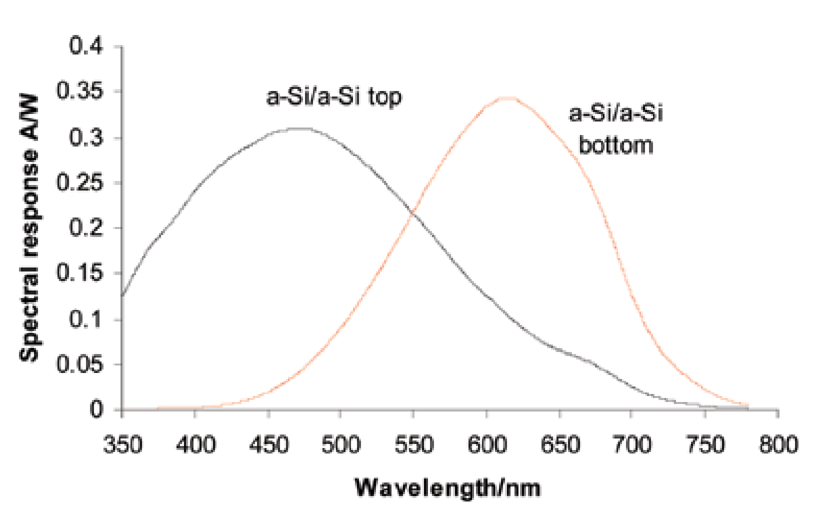


Figure 9. The spectral response of a tandem cell, showing the spectral responses of the top and bottom cell independently.

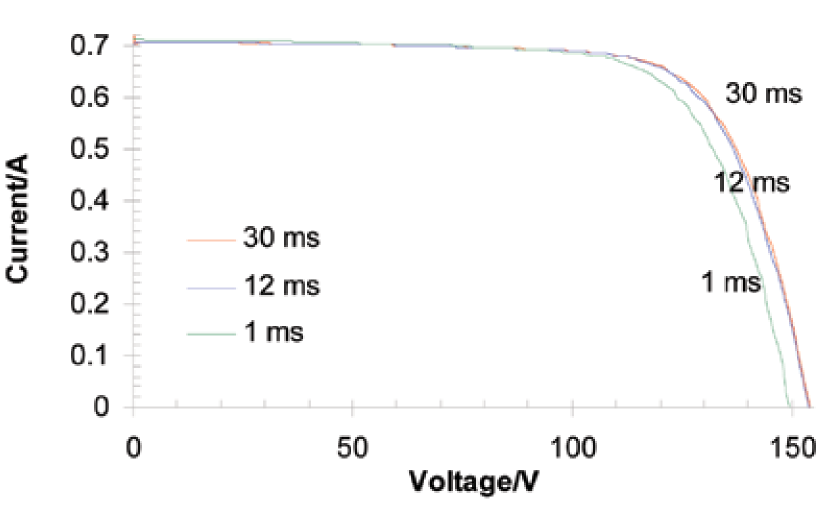


Figure 10. I-V curves resulting from use of different sweep times for CIGS.

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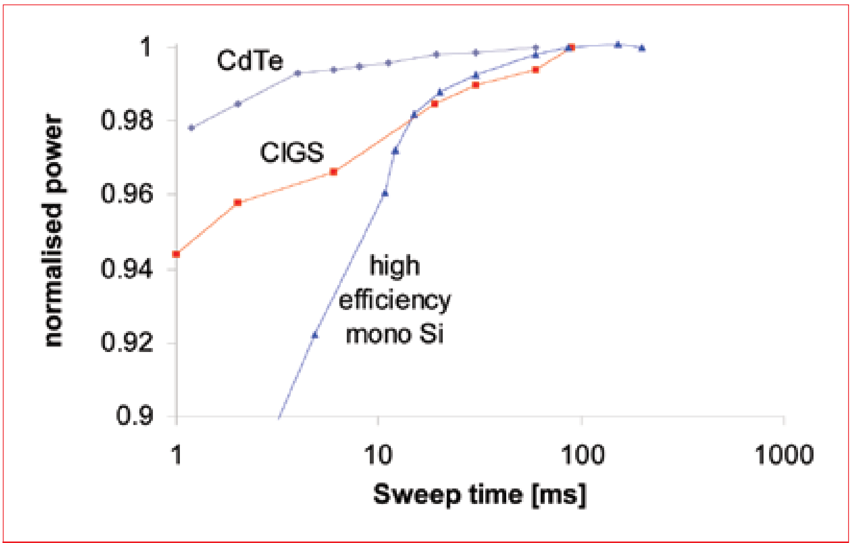


**Figure 11. Normalized power for different technologies vs. sweep time. The 'high efficiency mono-Si' cells are high-end back-contact sc-Si cells with efficiencies above 20%).**

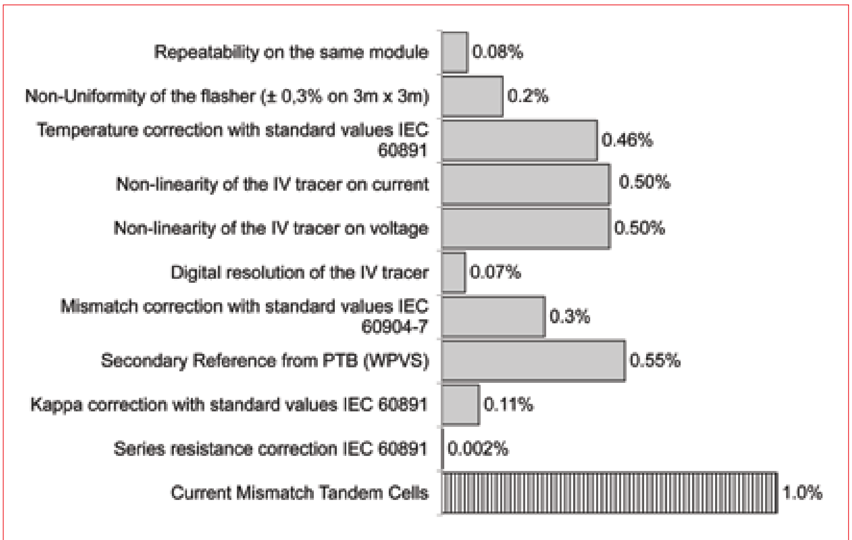


**Figure 12. Uncertainties of $P_{max}$ measurements.**

## About the Authors

**Prof. Stefan Krauter** received his Ph.D. in electrical engineering on the topic of 'Performance modelling of PV modules' from the University of Technology Berlin in 1993. In 1996 he co-founded Solon, and in 1997 he received a visiting professorship for PV systems at UFRJ-COPPE in Rio de Janeiro, and later at UECE in Fortaleza. On his return to Germany in 2006, he co-founded the Photovoltaic Institute Berlin where participates in the board of directors and acts as a senior consultant. He is a professor for PV Energy Systems at TUB and at the Biberach University for Applied Sciences (HBC).

**Dr. Paul Grunow** received his Ph.D. in physics in 1993 on 'Analysis of dynamics of charge carriers in Silicon and Silicon solar cells via photo-induced deflection of laser beams' from the Hahn Meitner Institute (now the Helmholtz-Center) and at the University of Technology Berlin (TUB). He pursued his post-doc studies on thin-film solar cells at the Federal University of Rio de Janeiro in Brazil (UFRJ-COPPE) and co-founded Solon AG in 1996. Together with Reiner Lemoine, he founded Q-Cells AG in 1998 and in 2006 he co-founded the Photovoltaic Institute Berlin where he is a member of the board of directors and acts as a senior consultant. He also lectured at the University of Applied Sciences for Technology and Economics Berlin (FHTW).

**Michael Schoppa** is head of the accredited and internationally accepted PV-testing laboratory of the PI Berlin AG. Since 2004, he has been a research associate at the Monash University in Melbourne, Australia and later worked at the Hahn Meitner Institute in Berlin where he was engaged in long-term stability on new solar concepts. From 2006 to 2007 he worked as a project engineer for TÜV Rheinland in the domain of international certifications. In addition to the formation of PI Berlin's PV-testing laboratory and quality management, Michael led the laboratory to national accreditation in 2008 and admission to the international CB Scheme (NCBTL) in 2009.

**Alexander Preiss** is responsible for the PV-Outdoor laboratory of PI Berlin AG, which is run in cooperation with the University of Technology in Berlin. From 2000 until 2007 he studied physics at the Humboldt University in Berlin and received his Master's degree in experimental solid-state physics. In his thesis he worked out a feasibility study for the optimization of CIS solar cells at the Hahn Meitner Institute. In 2007, he began the set-up of the outdoor laboratory of the PI Berlin AG and started his Ph.D. in the Department of Electrical Drives on 'Yield Simulation of PV generators' at the University of Technology Berlin.

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