LED solar simulators and new test approaches for high-efficiency solar cells

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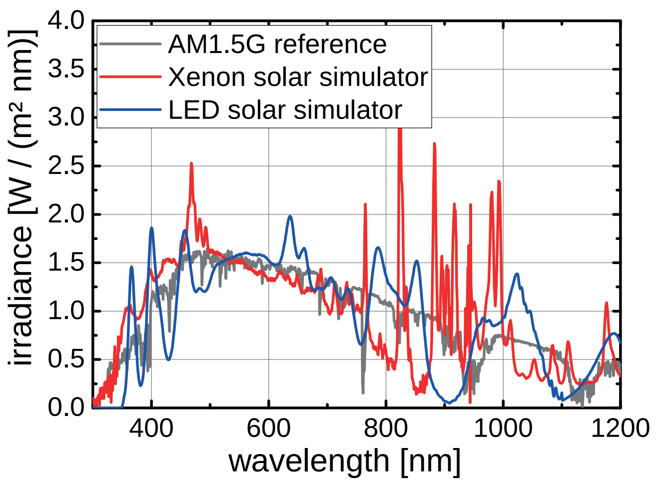
Abstract

Solar simulators are among the most important and fundamental measurement tools in photovoltaic production facilities as well as in R&D labs. Two major solar simulator technologies can be distinguished: xenon light sources and, more recently, light sources using light-emitting diodes (LEDs). While xenon solar simulators are a well-established technology, LED-based systems appear to be promising candidates for future applications, as they provide a higher flexibility with regard to the flash times, spectral light composition and intensity. Measurement recipes for power quantification under standard test conditions (STC) can be adapted to high-efficiency cells, which require longer flash times. Furthermore, fast inline spectral testing, such as a rapid external quantum efficiency (EQE) test or a rapid reflectivity test, becomes feasible. However, the development of LED-based systems requires well-designed optical and electronic components to ensure high-precision measurements on the basis of a laterally uniform and temporally stable light field.

Introduction

The most important solar cell or module characteristic is its output power, obtained by a current–voltage measurement under illumination. These measurements are performed, both in PV production and research labs, using artificial light with properties close to natural sunlight. In industry, virtually 100% of all cells and modules are characterized using solar simulators. The sorting of cells into various efficiency bins, and the pricing of the modules, rely on this data. For this reason, the requirements on the measurement procedure, as well as on the solar simulators as measurement devices, are described in several IEC standards [1]. In accordance with these standards, solar simulators are classified according to their spectral match, the lateral uniformity and the temporal stability of the irradiance.

Figure 1. Spectra of a LED solar simulator and a xenon-based flasher, in comparison to the AM1.5G reference spectrum.



Currently, there are two major solar simulator technologies available. First, there are the well-established *xenon-based solar simulators,* which are operated in either a flash mode or a steady-state mode, depending on the light source and field of application. Xenon lamps come with an irradiance spectrum that exhibits several sharp peaks on a broad background (see Fig. 1), which can be modified using optical elements such as filters. The light source itself is point-like, and shaping the lateral intensity requires lenses, apertures or light-guiding elements.

Second, there are the *solar simulators using light-emitting diodes* (LEDs), which have been gaining market share in recent years. Introduced around five years ago with the first commercial in-line LED lighting units, about hundred systems from different manufacturers are in operation today. The spectrum of the irradiated light is composed of the individual spectra of each LED type, and can be controlled by an electronic adjustment of the individual LED's power. The light engines are area-like, requiring a careful positioning of the individual LEDs, possibly combined with some special optical elements.

Either simulator technology must comply with the solar simulator standard, while different technical realizations exist, depending on the intended usage [2]. Typical spectra from a filtered xenon-based flasher and a 21-channel-LED solar simulator are presented in Fig. 1. The xenon spectrum shows good agreement with the norm spectrum for wavelengths below 800nm, whereas the contribution to the longer wavelengths is characterized by several sharp spectral peaks. The LED solar simulator spectrum, however, can be tailored to produce a fairly smooth representation of the AM1.5G reference spectrum defined in the norm, depending on the number of implemented LED colours.

Fields of application and requirements for solar simulators

In general, three fields of application for solar simulators can be distinguished.

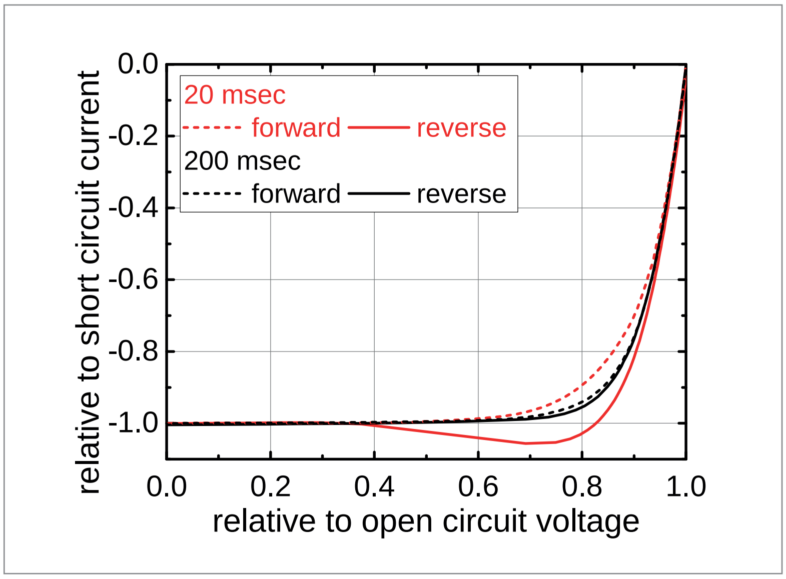
First, solar simulators are designed to provide high-quality data on the performance of solar cells and modules under standard test conditions (STC); here, a single fixed-measurement procedure is required which relies on a device to give precise and repeatable measurements. From a technical point of view, the focus therefore lies on a light source with minimal spectral mismatch when compared with the norm spectrum, and with a high temporal stability. All production tools and most R&D tools have to be designed to meet these requirements.

Second, solar simulators can be used for advanced quality control and loss analysis measurements; in this case, the solar simulator should provide the technical basis for more-flexible measurements beyond STC. This can include variations in intensity for series-resistance analysis, variations in the spectrum for spectral analysis, or variations in the measurement time for an analysis of capacity effects.

Third, extended solar simulator measurements can be employed for yield estimations and energy ratings, as well as supplying the data for a quantitative estimation of the levelized cost of electricity (LCOE) of PV power plants. For this solar simulator application, the measurement system has to provide specific measurement procedures adapted to non-standard spectra, and to measurements at different temperatures or with modifications to the angle of incidence.

In PV production, the emphasis is on fast and reproducible measurements, robust and reliable contacting solutions, short downtimes and low maintenance costs. R&D labs or calibration laboratories, on the other hand, usually focus on the realization of a much better-defined measurement

Figure 2. Hysteresis effect occurring between forward and reverse measurement directions, for a high-performance solar cell.



environment, such as temperature uniformity and stability, irradiance uniformity, and spectral accuracy and traceability. A second aspect in R&D labs concerns the flexibility of the measurement tools with regard to parameters such as the measurement times, the spectrum, the intensity of the irradiance, or the sample size.

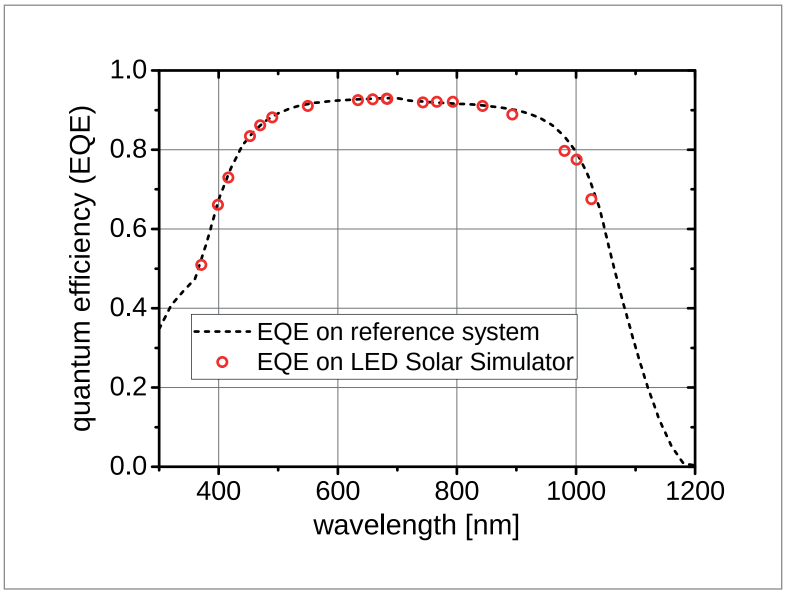


Figure 3. Typical EQE curve of a silicon solar cell, measured on a lab-based tool with a spectral resolution of 20nm over a three-minute measurement period, compared with the EQE based on an LED solar simulator, measured over 200ms.

Measurements under STC

Research labs usually have the means to repeatedly check the technical parameters of their solar simulators. A production tool, on the other hand, has to perform in a continuous operation mode for several weeks or months without the frequent application of more-sophisticated crosschecks on the measurement system. The ageing of the light sources is one example of an issue that might arise in this context: xenon-based systems show some shift in the spectrum and lose some of their intensity [3]. With a production cycle time of 1 sec per cell, the light sources are required to perform millions of flashes in a month; therefore, an exchange of the light source has to be performed on a regular basis when the flash bulb ageing has advanced too far. Similarly, xenon flash lamps exhibit a certain amount of spectral shift in the spectral match during a single flash [3]. From a technological point of view, these short- and long-time spectral shifts can be compensated in LED solar simulators if an appropriate feedback loop that controls the LED colours individually is implemented, ensuring stable spectral properties of the irradiance. Additionally, the lifetime of LEDs is significantly longer than that of xenon bulbs, although this depends somewhat on the wavelength of the particular LED. On the other hand, an exchange of individual LEDs is usually not possible in a short time, and so a very high level of quality control has to been ensured in the production of LED solar simulators. Hence, a well-designed LED solar simulator with an intrinsic control and feedback loop could lead to a reduction in maintenance and operation activities in PV production lines.

The better imitation of the AM1.5G reference spectrum by the LED solar simulator also results in a lower spectral mismatch correction factor for the short-circuit current. This is not just beneficial in R&D, where the spectral response (SR) of newly developed cell technologies differs from the spectral

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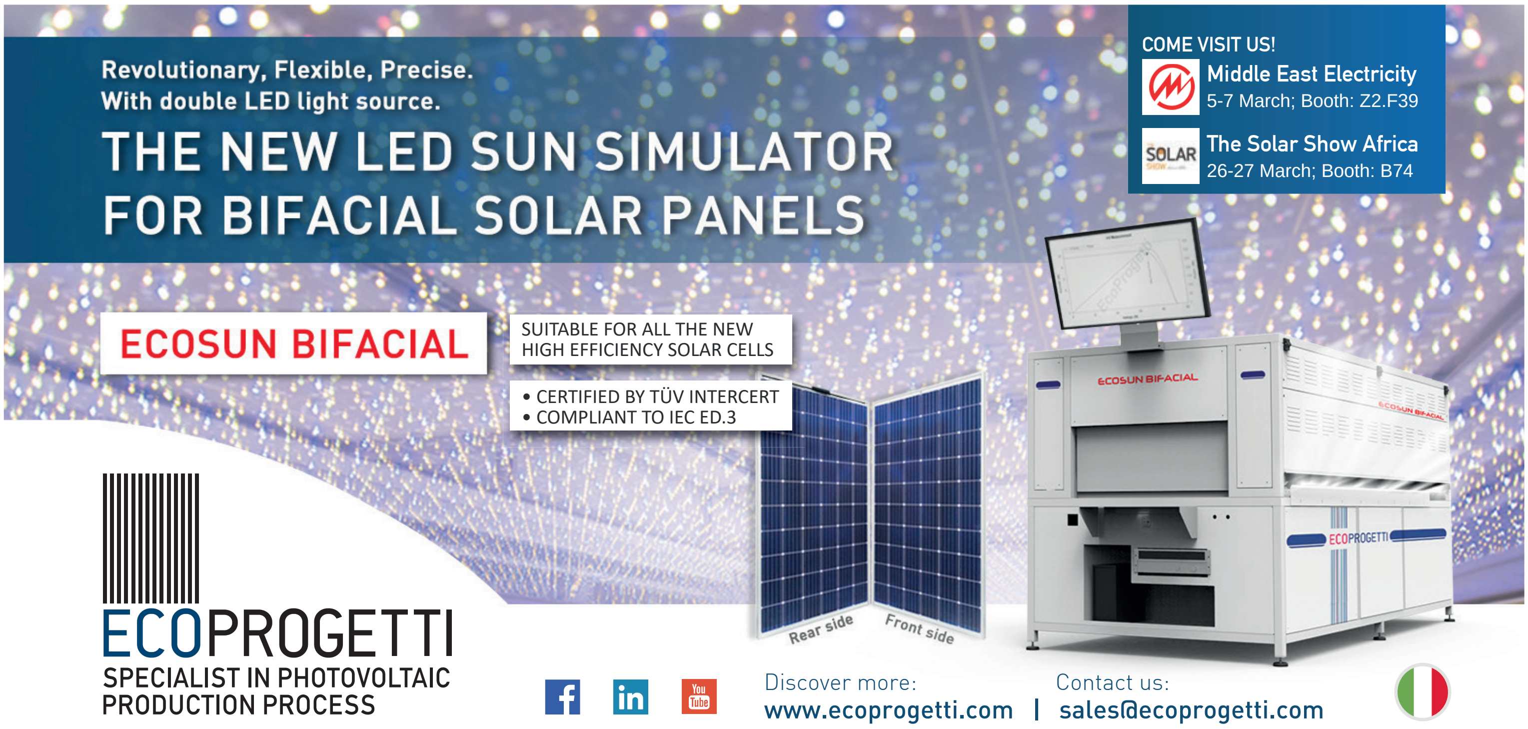

response of the available reference cells. It is also advantageous in production, where reference cells with a spectral response similar to that of produced cells *are* available, in which case the variations in spectral mismatch due to process variations are lower than for xenon-based systems [4].

New cell technologies and advanced quality control

Besides the maintenance and operation costs, a second aspect has recently come to light. More-advanced high-efficiency cell concepts, such as PERC/PERT or heterojunction cells, are increasingly coming onto the market; it is predicted that more than 50% of all cells will be comprised of these new technologies by 2020 [5]. Because of the longer charge-carrier lifetimes and the modified cell designs, these cell technologies are characterized by a higher internal capacitance. This effect can have some severe implications for the power measurement when performed over short time periods, as the resulting *I–V* curves exhibit some hysteresis effects, in dependence on the direction of measurement (Fig. 2).

The most straightforward approach to resolving the hysteresis issue is to slow down the measurements by increasing the sweep times; this also involves sufficiently long flash times, in some cases (such as for heterojunction cells) up to more than 100ms. While some xenon-based flash light measurement systems are capable of satisfying this requirement, this class of solar simulator is generally limited by the technical implementation of the flash bulbs. Consequently, a number of more-advanced measurement procedures have been developed for systems with limited flash times. The proposed solutions include:

- Implementation of adapted voltage ramps, e.g. Pasan's DragonBack® approach [6].

- Dynamic *I–V* curve measurements with adapted measurement times for each single point on the *I–V* curve, e.g. TUV Rheinland's approach [7].

- Multiple *I–V* curve measurements, e.g. Halm's advanced hysteresis approach [8], Endeas's capacitance compensation method (CAC) [9], and Fraunhofer CSP's approach [10].

In contrast, LED-based solar systems are highly flexible in terms of flash times, which can be electronically controlled and adjusted without any hardware changes if the system has an appropriate implementation of temperature control of the LEDs. This advantage can not only make more-sophisticated measurement approaches obsolete, but also allow new measurement approaches that provide the capacitance of a solar cell as an additional quality control parameter [10].

The new cell technologies mentioned earlier are accompanied by more-advanced front- and rear-side surface layers; for example, the major advantage of PERC solar cells results from the improved passivation of the rear side. Thus, fast and reliable inline-capable measurement approaches are needed in order to enable an adequate quality monitoring of individual cell components in modern production lines. Such a quality control

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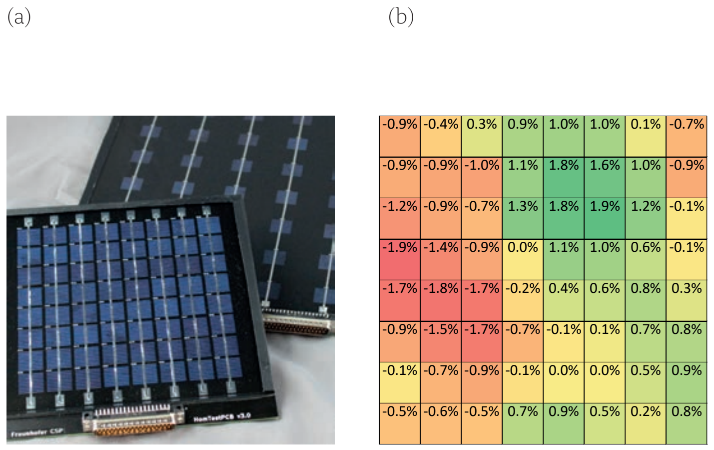
can be established by a depth-resolved loss analysis using spectral measurements, as developed by Fraunhofer CSP. This type of loss analysis can be performed by means of a rapid external quantum efficiency (rapid EQE, see Fig. 3) test, yielding insights into the electronic losses on the surfaces, in comparison to the bulk losses [11]. Some solar simulators are combined with imaging units, such as electroluminescence or infrared cameras, in which case a spatially resolved spectral measurement of the reflectivity (rapid REFL) can also be implemented [12]. On the basis of this rapid REFL measurement, a quantitative assessment and quality control of the passivation layer thickness and uniformity is feasible. Finally, the analysis of a multi-intensity measurement leads to very detailed information on the series resistance of a solar cell [13].

Cell-to-system approach: quantifying the yield for LCOE prediction

Power measurements of solar cells and modules under STC yield some indication of quality based on very well-defined conditions of operation. One cannot directly infer from this data, however, the performance of a module in a PV power plant under realistic operating conditions. Such a yield prediction under realistic conditions is nevertheless required in order to obtain a quantitative estimate of the LCOE for a given cell and module technology. In particular, a quantitative cell-to-system key figure requires power measurements of a module under various spectral conditions that go beyond the AM1.5G spectrum [14], at different temperatures, and with modifications to the angle of incidence. From a technological point of view, such an energy-rating tool could be realized by combining a series of measurements in an LED-based solar simulator for modules. This additionally requires a software algorithm that combines and weights these data to generate a yield prediction for a module installed in a specific region. Work towards this goal is being carried out within some ongoing research projects at Fraunhofer CSP.

Ensuring the quality of solar simulator measurements

In order to ensure a high quality of the measurement results, a solar simulator should be checked frequently with respect to its light intensity, the uniformity of its light field, the spectral composition of the irradiance, and the temporal stability. In production, where many samples of identical design are measured, the major quality assurance measure is the use of calibrated reference cells or modules. While this approach works well for identical samples, yielding power values with minimal errors, it does not ensure the basic requirements for the light source as defined in the standard. For example, calibration using a reference cell does not give any information on the uniformity, the spectral composition, or the temporal stability.



-0.9%	-0.4%	0.3%	0.9%	1.0%	1.0%	0.1%	-0.7%
-0.9%	-0.9%	-1.0%	1.1%	1.8%	1.6%	1.0%	-0.9%
-1.2%	-0.9%	-0.7%	1.3%	1.8%	1.9%	1.2%	-0.1%
-1.9%	-1.4%	-0.9%	0.0%	1.1%	1.0%	0.6%	-0.1%
-1.7%	-1.8%	-1.7%	-0.2%	0.4%	0.6%	0.8%	0.3%
-0.9%	-1.5%	-1.7%	-0.7%	-0.1%	0.1%	0.7%	0.8%
-0.1%	-0.7%	-0.9%	-0.1%	0.0%	0.0%	0.5%	0.9%
-0.5%	-0.6%	-0.5%	0.7%	0.9%	0.5%	0.2%	0.8%

Figure 4. (a) Fraunhofer CSP's 'reference cell +' in different sizes, adapted to the solar simulator under investigation. (b) Example of the irradiance non-uniformity of the AM1.5G spectrum, showing a slightly reduced irradiance at the left edge of the test plane.

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Most of the aforementioned properties, however, can be quantified using a 'reference cell +', as developed by Fraunhofer CSP (see Fig. 4). For example, an assessment of five different solar simulators has shown that there are major differences in the lateral uniformity of the light fields [15]. This sensor system has been designed for easy use in any kind of solar simulator, yielding data on the lateral uniformity and temporal stability of light sources. The system is currently available for cell-size solar simulators, but a larger version for module-size simulators is in development.

Conclusions

The solar simulator is one of the most important devices for measurement purposes in photovoltaic production facilities and research laboratories. There are two major technologies commercially available: xenon-based solar simulators and LED-based measurement systems. Xenon-based systems currently dominate the market simply because of the maturity of the technology; however, LED solar simulators are gaining market share because of their potential for better-controlled light field properties and their higher flexibility in terms of measurement recipes that go beyond taking power measurements under STC.

New high-efficiency cell technologies are accompanied by higher cell capacities, which require adaptations to the *I–V* measurements with regard to the measurement times. To this end, special solutions for xenon-based systems have been developed, while LED-based systems can compensate for these effects by adapting the measurement times. The development of new advanced measurement applications, such as rapid EQE or reflectivity testing, is a field of ongoing active research at Fraunhofer CSP. Furthermore, new sensor concepts are being developed to ensure the quality of the solar simulators while minimizing the downtimes of the measurement tools.

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About the Authors

Dr. Marko Turek studied physics at Dresden University, and received his Ph.D. in the field of condensed matter theory from the University of Regensburg. At Fraunhofer CSP he leads the team involved with electrical characterization of solar cells and modules. His research focuses on loss analysis of solar cells, advanced characterization methods and development of new test methods and devices.

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