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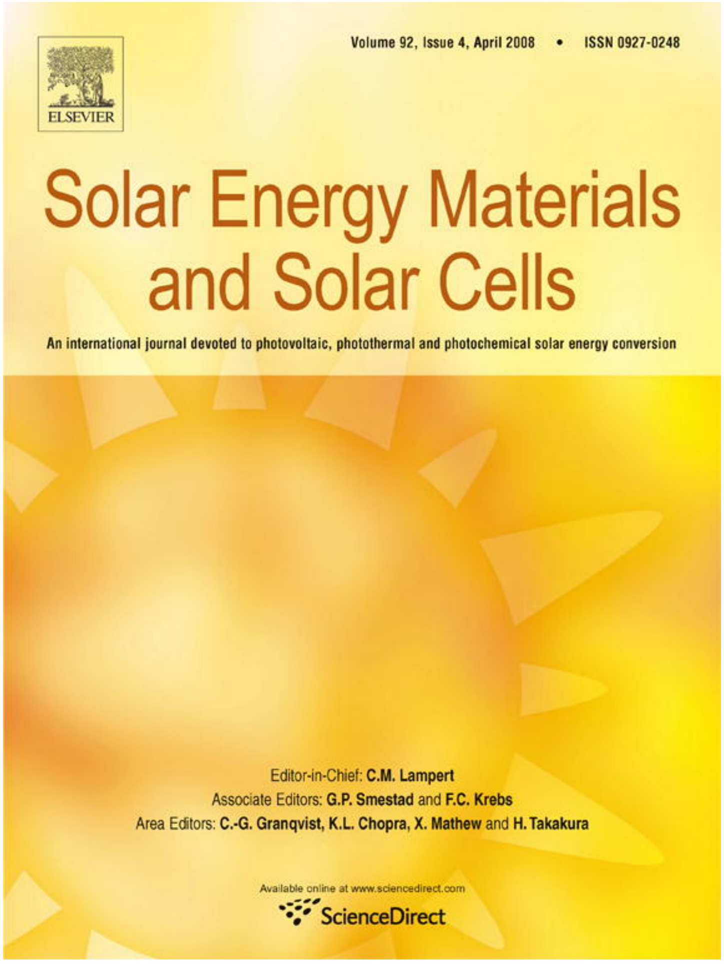


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Editorial

# Reporting solar cell efficiencies in Solar Energy Materials and Solar Cells


**Abstract**

In order to improve the accuracy, validity, reliability and reproducibility of reported power conversion efficiencies for solar cells, the journal, Solar Energy Materials and Solar Cells (SOLMAT), wishes to define how power conversion efficiencies should be reported. This expands upon what is specified in our Guide for Authors. This editorial also serves as a guide on how efficiency data should be checked within the reporting laboratory before sending cells or materials for testing at an independent laboratory. The threshold where the accuracy of efficiency values is important to the journal is whenever power conversion efficiencies require external quantum efficiencies (EQE) values above 50% over a large range of wavelengths or when reported power conversion efficiencies exceed 2.5%. Extra care should be taken in submitted manuscripts to document the measurement's quality, relevance and independent verification.

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## 1. Photocurrents

Solar cells have seen remarkable improvements since the first issue of the journal Solar Energy Materials in 1979. The photovoltaic (PV) field has given rise to a global industry capable of producing many Gigawatts (GW) of additional installed capacity per year. At times, the efficiencies reported for research devices are close to the theoretical limits of solar cells dictated by physics [1,2] and, in some cases, are even above thermodynamic limits. This is of great concern to many in the PV field [3], especially regarding the education of a new generation of researchers. As a consequence, the journal would like to ensure that the quality of the reported results is as high as possible and that they conform to known and accepted standards.

One such standard is the Air Mass 1.5 Global ($1000\,\mathrm{W\,m^{-2}}$, AM1.5G) solar spectrum [4–6]. Although it is usually given as spectral irradiance (in units of $\mathrm{W\,m^{-2}\,nm^{-1}}$), it can easily be converted to spectral photon flux density (in units of photons $\mathrm{m^{-2}\,s^{-1}\,nm^{-1}}$). Thus far, practical PV devices, when operated in an energy production mode, can produce only one electron in an external circuit for every incoming photon. The effects of quantum yields higher than 100%, as well as proposed advanced approaches, are excluded here and would require a more detailed description [2]. This places an upper limit on the current that is expected or believable. Thus, the maximum short circuit current for a quantum solar converter is the integral of the AM1.5 photon flux curve up to the bandgap of the absorber materials employed in the device (see Fig. 1 and Ref. [1]). This is even true of a solar converter with a concentrator if the reference area is taken as the entrance aperture of the system. It is also true for tandem PV solar cells or spectral splitting systems if the predicted current from each cell is added together.

Selected values for the maximum theoretical current are shown in Table 1, which is meant as a guide to check the observed current using the bandgap wavelength of the material. For organic materials, this wavelength can be calculated from the HOMO–LUMO transition, or, alternatively, the energy for exciton creation. It must be kept in mind that the values in the table represent an upper bound to the current densities that can be obtained, and the observed current densities should most often be much lower. This is because absorption of the incident light will never be complete over a given spectral range and because the conversion efficiency of photons into electrons in the external circuit is never 100%. All of these effects are measured when the external quantum efficiency (EQE), is determined [1]. Other names for EQE include calibrated spectral response and induced photo-current efficiency (IPCE). When this measurement is available, the expected current is given by the charge on an electron times the integral of the product of AM1.5 flux density and the EQE. Whenever possible, this value should be reported together with the short circuit current density obtained from a current–voltage (*I*–*V*) measurement.

If observed values for the current density approach the values in the table, we urge authors to carefully check their instrumentation and their experiment, along with the optical properties of the absorber materials. All reported measurements of EQE and power conversion efficiencies should be traceable to international standards [4–8] and any differences and deviations should be thoroughly described. Authors are

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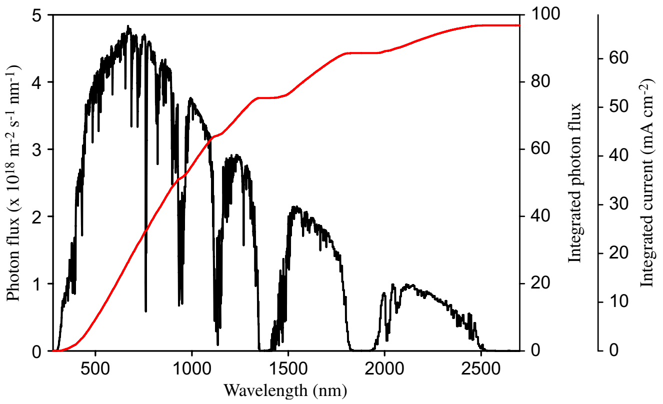


Fig. 1. Photon flux from the sun at the earth's surface (1000 W m$^{-2}$, AM1.5G) as a function of wavelength. The integral of the curve is shown on the right *y*-axis as a percentage of the total number of photons and as the obtainable short circuit current density for an absorber material with a step function absorbance at that wavelength.

Table 1
Values of maximum current density for direct and circumsolar (AM1.5D) and, in parenthesis, global (AM1.5G) solar irradiation

| Wavelength (nm) | Maximum harvested (%) from 280 nm to wavelength | Current density (mA cm$^{-2}$) |
|---|---|---|
| 500 | 8.0 (9.4) | 5.1 (6.5) |
| 550 | 12.5 (14.0) | 8.0 (9.7) |
| 600 | 17.3 (19.0) | 11.1 (13.2) |
| 650 | 22.4 (24.3) | 14.3 (16.8) |
| 700 | 27.6 (29.6) | 17.6 (20.4) |
| 750 | 32.6 (34.7) | 20.8 (23.9) |
| 800 | 37.3 (39.5) | 23.8 (27.2) |
| 900 | 46.7 (48.8) | 29.8 (33.7) |
| 1000 | 53.0 (55.0) | 33.9 (38.0) |
| 1100 | 61.0 (62.9) | 39.0 (43.4) |
| 1250 | 68.7 (70.4) | 43.9 (48.6) |
| 1500 | 75.0 (76.5) | 47.9 (52.8) |

This assumes step function absorbance at the wavelength indicated. The harvested number of photons (in %) is relative to the integral of the AM1.5 flux curve from 280 to 4000 nm. The current densities are for non-concentrated (one sun) sunlight.

advised to provide as much information as possible about the measurement and equipment, especially the light source(s). This includes the quality of the solar simulator according to standards such as ASTM E 927 [7] or IEC 60904 [8]. If quantum efficiency values of more than 50% are observed over a broad range of wavelengths or if power conversion efficiencies exceed 2.5%, we require a description, in the manuscript, of verification by an independent laboratory. This would include any lab (e.g. commercial or institutional) where solar cell or light detector measurements can be made. If for practical reasons, the device itself cannot be sent for verification, the author's equipment and measurement procedures must be verified using a suitable calibrated solar cell or photodiode (see item 2 in the list below). If power conversion efficiencies exceed 5%, the journal requires that the measurement be traceable to an ISO/IEC 17025 certified laboratory specializing in solar cell characterization (ISO is the International Organization for Standardization). Such labs include, but are not limited to, the National Renewable Energy Laboratory (NREL), Japanese National Institute of Advanced Industrial Science and Technology (AIST), Fraunhofer Institut für Solare Energiesysteme (Fraunhofer-ISE), or Energy Research Center of the Netherlands (ECN). Authors should note that there is a distinction between an independent lab and a certified lab.

## 2. Possible sources of error

One common source of error in efficiency measurements stems from improper calibration of the solar simulator. We urge authors to consult the accepted standards defined for solar simulators [7,8] and to employ one or more of the following:

(1) a bolometric or thermopile measurement of the luminous intensity of the light source in conjunction with its spectral analysis,
(2) a calibrated photodiode that employs an optical filter so that the spectral sensitivity of the diode plus filter combination approximates the PV device under test (further, the data must be corrected for mismatch [8,9]), and/or
(3) a measurement in the sun, which can be used as a reliable source of light if the conditions are documented and reported (e.g. angle vs. zenith, air mass, temperature and irradiance; see, for example, Ref. [10]).

Photodiodes are excellent for monitoring the flux from a solar simulator, but do not always accurately measure the energy that it emits. A calibrated photodiode can measure the flux up to a certain value of wavelength, but may not reveal information on energy contained in the spectrum at energies below the photodiode's bandgap or at wavelengths longer than those able to pass its filter. Thus, it is possible to obtain the same value for the power density of the incoming light with two widely different lamp spectra and therefore to significantly overestimate the efficiency of a solar cell. It is therefore not enough to state that the lamp gives 1000 W m$^{-2}$ or that a calibrated photodiode was utilized.

Another common source of error is the failure to mask the cell such that only light incident on the reported active area reaches the absorber. This is especially important when the area is small (e.g. 0.25–1 cm$^2$) or when there are edge effects. Measurements on very small cell areas often introduce large errors. It is recommended that efficiencies should be determined on devices with active areas of at least 0.4 cm$^2$ and that the total and active areas be reported. Estimated collection areas and point contact (dot) cells should be avoided. Another source of error involves the device temperature. This should be reported and compared with one or more of the standards mentioned. The experimental error of measurements needs to be reported and the cells should be tested multiple times. All of the factors mentioned above, and many others, must be taken into consideration when reporting efficiency results. We therefore encourage authors to utilize published sources that describe the

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measurement of solar cells under internationally accepted conditions (for example, Ref. [1] and references therein).

### 3. Solar conversion efficiencies

The solar conversion efficiency expected from Table 1 is given by the product of the current density, open circuit voltage ($V_{OC}$) and fill factor (FF) divided by the incoming light's power density. Thus, a silicon solar cell with a bandgap of 1.1 eV, a bandgap wavelength of 1100 nm and a FF and $V_{OC}$ of 0.7 and 0.7 V, respectively, would be limited to an AM1.5 power conversion efficiency below 22%. The thermodynamic limit for a single bandgap device under one sun at AM1.5 is approximately 33%. If authors propose that their solar conversion device operates beyond standard thermodynamic limits [1,2], rigorous proof must be provided with considerations of the aspects set forth in this editorial.

The journal would also like to comment on noteworthy efficiency levels. For all of the more developed PV technologies such as crystalline silicon (c-Si) or multicrystalline silicon (mc-Si), as well as thin film CdTe and copper indium gallium diselenide and related materials, an efficiency of at least 10% is expected in order for a manuscript to be considered state of the art. For amorphous Si (a-Si), microcrystalline Si and other thin film technologies (including organic materials), 5% is currently considered significant. If efficiency levels are below these values, a comparison should be made to literature values of the efficiency obtained for devices using the same absorber material and reasons should be given for the shortfall. These might include a novel deposition or preparation technique, a new material source or a list of factors that can be optimized (e.g. anti-reflection coating, contact grid, absorber thickness and doping levels).

With all of the things mentioned in this editorial in mind, authors will find it easier to publish in Solar Energy Materials and Solar Cells. In addition to manuscripts on materials science and technology related to PV, photothermal and photoelectrochemical solar energy conversion, we also encourage the submission of original work and reviews that describe techniques for the accurate measurement of solar cell efficiencies. Like many others [11], we believe that solar energy can meet a significant amount of the world's energy needs. Research reported in this journal will continue to assist the PV field as it matures into a respected and valued global industry. Reporting solar cell efficiencies accurately and consistently will assist in this process.


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