Solar Cell Efficiency Table Guide

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This guide introduces each column in the spreadsheet, which can be downloaded at https://www.nrel.gov/pv/cell-efficiency.html.

Measurement Date:

- The month and year that the photovoltaic cell's efficiency was measured by the accredited test centers (which can be weeks after the sample was originally fabricated).
- The complete measurement process can take a few weeks. The date indicated is that provided by the accredited test center.
- Sometimes samples are then remeasured by an additional accredited test center. Multiple measurements should be expected to differ but to agree within the uncertainties noted.

First *Progress in Photovoltaics* (*PIP*) reference:

- *Progress in Photovoltaics* (*PIP*) regularly publishes solar cell and cell efficiency tables summarizing the highest verified efficiency results for different technologies [1]. All efficiencies were measured by one or more accredited test centers under standard test conditions (e.g., 1,000 W/m^2, 25°C). The Solar Cell Efficiency Tables are traditionally published twice a year, typically in January and July. The article title has remained the same with the inclusion of an updated version number. This column provides the version number in which the efficiency record was first published. Each version of the tables includes all record efficiency cells and cells (not only the most recent records), meaning that each version is the reference of the state of the art of *all PV technologies* at the time of publication. For example, the complete reference for version 55 of the efficiency tables is:
  Green, Martin A., Ewan D. Dunlop, Jochen Hohl‐Ebinger, Masahiro Yoshita, Nikos Kopidakis, and Anita W.Y. Ho‐Baillie. "Solar Cell Efficiency Tables (Version 55)." *Progress in Photovoltaics: Research and Applications* 28, no. 1: 3–15. https://onlinelibrary.wiley.com/doi/full/10.1002/pip.3228.
- Some of the measurements, especially some early measurements, were never published in the *PIP* tables. These are labeled as NA in this column.

Progress in Photovoltaics (*PIP*) Table:

- This column specifies the *PIP* table from which the data were taken. The *PIP* series of publications has organized the record efficiencies into tables. Table 1 includes cells and subcells (i.e., small cells or cells comparable to large commercial cells) [2]. Table 2 contains cells and is where most cell efficiencies are found. Table 3 is dedicated mostly to concentrator cells and concentrator cell efficiencies. Table 4 contains solar cells and cells that have been selected as "notable exceptions." While not conforming to the requirements to be recognized as a class record, the cells and cells in this table have notable characteristics that are of interest to sections of the photovoltaic community. Entries on this table are selected based on their significance and timeliness [3]. The tables over time were reorganized; therefore, this column refers to the table used for the initial publication of the corresponding point.

- Measurements never reported in a *PIP* table are listed in this column as NA. For some of these measurements, references are available in the reference column.

Cell Material Class:

- **a-Si: Amorphous Silicon:H** — Includes single-junction, two-junction, and three-junction thin-film silicon cells grown on glass or other low-cost substrates. Some multijunction stacks include alloys with germanium and some partially crystallized layers to help achieve layers with lower band gaps. These films invariably have a relatively high hydrogen content, though this is not usually indicated in the description but is assumed.
- **Chalcogenide** — Materials that have at least one element from the sixth column of the periodic table, such as sulfides, selenides, and tellurides. The most common of these are CdTe and CIGS (copper indium gallium selenide).
- **Dye-Sensitized** — Typically, these cells use a porous titanium dioxide matrix coated with a thin layer of strongly absorbing dye. The dye absorbs the light, and the photocarriers (excitons) are separated at the interface between the titanium oxide and an electrolyte that is infiltrated into the titania.
- **Hybrid** — These cells use materials from multiple categories, most notably, silicon combined with III-Vs or perovskites as well as perovskites combined with CIGS. More combinations are anticipated.
- **III-V** — These cells use elements from the third and fifth columns of the periodic table. The materials may be fabricated with a wide range of band gaps, so many of these reports are for stacks of multiple layers, also known as multijunctions. Gallium arsenide is commonly grown on germanium because of the very similar lattice constants. For convenience, germanium-containing cells are included in this category.
- **OPV (Organic Photovoltaic)** — The most common OPV technologies use bulk heterojunction cells comprising polymeric and/or organic small molecules. The bulk heterojunction concept is designed to facilitate separation of the photoinduced exciton to free electrons and holes that result in photocurrent.
- **Perovskite** — These cells are made from materials of the perovskite structure, usually denoted as ABX_3, with *A* as an inorganic or organic cation (e.g., methylammonium), *B* as a metal cation (typically Pb^{2+}), and *X* as a halide (typically I^- and/or Br^-). The most commonly used structure is denoted as a *hybrid organic-inorganic methylammonium lead halide perovskite*. The general perovskite structure is represented by the crystal structure of $CaTiO_3$.
- **Si: Crystalline Silicon** — More than 90% of today's PV systems use crystalline silicon cells. The structures of the cells and cells themselves can differ in somewhat subtle, but important, ways. While each of the other types of cells may reflect differences in cell design, because of the broad deployment of crystalline silicon cells, the crystalline silicon cell types are subdivided, as described below, to better track the technology's evolution.

Cell Type:

Note: this column corresponds to how the entry is labeled in the Best Research Cell Efficiency Chart (https://www.nrel.gov/pv/cell-efficiency.html). In every category, the addition of "conc" to any category indicates that the measurement was done under concentrated light. If a specific result is not represented in the efficiency chart, it is labeled as "(not on chart)".

Detailed Description:

- Provides a description of the photovoltaic cell, if available.

Group:

- The organization or company that produced the solar cell whose efficiency was tested. In some cases, multiple organizations were involved in the cell fabrication.

Efficiency:

- The power conversion efficiency (light to electricity) is reported for standard test conditions. Most measurements used 1,000 W/m^2, 25°C, and the AM1.5 global spectrum (IEC 60904-3 or ASTM E892-87). The concentrator cell measurements also used the AM1.5 direct spectrum (IEC 60904-3 or ASTM E891-87).
- All efficiencies were measured at accredited test centers under standard conditions, though different measurement techniques were used per test center.
- Intercomparisons of cell measurements, usually referred to as "round-robins," are conducted between the major testing laboratories every few years to characterize the consistency and uncertainties of the results. For example, see [5].

Revised/New Efficiency:

- In Version 33 and onward of the *Progress in Photovoltaics* Journal, standardized testing conditions were updated to the new internationally accepted reference spectrum (IEC 60904-3, Ed. 2, 2008). The change in spectrum changed most efficiency measurements on the order of 1% (relative). The efficiencies recalculated and/or measured with the new spectrum are recorded in a separate column to differentiate the two efficiency measurements.

Combined Efficiency:

- For convenience, the "Efficiency" and "Revised/New Efficiency" columns are combined into a single column. Data fall into three categories:
    - Data measured using the new spectrum
    - Data updated in Version 33 to reflect the new spectrum, as noted in the description of the "Revised/New Efficiency" column
    - Data reported using the original spectrum and not updated in Version 33 were updated using an example from category #2 for each technology. Specifically, the following adjustments were applied—amorphous silicon: no adjustment; CdTe:

multiply by 1.02; CIGS: multiply by 1.01; Si: multiply by 1.01. No correction was applied for multijunction cells.

Uncertainty:

- The stated uncertainty is that reported by the test center, which is based on the accuracy analysis done for the measurement type and conditions of the particular measurement and verified during the round-robin comparisons. In general, the consistency of measurements between the accredited test centers is periodically evaluated using round-robin testing [5].

Area:

- The area of a cell is an important parameter in determining its efficiency. Accredited test centers measure the areas and typically ensure an uncertainty lower than 0.5% [1]. There are three types of areas reported: total, aperture, and designated illumination area, as defined in the next section.

Types of Areas:

- **Total Area *(t)***: The area that would be measured by taking a photograph of the device against a white background and measuring the area of the background shaded by the device [1].
- **Aperture Area *(ap)***: The most highly reported type of area. The device is masked so the illuminated area is smaller than the total cell area, but all essential components of the device, including busbars, fingers, and interconnects, lie within the masked area [1].
- **Designated Illuminated Area *(da):*** The cell is masked to an area smaller than the total device area, but major cell components lie outside the masked area [1].

Open-Circuit Voltage, V_{OC}:

- The reported open-circuit voltage is measured (in volts) under the standard test conditions when no current is flowing in the circuit.

Short Circuit Current Density J_{SC}:

- The reported short circuit current is measured (in mA/cm^2) under the standard test conditions when the cell is biased to zero voltage.

New Short Circuit Current Density J_{SC}:

- After revision of the standard reference spectrum, Version 33 of the *PIP* tables updated the short circuit current densities of the initial measurements to reflect the new reference spectrum. This column reports only short circuit current densities measured under these new conditions.

Fill Factor:

- The fill factor is the ratio of maximum power (from the current-voltage scan) to the product of the open-circuit voltage and the short circuit current, all measured under standard test conditions.

Accredited Testing Centers:

- This column indicates the test center at which the measurement was completed.
- List of recognized test centers is provided in the *PIP* tables.

References:

- We provide a reference for more information about the measurement, especially for measurements that were not reported in the *Progress in Photovoltaics* journal. Some of these references are no longer available online, but these have been left to provide a clue about the origin of the report. Readers are encouraged to supply references that are improvements over those listed.

Efficiency Checks:

- Two columns are included to confirm that the reported efficiency is consistent with the reported cell parameters. These may differ slightly from unity because of round-off error. The efficiency check is omitted for concentrator cells and whenever the measurements of open-circuit voltage, etc. are not available.

Notes:

- This column may mention important information not captured in other fields, such as if the cell might be unstable.

References:

[1] Green, Martin A., and Keith Emery. 1993. "Solar Cell Efficiency Tables." *Progress in Photovoltaics: Research and Applications* 1, no. 1: 25–29. https://onlinelibrary.wiley.com/doi/10.1002/pip.4670010104.

[2] Green, Martin A., and Keith Emery. 1993. "Short Communication: Solar Cell Efficiency Tables (Version 2)," *Progress in Photovoltaics: Research and Applications* 1, no. 2: 225-227. https://onlinelibrary.wiley.com/doi/abs/10.1002/pip.4670010306.

[3] Green, Martin A., Keith Emery, Yoshihiro Hishikawa, and Wilhelm Warta. 2008. "Solar Cell Efficiency Tables (Version 33)." *Progress in Photovoltaics: Research and Applications* 33, no. 17: 85-94. https://onlinelibrary.wiley.com/doi/10.1002/pip.880.

[4] Green, Martin A., and Keith Emery. 1994. "Solar Cell Efficiency Table (Version 3)" *Progress in Photovoltaics: Research and Applications* 2, no. 3: 27-34. https://onlinelibrary.wiley.com/doi/abs/10.1002/pip.4670020105.

[5] Salis, Elena, Diego Pavanello, Michael Field, Ulli Kräling, Frank Neuberger, Klaus Kiefer, Carl Osterwald, Steve Rummel, Dean Levi, Yoshihiro Hishikawa, Kengo Yamagoe, Hironori Ohshima, Masahiro Yoshita, and Harald Müllejans. 2017. "Improvements in World-Wide Intercomparison of PV Cell Calibration. *Solar Energy* 155: 1451-1461. https://www.sciencedirect.com/science/article/pii/S0038092X17306667?via%3Dihub.

[6] Cormican, James. "Solar Panels (PV) and Voltages" n.d. altE Store. Accessed October 28, 2018. https://www.altestore.com/howto/solar-panels-pv-and-voltages-a98/.

[7] Wikipedia. 2018. "Open-Circuit Voltage." Last modified June 26, 2018. https://en.wikipedia.org/wiki/Open-circuit_voltage.

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