Solar Module Efficiency Table Guide

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

Measurement Date:

- The month and year that the photovoltaic module'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 agree within the uncertainties noted.

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

- *Progress in Photovoltaics* regularly publishes solar cell and module 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. 1000 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 modules (not only the most recent records), i.e. 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 MA, Dunlop ED, Hohl-Ebinger J, Yoshita M, Kopidakis N, Ho-Baillie AWY. Solar cell efficiency tables (Version 55). *Prog Photovolt Res Appl.* **28** (2020) 3–15. https://doi.org/10.1002/pip.3228

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 submodules (small modules or modules comparable to large commercial cells) [2]. Table 2 contains modules and is where most module efficiencies are found. Table 3 is dedicated mostly to concentrator cells and concentrator module efficiencies. Table 4 contains solar cells and modules that have been selected as "notable exceptions." While not conforming to the requirements to be recognized as a class record, the cells and modules 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.

Cell Material Class:

- **a-Si: Amorphous Silicon —** 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.

- **Chalcogenide —** Materials that have at least one element from 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 modules 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 modules use materials from multiple categories. Most notably, a combination of III-V and silicon cells. In the future, this category may also include modules made from other material combinations including perovskites.
- **III-V —** These modules use elements from the third and fifth columns of the periodic table. These 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 modules 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 to photocurrent.
- **Perovskite —** These modules are made from materials of the perovskite structure usually denoted as ABX_3, with A an inorganic or organic cation (e.g. methylammonium), B a metal cation (typically Pb^{2+}) and X 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 modules. The structures of the cells and modules can differ in somewhat subtle, but important, ways. While each of the other types of modules may reflect differences in cell designs, because of the broad deployment of crystalline silicon modules, the crystalline silicon cell types are subdivided as described below to better track the technology's evolution.

Cell Type:

- a-Si: Amorphous Silicon
  - **a-Si-1j —** Single-junction cells.
  - **a-Si-2j —** Double-junction cells.
    - **a-Si/a-Si —** Two-junction cells that use a thin top cell that intentionally transmits some light to the second junction, which, in some cases, may have the same band gap as the top cell.
    - **a-Si/a-SiGe —** The lower junction is made from an amorphous silicon-germanium alloy, which has a lower band gap than amorphous silicon.

    - **a-Si/nc-Si —** The lower junction is made from nanocrystalline silicon, which has a lower band gap than amorphous silicon.
  - **a-Si-3j —** Triple-junction cells.
    - a-Si/a-Si/a-Si:Ge
    - a-Si/a-SiGe/a-SiGe
    - a-Si/a-SiGe/nc-Si

- Chalcogenide
  - **CdTe —** Cadmium telluride modules represent several percent of world deployments of solar systems. CdTe is usually deposited on the back of a sheet of glass in a superstrate configuration with the final deposited layer being the back contact of the solar cells.
  - **CI(G)S - CuInGaSe$_2$ —** These alloys are generally made in polycrystalline form using the chalcopyrite structure. The gallium replaces some indium atoms; the composition may vary within the cell. The following are closely related and are listed under this subheading.
    - **CIS - CuInSe$_2$ —** These alloys are generally made in polycrystalline form using a chalcopyrite structure. The material may deviate slightly from this stoichiometric ratio and there may be some disordering of the alloy.
    - **CIGSS - CuInGa(SSe)$_2$ —** These alloys are similar to CIGS, but sulfur shares the sublattice with selenium.
- Dye-Sensitized — See above.
- **Hybrid —** See above.
- **III-V**
  - **GaAs - 1j —** Single-junction modules that are made from GaAs cells. The cells are grown epitaxially on GaAs single-crystal wafer substrates. Some are encapsulated into a module on the wafer; others are removed from the wafer to be incorporated as a thin film into a module.
  - **GaAs - 2j —** May be a variety of combinations of two junctions; the earliest entry combined GaAs with GaSb.
  - **GaAs - 3j —**A designation as “- conc” implies that the module includes concentrating optics. These modules typically combine GaInP/GaAs with a lower junction of either Ge or GaInAs.
  - **GaAs - 4j —** A designation as “- conc” implies that the module includes concentrating optics. These modules typically combine a GaInP/GaAs dual junction top cell with a GaInAsP/GaInAs dual junction bottom cell.
- **OPV (ORGANIC)** — See above.
- **Perovskite** — See above.
- Si: Crystalline Silicon
  - **Si - mono - conc —** These concentrator modules are made with single-crystal silicon cells.
  - **Si - mono - HJ —** These use single-crystal silicon with amorphous silicon heterojunction front and back contacts.

    - **Si - mono HJ - IBC —** These use single-crystal silicon with amorphous silicon heterojunction contacts but the p- and n-type contacts are all made on the back of the cell.
    - **Si - mono - IBC —** These use single-crystal silicon with interdigitated back contacts.
    - **Si - mono - PERC —** These types of silicon cells include a variety of configurations that improve passivation and light trapping including Passivated Emitter Rear Cell, Passivated Emitter Rear Contact, and Passivated Emitter Rear Locally Diffused (PERL).
    - **Si - multi —** These modules use cells made from multi-crystalline silicon with a conventional aluminum-back-surface-field structure. This structure has been the workhorse of the industry as a low-cost process, but with efficiencies that are typically inferior to the above structures because of the poor passivation and low reflectivity properties of the aluminum back contact.
    - **Si - other —** A variety of silicon cells that were not easily categorized with the above
        - Laser-grooved silicon allows the grid metallization to be buried in grooves.
        - Spheral silicon uses small silicon balls interconnected in a module. The technology was commercialized by Texas Instruments.
    - **Si - thin film —** These cells are meant to be crystalline, but are similar to and about the same thickness as the amorphous silicon cells.

Detailed Description:

- Provides a description of the photovoltaic module.
- The conventions for size labeling are as follows, as a function of the area of the module:
    - <200 cm^2 : minimodules.
    - 200-800 cm^2 : submodule
    - 800-6500 cm^2 : small module
    - 6500-14000 cm^2 : standard module
    - >14000 cm^2 : large module

Group:

- The organization or company that produced the solar modules whose efficiencies were tested. In some cases, multiple organizations were involved in the module fabrication.

Efficiency:

- The power conversion efficiency (light to electricity) is reported for standard test conditions. Most measurements used 1000 W/m^2, 25°C, and the AM1.5 global spectrum (IEC 60904-3 or ASTM E892-87). The concentrator module 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. For example, Sandia National Laboratories' measurements were based on a large number of outdoor measurements taken over an entire day, while European Solar Test Installation results were based on a combination of indoor and outdoor measurements [4].

- Intercomparisons of module 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, the 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 with spectral correction factors and/or measured with the new spectrum are recorded in a separate column to differentiate the two efficiency measurements. [3]

Combined Efficiency:

- For convenience, the “Efficiency” and “Revised/New Efficiency” columns are combined into a single column. Data fall into three categories:
    1. Data measured using the new spectrum.
    2. Data updated in Version 33 to reflect the new spectrum, as noted in the description of the “Revised/New Efficiency” column.
    3. 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.

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 module is an important parameter in determining its efficiency. Accredited test centers measure the areas and typically attempt to achieve 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 illuminated area is smaller than the total module area, but all essential components of the device, such as busbars, fingers and interconnects, lie within the masked area [1].

- **Designated Illuminated Area *(da)*:** The module is masked to an area smaller than the total device area, but major module 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 I_{SC}:

- The reported short-circuit current is measured (in amps) under the standard test conditions when the module is biased to zero voltage.
- Some submodules and minimodules were reported in current density J_{SC} (mA/cm^2) in the PIP tables. To reduce confusion, only the efficiency data are reported for these, leaving the short-circuit current column blank.

New Short-Circuit Current I_{SC}:

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

Fill Factor:

- The fill factor is the ratio of the 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 [Version 33 and onward]
  - European Solar Test Installation (ESTI)
  - Fraunhofer-Institute for Solar Energy Systems (FhG-ISE)
  - National Institute of Advanced Industrial Science and Technology (AIST)
  - National Renewable Energy Laboratory (NREL)
  - Physikalisch-Technische Bundesanstalt (PTB)
  - Sandia National Laboratories (Sandia)

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.

Notes:

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

References:

[1]	M. A. Green and K. Emery, "Solar Cell Efficiency Tables," *Progress in Photovoltaics: Research and Applications,* vol. 1 (1993): 25-29.
[2]	M. A. Green and K. Emery, "Short Communication: Solar Cell Efficienty Tables (Version 2)," *Progress in Photovoltaics: Research and Applications,* vol. 1, no. 2 (1993): 225-227.
[3]	M. A. Green, K. Emery, Y. Hishikawa and W. Warta, "Solar Cell Efficiency Tables (Version 33)," *Progress in Photovoltaics: Research and Applications,* vol. 33, no. 17(2008): 85-94.
[4]	M. A. Green and K. Emery, "Solar Cell Efficiency Table (Version 3)," *Progress in Photovoltaics: Research and Applications,* vol. 2, no. 3 (1994): 27-34.
[5]	E. Salis, D. Pavanello, M. Field, U. Kräling, F. Neuberger, K. Kiefer, C. Osterwald, S. Rummel, D. Levi, Y. Hishikawa, K. Yamagoe, H. Ohshima, M. Yoshita, H. Müllejans, Improvements in world-wide intercomparison of PV module calibration, *Solar Energy*, **155** (2017) 1451-1461

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