

Solar cell efficiency tables (version 56)

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Funding information

New Energy and Industrial Technology Development Organization, Grant/Award Number: General; U.S. Department of Energy (Office of Science, Office of Basic Energy Sciences and Energy Efficiency and Renewable Energy, Solar Energy Technology Program), Grant/Award Number: Contract No. DE-AC36-08-GO28308

Abstract

Consolidated tables showing an extensive listing of the highest independently confirmed efficiencies for solar cells and modules are presented. Guidelines for inclusion of results into these tables are outlined, and new entries since January 2020 are reviewed.

KEYWORDS

energy conversion efficiency, photovoltaic efficiency, solar cell efficiency

1 | INTRODUCTION

Since January 1993, “Progress in Photovoltaics” has published six monthly listings of the highest confirmed efficiencies for a range of photovoltaic cell and module technologies.^{1–3} By providing guidelines for inclusion of results into these tables, this not only provides an authoritative summary of the current state-of-the-art but also encourages researchers to seek independent confirmation of results and to report results on a standardised basis. In version 33 of these tables,³

results were updated to the new internationally accepted reference spectrum (International Electrotechnical Commission IEC 60904-3, Ed. 2, 2008).

The most important criterion for inclusion of results into the tables is that they must have been independently measured by a recognised test centre listed elsewhere² (one new test centre listed in the Appendix of version 55). A distinction is made between three different eligible definitions of cell area: total area, aperture area and designated illumination area, as also defined elsewhere² (note that, if

TABLE 1 Confirmed single-junction terrestrial cell and submodule efficiencies measured under the global AM1.5 spectrum (1000 W/m²) at 25°C (International Electrotechnical Commission [IEC] 60904-3: 2008, ASTM G-173-03 global)

Classification	Efficiency (%)	Area (cm ²)	V _{oc} (V)	J _{sc} (mA/cm ²)	Fill factor (%)	Test Centre (date)	Description
Silicon							
Si (crystalline cell)	26.7 ± 0.5	79.0 (da)	0.738	42.65 ^a	84.9	AIST (3/17)	Kaneka, n-type rear IBC ⁴
Si (DS wafer cell)	23.8 ± 0.3	246.44 (t)	0.7087	40.88^b	82.2	ISFH (12/19)	Canadian solar, n-type
Si (thin transfer submodule)	21.2 ± 0.4	239.7 (ap)	0.687 ^c	38.50 ^{c,d}	80.3	NREL (4/14)	Solexel (35 µm thick) ⁵
Si (thin-film minimodule)	10.5 ± 0.3	94.0 (ap)	0.492 ^c	29.7 ^{c,e}	72.1	FhG-ISE (8/07)	CSG solar (<2 µm on glass) ⁶
III-V cells							
GaAs (thin film cell)	29.1 ± 0.6	0.998 (ap)	1.1272	29.78 ^f	86.7	FhG-ISE (10/18)	Alta Devices ⁷
GaAs (multicrystalline)	18.4 ± 0.5	4.011 (t)	0.994	23.2	79.7	NREL (11/95)	RTI, Ge substrate ⁸
InP (crystalline cell)	24.2 ± 0.5 ^g	1.008 (ap)	0.939	31.15 ^a	82.6	NREL (3/13)	NREL ⁹
Thin-film chalcogenide							
CIGS (cell) (cd free)	23.35 ± 0.5	1.043 (da)	0.734	39.58 ^h	80.4	AIST (11/18)	Solar Frontier ¹⁰
CdTe (cell)	21.0 ± 0.4	1.0623 (ap)	0.8759	30.25 ^d	79.4	Newport (8/14)	First solar, on glass ¹¹
CZTSSe (cell)	11.3 ± 0.3	1.1761 (da)	0.5333	33.57 ^f	63.0	Newport (10/18)	DGIST, Korea ¹²
CZTS (cell)	10.0 ± 0.2	1.113 (da)	0.7083	21.77 ^a	65.1	NREL (3/17)	UNSW ¹³
Amorphous/microcrystalline							
Si (amorphous cell)	10.2 ± 0.3 ^{i,g}	1.001 (da)	0.896	16.36 ^d	69.8	AIST (7/14)	AIST ¹⁴
Si (microcrystalline cell)	11.9 ± 0.3 ^g	1.044 (da)	0.550	29.72 ^a	75.0	AIST (2/17)	AIST ¹⁵
Perovskite							
Perovskite (cell)	21.6 ± 0.6 ^{i,k}	1.0235 (da)	1.193	21.64 ^l	83.6	CSIRO (6/19)	ANU ¹⁶
Perovskite (minimodule)	18.0 ± 0.6^{j,m}	19.276 (da)	1.070^c	21.53^{c,b,n}	78.4	Newport (12/19)	Microquanta, 7 serial cells¹⁷
Dye sensitised							
Dye (cell)	11.9 ± 0.4 ^o	1.005 (da)	0.744	22.47 ^p	71.2	AIST (9/12)	Sharp ¹⁸
Dye (minimodule)	10.7 ± 0.4 ^o	26.55 (da)	0.754 ^c	20.19 ^{c,q}	69.9	AIST (2/15)	Sharp, 7 serial cells ¹⁹
Dye (submodule)	8.8 ± 0.3 ^o	398.8 (da)	0.697 ^c	18.42 ^{c,r}	68.7	AIST (9/12)	Sharp, 26 serial cells ¹⁹
Organic							
Organic (cell)	13.45 ± 0.2 ^s	1.023 (da)	0.8422	23.28 ^l	68.6	FhG-ISE (6/19)	Uni Potsdam ²⁰
Organic (minimodule)	12.6 ± 0.2 ^s	26.129 (da)	0.8315 ^c	21.32 ^{c,l}	71.1	FhG-ISE (9/19)	ZAE Bayern (12 cells) ²¹
Organic (submodule)	11.7 ± 0.2 ^s	203.98 (da)	0.8177 ^c	20.68 ^{c,l}	69.3	FhG-ISE (10/19)	ZAE Bayern (33 cells) ²¹

Note. Any changes in the table from those previously published are set in bold type.

Abbreviations: AIST, Japanese National Institute of Advanced Industrial Science and Technology; (ap), aperture area; CIGS, CuIn_{1-x}Ga_xSe₂; a-Si, amorphous silicon/hydrogen alloy; CZTSSe, Cu₂ZnSnS₄-_ySe_y; CZTS, Cu₂ZnSnS₄; (da), designated illumination area; DS, directionally solidified (including mono cast and multicrystalline); FhG-ISE, Fraunhofer Institut für Solare Energiesysteme; nc-Si, nanocrystalline or microcrystalline silicon; NREL, National Renewable Energy Laboratory; (t), total area.

^aSpectral response and current-voltage curve reported in version 50 of these tables.

^bSpectral response and current-voltage curve reported in the present version of these tables.

^cReported on a 'per cell' basis.

^dSpectral responses and current-voltage curve reported in version 45 of these tables.

^eRecalibrated from original measurement.

^fSpectral response and current-voltage curve reported in the version 53 of these tables.

^gNot measured at an external laboratory.

^hSpectral response and current-voltage curve reported in version 54 of these tables.

ⁱStabilised by 1000-h exposure to one sun light at 50°C.

^jInitial performance.

^kAverage of forward and reverse sweeps at 150 mV/s (hysteresis ±0.26%).

^lSpectral response and current-voltage curve reported in version 55 of these tables.

^mMeasured using 13-point IV sweep with constant bias until data constant at 0.05% level.

ⁿSpectral response and current–voltage curve reported in version 52 of these tables.

^oInitial efficiency. Krašovec et al.²² review the stability of similar devices.

^pSpectral response and current–voltage curve reported in version 41 of these tables.

^qSpectral response and current–voltage curve reported in version 46 of these tables.

^rSpectral response and current–voltage curve reported in version 43 of these tables.

^sInitial performance. Tanenbaum et al. and Krebs^{23,24} review the stability of similar devices.

masking is used, masks must have a simple aperture geometry, such as square, rectangular or circular). ‘Active area’ efficiencies are not included. There are also certain minimum values of the area sought for the different device types (above 0.05 cm² for a concentrator cell, 1 cm² for a one-sun cell, 800 cm² for a module and 200 cm² for a ‘submodule’).

Results are reported for cells and modules made from different semiconductors and for subcategories within each semiconductor grouping (e.g., crystalline, polycrystalline and thin film). From version 36 onwards, spectral response information is included (when possible) in the form of a plot of the external quantum efficiency (EQE) versus wavelength, either as absolute values or normalised to the peak measured value. Current–voltage (IV) curves have also been included where possible from version 38 onwards. A graphical summary of progress over the first 25 years during which the tables have been published has been included in version 51.²

Highest confirmed ‘one sun’ cell and module results are reported in Tables 1–4. Any changes in the tables from those previously published¹ are set in bold type. In most cases, a literature reference is provided that describes either the result reported or a similar result (readers identifying improved references are welcome to submit to the lead author). Table 1 summarises the best-reported measurements for one-sun (non-concentrator) single-junction cells and submodules.

Table 2 contains what might be described as ‘notable exceptions’ for one-sun single-junction cells and submodules in the above category. While not conforming to the requirements to be recognised as a class record, the devices in Table 2 have notable characteristics that will be of interest to sections of the photovoltaic community, with entries based on their significance and timeliness. To encourage discrimination, the table is limited to nominally 12 entries with the present authors having voted for their preferences for inclusion. Readers who have suggestions of notable exceptions for inclusion into this or subsequent tables are welcome to contact any of the authors with full details. Suggestions conforming to the guidelines will be included on the voting list for a future issue.

Table 3 was first introduced in version 49 of these tables and summarises the growing number of cell and submodule results involving high-efficiency, one-sun multiple-junction devices (previously reported in Table 1). Table 4 shows the best results for one-sun modules, both single junction and multiple junctions, while Table 5 shows the best results for concentrator cells and concentrator modules. A small number of notable exceptions are also included in Tables 3–5.

2 | NEW RESULTS

Eight new results are reported in the present version of these tables. The first new result in Table 1 (‘one-sun cells’) is 23.8% efficiency for a large area (246 cm²) cell fabricated upon an *n*-type directionally solidified (DS) wafer (commonly called a ‘cast mono’ wafer), with the cell fabricated by Canadian Solar⁷⁰ and the result confirmed by the Institute für Solarenergieforschung (ISFH). The broader ‘DS wafer’ category displaces the earlier ‘multicrystalline’ category. Apart from challenges in defining and identifying multicrystallinity, to paraphrase a representative of one major wafer supplier,⁷¹ rather than the present competition being between monocrystalline and multicrystalline products, it is now between the ingot casting process (DS) and the Czochralski growth process.

The second new result in Table 1 is a new efficiency record for a perovskite minimodule. An efficiency of 18.0% is reported for a 19-cm² minimodule fabricated by Microquanta Semiconductor¹⁸ and measured at the Newport PV Laboratory. For perovskite cells, the tables now accept results based on “quasi-steady-state” measurements (sometimes called “stabilized” in the perovskite field, although this conflicts with usage in other areas of photovoltaics). Along with other emerging technologies, perovskite cells may not demonstrate the same level of stability as conventional cells, with references given below. Five new results are reported in Table 3 relating to one-sun, multijunction devices, three for devices involving Pb-halide perovskites as the top cell material but with three different materials for the bottom cell. The first new result is for a 4-cm² monolithic, 2-junction, 2-terminal GaAsP/Si tandem device fabricated by a joint effort of Ohio State University (OSU), the University of New South Wales, Sydney (UNSW) and SolAero Technologies Corporation and measured at the US National Renewable Energy Laboratory (NREL). The first of the new perovskite results is 29.15% efficiency for a 1-cm² perovskite/silicon monolithic two-junction, two-terminal device fabricated by Hemholtz Centrum Berlin (HZB)⁷² and measured by the Fraunhofer Institute for Solar Energy Systems (FhG-ISE). This efficiency pushes further beyond the highest efficiency for a single-junction silicon cell (Table 1) with a 9% relative advantage, although for a much smaller area device.

The third new result in Table 3 is for a cell fabricated by the same group (HZB) and measured by the same institute (FhG-ISE) but uses CIGS (CuIn_xGa_{1-x}Se₂) as the bottom cell material making it an all thin-film device. An efficiency of 24.2% was measured for a 1-cm² perovskite/CIGS monolithic two-junction, two-terminal device,⁷³ now

TABLE 2 'Notable exceptions' for single-junction cells and submodules: 'Top dozen' confirmed results, not class records, measured under the global AM1.5 spectrum (1000 W m^{-2}) at 25°C (International Electrotechnical Commission [IEC] 60904-3: 2008, ASTM G-173-03 global)

Classification	Efficiency (%)	Area (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	Fill factor (%)	Test Centre (date)	Description
<u>Cells (silicon)</u>							
Si (crystalline)	26.0 ± 0.5^a	4.015 (da)	0.7323	42.05^b	82.3	FhG-ISE (11/19)	FhG-ISE, p-type top/rear contacts ²⁵
Si (crystalline)	25.8 ± 0.5^a	4.008 (da)	0.7241	42.87^c	83.1	FhG-ISE (7/17)	FhG-ISE, n-type top/rear contacts ²⁶
Si (crystalline)	26.1 ± 0.3^a	3.9857 (da)	0.7266	42.62^d	84.3	ISFH (2/18)	ISFH, p-type rear IBC ²⁷
Si (large crystalline)	25.1 ± 0.4	244.45 (t)	0.7470	39.55^b	85.0	ISFH (9/19)	Hanergy, n-type top/rear contacts ²⁸
Si (large crystalline)	26.6 ± 0.5	179.74 (da)	0.7403	42.5^e	84.7	FhG-ISE (11/16)	Kaneka, n-type rear IBC ⁴
Si (DS wafer)	22.8 ± 0.3	246.7 (t)	0.6871	40.90^b	81.2	ISFH (9/19)	Canadian solar, p-type PERC ²⁹
<u>Cells (III-V)</u>							
GaInP	22.0 ± 0.3^a	0.2502 (ap)	1.4695	16.63^f	90.2	NREL (1/19)	NREL, rear HJ, strained AlInP ³⁰
<u>Cells (chalcogenide)</u>							
CdTe (thin film)	22.1 ± 0.5	0.4798 (da)	0.8872	31.69^g	78.5	Newport (11/15)	First Solar on glass ³¹
CZTSSe (thin film)	12.6 ± 0.3	0.4209 (ap)	0.5134	35.21^h	69.8	Newport (7/13)	IBM solution grown ³²
CZTS (thin film)	11.0 ± 0.2	0.2339 (da)	0.7306	21.74^e	69.3	NREL (3/17)	UNSW on glass ³³
<u>Cells (other)</u>							
Perovskite (thin film)	25.2 ± 0.8^{ij}	0.0937 (ap)	1.1805	25.14^b	84.8	Newport (7/19)	KRICT/MIT ³⁴
Organic (thin film)	17.35 ± 0.2^k	0.032 (da)	0.862	25.83^b	78.0	NREL (10/19)	SJTU/UMass ³⁵
Dye sensitised	12.25 ± 0.4^{lj}	0.0963 (ap)	1.0203	15.17^b	79.1	Newport (8/19)	EPFL ³⁶

Abbreviations: AIST, Japanese National Institute of Advanced Industrial Science and Technology; (ap), aperture area; CIGSSe, CuInGaSSe ; CZTSSe, $\text{Cu}_2\text{ZnSnS}_4 - \text{ySe}_y$; CZTS, $\text{Cu}_2\text{ZnSnS}_4$; (da), designated illumination area; DS, directionally solidified (including mono cast and multicrystalline); FhG-ISE, Fraunhofer-Institut für Solare Energiesysteme; ISFH, Institute for Solar Energy Research, Hamelin; NREL, National Renewable Energy Laboratory; (t), total area.

^aNot measured at an external laboratory.

^bSpectral response and current-voltage curves reported in version 55 of these tables.

^cSpectral response and current-voltage curves reported in version 51 of these tables.

^dSpectral response and current-voltage curve reported in version 52 of these tables.

^eSpectral response and current-voltage curves reported in version 50 of these tables.

^fSpectral response and current-voltage curve reported in version 54 of these tables.

^gSpectral response and/or current-voltage curves reported in version 46 of these tables.

^hSpectral response and current-voltage curves reported in version 44 of these tables.

ⁱStability not investigated.

^jMeasured using 10-point IV sweep with constant voltage bias until current determined as unchanging.

^kLong-term stability not investigated.

^lLong-term stability not investigated. Krašovec et al.²³ document stability of similar devices.

4% higher than that measured for the best CIGS cell (Table 1). The third new result is for an all-perovskite device. An efficiency also of 24.2% was measured for a 1-cm^2 perovskite/perovskite two-junction, two-terminal device fabricated by Nanjing University⁷⁴ and measured by the Japan Electrical Safety and Environment Technology Laboratories (JET). The efficiency is 12% higher than the highest

efficiency perovskite cell of similar size in Table 1 (smaller area cells in Table 2 have their efficiency inflated by avoiding series resistance and other compromises normally required in practical devices).

As for other emerging technologies, Pb-halide perovskite cells such as those used as the top cells in these three devices may not

TABLE 3 Confirmed multiple-junction terrestrial cell and submodule efficiencies measured under the global AM1.5 spectrum (1000 W/m²) at 25°C (International Electrotechnical Commission [IEC] 60904-3: 2008, ASTM G-173-03 global)

Classification	Efficiency (%)	Area (cm ²)	Voc (V)	Jsc (mA/cm ²)	Fill factor (%)	Test centre (date)	Description
<u>III–V multijunctions</u>							
5 junction cell (bonded) (2.17/1.68/1.40/1.06/.73 eV)	38.8 ± 1.2	1.021 (ap)	4.767	9.564	85.2	NREL (7/13)	Spectrolab, 2-terminal ³⁷
InGaP/GaAs/InGaAs	37.9 ± 1.2	1.047 (ap)	3.065	14.27 ^a	86.7	AIST (2/13)	Sharp, 2 term. ³⁸
GaInP/GaAs (monolithic)	32.8 ± 1.4	1.000 (ap)	2.568	14.56 ^b	87.7	NREL (9/17)	LG Electronics, 2 term.
<u>Multijunctions with c-Si</u>							
GaInP/GaAs/Si (mech. stack)	35.9 ± 0.5 ^c	1.002 (da)	2.52/0.681	13.6/11.0	87.5/78.5	NREL (2/17)	NREL/CSEM/EPFL, 4-term. ³⁹
GaInP/AlGaAs/Si (wafer bonded)	34.1 ± 1.2 ^c	3.987 (ap)	3.177	12.4 ^d	86.4	FhG-ISE (8/19)	Fraunhofer ISE, 2-term. ⁴⁰
GaInP/GaAs/Si (monolithic)	24.3 ± 0.9 ^c	3.987 (ap)	2.662	12.2 ^d	74.5	FhG-ISE (6/19)	Fraunhofer ISE, 2-term. ⁴¹
GaAsP/Si (monolithic)	23.4±0.3 ^c	1.026(ap)	1.732	17.34 ^e	77.7	NREL (5/20)	OSU/UNSW/SolAero, 2-term. ⁴²
GaAs/Si (mech. stack)	32.8 ± 0.5 ^c	1.003 (da)	1.09/0.683	28.9/11.1 ^e	85.0/79.2	NREL (12/16)	NREL/CSEM/EPFL, 4-term. ³⁹
Perovskite/Si (2-terminal)	29.15 ± 0.7 ^f	1.060 (da)	1.897	19.75 ^g	77.8	FhG-ISE (1/20)	HZB ⁷⁷
GaInP/GaInAs/Ge; Si (spectral split minimodule)	34.5 ± 2.0	27.83 (ap)	2.66/0.65	13.1/9.3	85.6/79.0	NREL (4/16)	UNSW/Azur/Trina, 4-term. ⁴³
<u>Other multijunctions</u>							
Perovskite/CIGS	24.2 ± 0.7 ^f	1.045 (da)	1.768	19.24 ^g	72.9	FhG-ISE (1/20)	HZB, 2-terminal ⁷³
Perovskite/perovskite	24.2 ± 0.8 ^f	1.041(da)	1.986	15.93 ^g	76.6	JET (12/19)	Nanjing U, 2-term. ⁷⁴
a-Si/nc-Si/nc-Si (thin film)	14.0 ± 0.4 ^{h,c}	1.045 (da)	1.922	9.94 ⁱ	73.4	AIST (5/16)	AIST, 2-term. ⁴⁴
a-Si/nc-Si (thin-film cell)	12.7 ± 0.4 ^{h,c}	1.000(da)	1.342	13.45 ^j	70.2	AIST (10/14)	AIST, 2-term. ⁴⁵
<u>Notable exceptions</u>							
GaInP/GaAs	32.9 ± 0.5 ^c	0.250 (ap)	2.500	15.36 ^{g,k}	85.7	NREL (1/20)	NREL, multiple QW ⁷⁷
GaInP/GaAs/GaInAs	37.8 ± 1.4	0.998 (ap)	3.013	14.60 ^k	85.8	NREL (1/18)	Microlink (ELO) ⁴⁶
6 junction (monolithic) (2.19/1.76/1.45/1.19/.97/.7 eV)	39.2 ± 3.2 ^c	0.247 (ap) ^l	5.549	8.457 ^g	83.5	NREL (11/18)	NREL, inv. metamorphic ⁴⁷

Note. Any changes in the table from those previously published are set in bold type.

Abbreviations: a-Si, amorphous silicon/hydrogen alloy; AIST, Japanese National Institute of Advanced Industrial Science and Technology; (ap), aperture area; (da), designated illumination area; ELO, epitaxial lift-off; FhG-ISE, Fraunhofer Institut für Solare Energiesysteme; nc-Si, nanocrystalline or microcrystalline silicon; NREL, National Renewable Energy Laboratory; (t), total area.

^aSpectral response and current–voltage curve reported in version 42 of these tables.

^bSpectral response and current–voltage curve reported in the version 51 of these tables.

^cNot measured at an external laboratory.

^dSpectral response and current–voltage curve reported in the present version of these tables.

^eSpectral response and current–voltage curve reported in version 52 of these tables.

^fInitial efficiency.

^gSpectral response and current–voltage curve reported in the present version of these tables.

^hStabilised by 1000-h exposure to one sun light at 50°C.

ⁱSpectral response and current–voltage curve reported in version 49 of these tables.

^jSpectral responses and current–voltage curve reported in version 45 of these tables.

^kSpectral response and current–voltage curve reported in version 53 of these tables.

^lArea too small to qualify as outright class record.

TABLE 4 Confirmed terrestrial module efficiencies measured under the global AM1.5 spectrum (1000 W/m²) at a cell temperature of 25°C (International Electrotechnical Commission [IEC] 60904-3: 2008, ASTM G-173-03 global)

Classification	Effic. (%)	Area (cm ²)	V _{oc} (V)	I _{sc} (A)	FF (%)	Test Centre (date)	Description
Si (crystalline)	24.4 ± 0.5	13 177 (da)	79.5	5.04 ^a	80.1	AIST (9/16)	Kaneka (108 cells) ⁴
Si (multicrystalline)	20.4 ± 0.3	14 818 (ap)	39.90	9.833 ^b	77.2	FhG-ISE (10/19)	Hanwha Q cells (60 cells) ⁴⁸
GaAs (thin film)	25.1 ± 0.8	866.45 (ap)	11.08	2.303 ^c	85.3	FhG-ISE (11/17)	Alta Devices ⁴⁹
CIGS (Cd free)	19.2 ± 0.5	841 (ap)	48.0	0.456 ^c	73.7	AIST (1/17)	Solar frontier (70 cells) ⁵⁰
CdTe (thin film)	19.0 ± 0.9	23 573 (da)	227.8	2.560 ^b	76.6	FhG-ISE (9/19)	First Solar ⁵¹
a-Si/nc-Si (tandem)	12.3 ± 0.3 ^d	14 322 (t)	280.1	0.902 ^e	69.9	ESTI (9/14)	TEL solar, Trubbach Labs ⁵²
Perovskite	17.9 ± 0.5^f	804 (da)	58.7	0.323^g	70.3	AIST (1/20)	Panasonic (55 cells)⁷⁸
Organic	8.7 ± 0.3 ^h	802 (da)	17.47	0.569 ⁱ	70.4	AIST (5/14)	Toshiba ⁵³
<u>Multijunction</u>							
InGaP/GaAs/InGaAs	31.2 ± 1.2	968 (da)	23.95	1.506	83.6	AIST (2/16)	Sharp (32 cells) ⁵⁴
<u>Notable exception</u>							
CIGS (large)	18.6 ± 0.6	10 858 (ap)	58.00	4.545 ^b	76.8	FhG-ISE (10/19)	Miasole ⁵⁵

Note. Any changes in the table from those previously published are set in bold type.

Abbreviations: a-Si, amorphous silicon/hydrogen alloy; a-SiGe, amorphous silicon/germanium/hydrogen alloy; (ap), aperture area; CIGSS, CuInGaSSe; (da), designated illumination area; Effic., efficiency; nc-Si, nanocrystalline or microcrystalline silicon; (t), total area..

^aSpectral response and current voltage curve reported in version 49 of these tables.

^bSpectral response and current–voltage curve reported in version 55 of these tables.

^cSpectral response and current–voltage curve reported in version 50 or 51 of these tables.

^dStabilised at the manufacturer to the 2% level following IEC procedure of repeated measurements.

^eSpectral response and/or current–voltage curve reported in version 46 of these tables.

^fInitial performance.

^gSpectral response and current–voltage curve reported in the present version of these tables.

^hInitial performance.

ⁱSpectral response and current–voltage curve reported in version 45 of these tables.

demonstrate the same level of stability as conventional cells, with the stability of such perovskite cells discussed elsewhere.^{75,76} For the present devices, the assigned efficiency was based on measuring the steady-state power at a voltage held constant for 5 min.

The final new result for Table 3 is a 'notable exception' because the cell area was too small for classification as an outright record. Efficiency of 32.9% at one sun was measured for a 0.25-cm² two-junction, monolithic GaInP/GaAs cell fabricated and measured at the US National Renewable Energy Laboratory.⁷⁷ The cells have a strained, higher bandgap window layer in the GaInP cell to increase the absorption and strain-balanced multiple quantum wells in the bottom cell to extend the range of absorption.

There is one new entry in Table 4 ('one-sun modules'). An efficiency of 17.9% was measured for an 802-cm² perovskite module fabricated by Panasonic and measured by the Japanese National Institute of Advanced Industrial Science and Technology. This extends the 16.1% result also from Panasonic reported in the previous version of these tables, with earlier efforts by the same team reported elsewhere.⁷⁸

In Table 5 ('concentrator cells and modules'), one entry originally included in version 53 but inadvertently excluded from subsequent

versions has been reinstated as a 'notable exception'. An efficiency of 41.4% is again reported for a 122-cm² concentrator minimodule consisting of 10 glass achromatic lenses and 10 wafer-bonded GaInP/GaAs, GaInAsP/GaInAs four-junction solar cells fabricated and measured by FhG-ISE.⁷⁹ This is the highest efficiency measured for such an inter-connected concentrator module.

The EQE spectra for the new silicon cell reported in the present issue of these tables are shown in Figure 1A, with Figure 1B showing the current density–voltage (JV) curves for the same devices. Figure 2A,B shows the corresponding EQE and JV curves for the new multijunction cell results, while Figure 3A,B shows these for the new perovskite module result.

3 | DISCLAIMER

While the information provided in the tables is provided in good faith, the authors, editors and publishers cannot accept direct responsibility for any errors or omissions.

TABLE 5 Terrestrial concentrator cell and module efficiencies measured under the ASTM G-173-03 direct beam AM1.5 spectrum at a cell temperature of 25°C

Classification	Effic. (%)	Area (cm ²)	Intensity ^a (suns)	Test Centre (date)	Description
<u>Single cells</u>					
GaAs	29.3 ± 0.7 ^b	0.09359 (da)	49.9	NREL (10/16)	LG Electronics
Si	27.6 ± 1.2 ^c	1.00 (da)	92	FhG-ISE (11/04)	Amonix back-contact ⁵⁶
CIGS (thin film)	23.3 ± 1.2 ^{d,e}	0.09902 (ap)	15	NREL (3/14)	NREL ⁵⁷
<u>Multijunction cells</u>					
AlGaInP/AlGaAs/GaAs/GaInAs(3) (2.15/1.72/1.41/1.17/0.96/0.70 eV)	47.1 ± 2.6 ^{d,f}	0.099 (da)	143	NREL (3/19)	NREL, 6j inv. m'morphic ⁴⁷
GaInP/GaAs/GaInAsP/GaInAs	46.0 ± 2.2 ^g	0.0520 (da)	508	AIST (10/14)	Soitec/CEA/FhG-ISE 4j bonded ⁵⁸
GaInP/GaAs/GaInAs/GaInAs	45.7 ± 2.3 ^{d,h}	0.09709 (da)	234	NREL (9/14)	NREL, 4j monolithic ⁵⁹
InGaP/GaAs/InGaAs	44.4 ± 2.6 ⁱ	0.1652 (da)	302	FhG-ISE (4/13)	Sharp, 3j inverted metamorphic ⁶⁰
GaInAsP/GaInAs	35.5 ± 1.2 ^{j,d}	0.10031 (da)	38	NREL (10/17)	NREL 2-junction (2j) ⁶¹
<u>Minimodule</u>					
GaInP/GaAs; GaInAsP/GaInAs	43.4 ± 2.4 ^{d,k}	18.2 (ap)	340 ^l	FhG-ISE (7/15)	Fraunhofer ISE 4j (lens/cell) ⁶²
<u>Submodule</u>					
GaInP/GaInAs/Ge; Si	40.6 ± 2.0 ^k	287 (ap)	365	NREL (4/16)	UNSW 4j split spectrum ⁶³
<u>Modules</u>					
Si	20.5 ± 0.8 ^d	1875 (ap)	79	Sandia (4/89) ^m	Sandia/UNSW/ENTECH (12 cells) ⁶⁴
Three junction (3j)	35.9 ± 1.8 ⁿ	1092 (ap)	N/A	NREL (8/13)	Amonix ⁶⁵
Four junction (4j)	38.9 ± 2.5 ^o	812.3 (ap)	333	FhG-ISE (4/15)	Soitec ⁶⁶
<u>Notable exceptions</u>					
Si (large area)	21.7 ± 0.7	20.0 (da)	11	Sandia (9/90) ^k	UNSW laser grooved ⁶⁷
Luminescent Minimodule	7.1 ± 0.2	25 (ap)	2.5 ^l	ESTI (9/08)	ECN Petten, GaAs cells ⁶⁸
4j Minimodule	41.4 ± 2.6^d	121.8 (ap)	230	FhG-ISE (9/18)	FhG-ISE, 10 cells⁷⁹

Note. Any changes in the table from those previously published are set in bold type.

Abbreviations: (ap), aperture area; CIGS, CuInGaSe₂; (da), designated illumination area; Effic., efficiency; FhG-ISE, Fraunhofer-Institut für Solare Energiesysteme; NREL, National Renewable Energy Laboratory.

^aOne sun corresponds to direct irradiance of 1000 Wm⁻².

^bSpectral response and current–voltage curve reported in version 50 of these tables.

^cMeasured under a low aerosol optical depth spectrum similar to ASTM G-173-03 direct.⁶⁹

^dNot measured at an external laboratory.

^eSpectral response and current–voltage curve reported in version 44 of these tables.

^fSpectral response and current–voltage curve reported in version 54 of these tables.

^gSpectral response and current–voltage curve reported in version 45 of these tables.

^hSpectral response and current–voltage curve reported in version 46 of these tables.

ⁱSpectral response and current–voltage curve reported in version 42 of these tables.

^jSpectral response and current–voltage curve reported in version 51 of these tables.

^kDetermined at International Electrotechnical Commission 62670-1 CSTC reference conditions.

^lGeometric concentration.

^mRecalibrated from original measurement.

ⁿReferenced to 1000 W/m² direct irradiance and 25°C cell temperature using the prevailing solar spectrum and an in-house procedure for temperature translation.

^oMeasured under International Electrotechnical Commission (IEC) 62670-1 reference conditions following the current IEC power rating draft 626703.

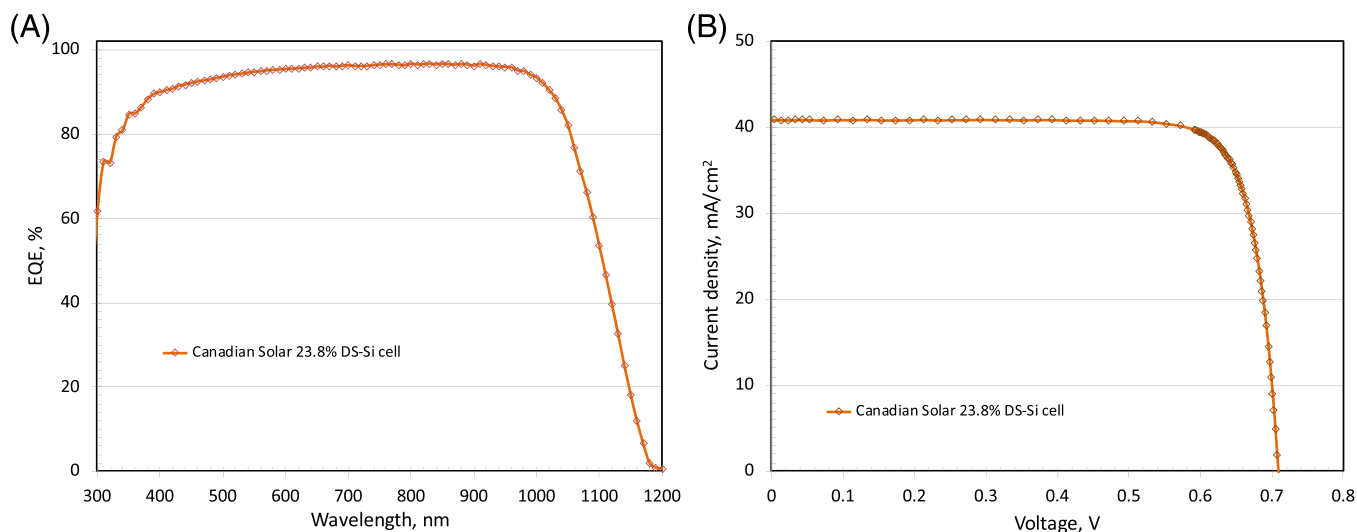


FIGURE 1 A, External quantum efficiency (EQE) for the Si cell reported in this issue (some results may be normalised), B, corresponding current density–voltage (JV) curves [Colour figure can be viewed at wileyonlinelibrary.com]

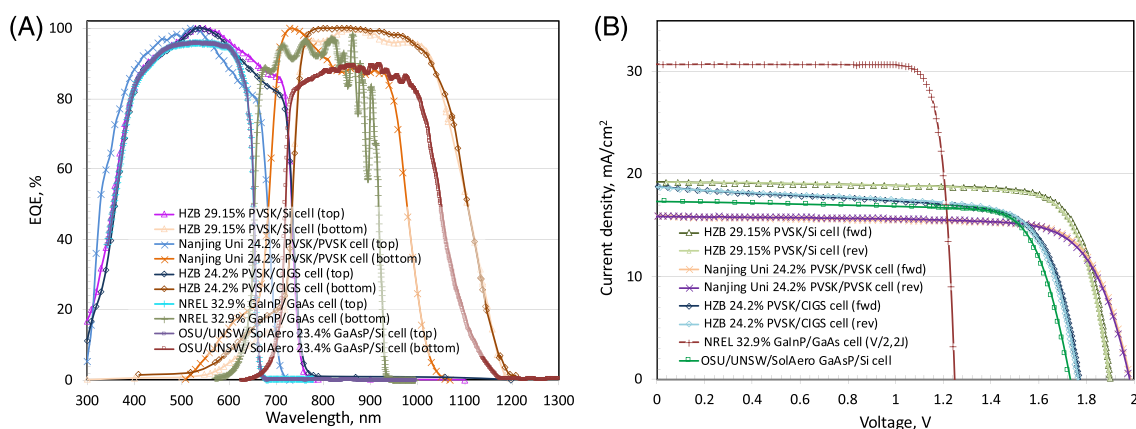


FIGURE 2 A, External quantum efficiency (EQE) for the multijunction cell results reported in this issue (some results may be normalised), B, corresponding current density–voltage (JV) curves [Colour figure can be viewed at wileyonlinelibrary.com]

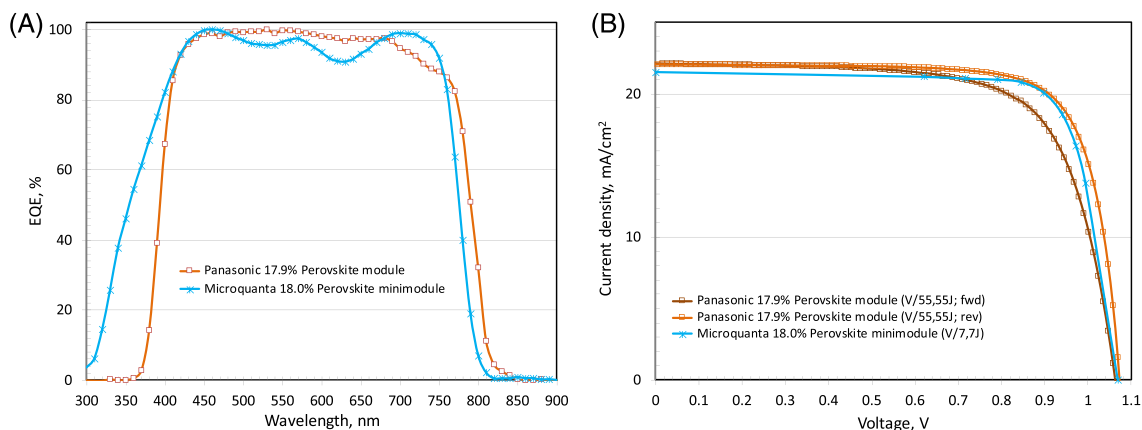


FIGURE 3 A, External quantum efficiency (EQE) for the perovskite module results reported in this issue (some results may be normalised), B, corresponding current density–voltage (JV) curves [Colour figure can be viewed at wileyonlinelibrary.com]

ACKNOWLEDGEMENT

The Australian Centre for Advanced Photovoltaics commenced operation in February 2013 with support from the Australian Government through the Australian Renewable Energy Agency (ARENA). The Australian Government does not accept responsibility for the views, information or advice expressed herein. The work at NREL was supported by the US Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory. The work at AIST was supported in part by the Japanese New Energy and Industrial Technology Development Organisation (NEDO) under the Ministry of Economy, Trade and Industry (METI).

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How to cite this article: Green MA, Dunlop ED, Hohl-Ebinger J, Yoshita M, Kopidakis N, Hao X. Solar cell efficiency tables (version 56). *Prog Photovolt Res Appl*. 2020;28:629-638. <https://doi.org/10.1002/pip.3303>