Received: 12 May 2017 | Accepted: 30 May 2017
DOI: 10.1002/pip.2909

WILEY

ACCELERATED PUBLICATION

Solar cell efficiency tables (version 50)

Martin A. Green[1] | Yoshihiro Hishikawa[2] | Wilhelm Warta[3] | Ewan D. Dunlop[4] | Dean H. Levi[5] | Jochen Hohl-Ebinger[3] | Anita W.Y. Ho-Baillie[1]

[1] Australian Centre for Advanced Photovoltaics, University of New South Wales, Sydney 2052, Australia

[2] National Institute of Advanced Industrial Science and Technology (AIST), Research Center for Photovoltaics (RCPV), Central 2, Umezono 1-1-1, Ibaraki, Tsukuba 305-8568, Japan

[3] Department: Characterisation and Simulation/CalLab Cells, Fraunhofer-Institute for Solar Energy Systems, Heidenhofstr. 2, Freiburg D-79110, Germany

[4] European Commission—Joint Research Centre, Directorate C—Energy, Transport and Climate, Via E. Fermi 2749, Ispra IT-21027VA, Italy

[5] National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, CO 80401, USA

Correspondence
Martin A. Green, School of Photovoltaic and Renewable Energy Engineering, University of New South Wales, Sydney 2052, Australia.
Email: m.green@unsw.edu.au

Funding information
Australian Renewable Energy Agency, Grant/Award Number: SRI001; Japanese New Energy and Industrial Technology Development Organisation (NEDO); US Department of Energy, Grant/Award Number: 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 2017 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.[1-4] 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,[2] 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 elsewhere.[1] A distinction is made between 3 different eligible definitions of cell area: total area, aperture area, and designated illumination area, as also defined elsewhere.[1] "Active area" efficiencies are not included. There are also certain minimum values of the area sought for the different device types (above 0.05-cm^2 for a concentrator cell, 1-cm^2 for a one-sun cell, and 800-cm^2 for a module).

Results are reported for cells and modules made from different semiconductors and for subcategories within each semiconductor grouping (eg, crystalline, polycrystalline, and thin film). From version 36 onwards, spectral response information is included when available 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.

Highest confirmed "one sun" cell and module results are reported in Tables 1–4. Any changes in the tables from those previously published[3] 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 summarizes the best-reported measurements for "one-sun" (nonconcentrator) single-junction cells and submodules.

TABLE 1 Confirmed single-junction terrestrial cell and submodule efficiencies measured under the global AM1.5 spectrum (1000 W/m^2) at 25°C (IEC 60904-3: 2008, ASTM G-173-03 global). New entries in bold type

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[5]**
Si (multicrystalline cell)	**21.9 ± 0.4[b]**	**4.0003 (t)**	**0.6726**	**40.76[a]**	**79.7**	**FhG-ISE (2/17)**	**FhG-ISE, n-type[6]**
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)[7]
Si (thin film minimodule)	10.5 ± 0.3	94.0 (ap)	0.492[c]	29.7[c]	72.1	FhG-ISE (8/07)[e]	CSG Solar (<2 μm on glass)[8]
III-V cells							
GaAs (thin film cell)	28.8 ± 0.9	0.9927 (ap)	1.122	29.68[f]	86.5	NREL (5/12)	Alta Devices[9]
GaAs (multicrystalline)	18.4 ± 0.5	4.011 (t)	0.994	23.2	79.7	NREL (11/95)	RTI, Ge substrate[10]
InP (crystalline cell)	**24.2 ± 0.5[b]**	**1.008 (ap)**	**0.939**	**31.15[a]**	**82.6**	**NREL (9/12)**	**NREL[11]**
Thin film chalcogenide							
CIGS (cell)	**21.7 ± 0.5**	**1.044 (da)**	**0.718**	**40.70[a]**	**74.3**	**AIST (1/17)**	**Solar Frontier[12]**
CdTe (cell)	21.0 ± 0.4	1.0623 (ap)	0.8759	30.25[d]	79.4	Newport (8/14)	First Solar, on glass[13]
CZTS (cell)	**10.0 ± 0.2**	**1.113 (da)**	**0.7083**	**21.77[a]**	**65.1**	**NREL (3/17)**	**UNSW[14]**
Amorphous/microcrystalline							
Si (amorphous cell)	10.2 ± 0.3[g,b]	1.001 (da)	0.896	16.36[d]	69.8	AIST (7/14)	AIST[15]
Si (microcrystalline cell)	**11.9 ± 0.3[b]**	**1.044 (da)**	**0.550**	**28.72[a]**	**75.0**	**AIST (2/17)**	**AIST[16]**
Perovskite							
Perovskite (cell)	19.7 ± 0.6[g,h]	0.9917 (da)	1.104	24.67[i]	72.3	Newport (3/16)	KRICT/UNIST[17]
Perovskite (minimodule)	**16.0 ± 0.4[g,h]**	**16.29 (ap)**	**1.029[c]**	**19.51[c,a]**	**76.1**	**Newport (4/17)**	**Microquanta, 6 serial cells[18]**
Dye sensitised							
Dye (cell)	11.9 ± 0.4[j]	1.005 (da)	0.744	22.47[k]	71.2	AIST (9/12)	Sharp[19]
Dye (minimodule)	10.7 ± 0.4[j]	26.55 (da)	0.754[c]	20.19[c,l]	69.9	AIST (2/15)	Sharp, 7 serial cells[19]
Dye (submodule)	8.8 ± 0.3[j]	398.8 (da)	0.697[c]	18.42[c,m]	68.7	AIST (9/12)	Sharp, 26 serial cells[20]
Organic							
Organic (cell)	11.2 ± 0.3[n]	0.992 (da)	0.780	19.30[d]	74.2	AIST (10/15)	Toshiba[21]
Organic (minimodule)	9.7 ± 0.3[n]	26.14 (da)	0.806	16.47[c,l]	73.2	AIST (2/15)	Toshiba (8 series cells)[22]

Abbreviations: CIGS, $CuIn_{1-y}Ga_ySe_2$; a-Si, amorphous silicon/hydrogen alloy; nc-Si, nanocrystalline or microcrystalline silicon; CZTSS, $Cu_2ZnSnS_{4-y}Se_y$; CZTS, Cu_2ZnSnS_4; (ap), aperture area; (t), total area; (da), designated illumination area; FhG-ISE, Fraunhofer Institut für Solare Energiesysteme; AIST, Japanese National Institute of Advanced Industrial Science and Technology.

[a]Spectral response and current-voltage curve reported in the present version of these tables.

[b]Not measured at an external laboratory.

[c]Reported on a "per cell" basis.

[d]Spectral responses and current-voltage curve reported in version 45 of these tables.

[e]Recalibrated from original measurement.

[f]Spectral response and current-voltage curve reported in version 40 of these tables.

[g]Stabilized by 1000 hours exposure to 1 sunlight at 50°C.

[h]Initial performance (not stabilized). Han et al[65] reviews the stability of similar devices.

[i]Spectral response and current-voltage curve reported in version 48 of these tables.

[j]Not stabilized, initial efficiency. Krašovec et al[66] reviews the stability of similar devices.

[k]Spectral response and current-voltage curve reported in version 41 of these tables.

[l]Spectral response and current-voltage curve reported in version 46 of these tables.

[m]Spectral response and current-voltage curve reported in version 43 of these tables.

[n]Initial performance (not stabilized). Other works[47,67] review the stability of similar devices.

Table 2 is new to the previous issue[3] of these Tables (version 49) and summarizes the growing number of cell and submodule results involving high-efficiency, one-sun multiple-junction devices, with these previously reported in Table 1. Table 3 shows the best results for one-sun modules. Table 4 contains what might be described as "notable exceptions." While not conforming to the requirements to be recognized as a class record, the one-sun cells and modules in this table 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, Table 4 is limited to nominally 10 entries with the present authors having voted for their preferences

TABLE 2 Confirmed multiple-junction terrestrial cell and submodule efficiencies measured under the global AM1.5 spectrum (1000 W/m^2) at 25°C (IEC 60904-3: 2008, ASTM G-173-03 global). New entries in bold type

Classification	Efficiency (%)	Area (cm^2)	Voc (V)	Jsc (mA/cm^2)	Fill Factor (%)	Test Centre (date)	Description
III-V Multijunctions							
5 junction cell (bonded)	38.8 ± 1.2	1.021 (ap)	4.767	9.564	85.2	NREL (7/13)	Spectrolab, 2-terminal[23]
(2.17/1.68/1.40/1.06/0.73 eV)							
InGaP/GaAs/InGaAs	37.9 ± 1.2	1.047 (ap)	3.065	14.27[a]	86.7	AIST (2/13)	Sharp, 2 term.[24]
GaInP/GaAs(monolithic)	31.6 ± 1.5	0.999 (ap)	2.538	14.18[b]	87.7	NREL (1/16)	Alta Devices, 2 term.[25]
Multijunctions with c-Si							
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.**[26]
GaInP/GaAs/Si (wafer bonded)	**31.3 ± 1.1**[c]	**3.981 (ap)**	**3.046**	**11.7**[d]	**87.5**	**FhG-ISE (3/17)**	**Fraunhofer ISE, 2-term.**[27]
GaInP/GaAs/Si (monolithic)	19.7 ± 0.7[c]	3.943 (ap)	2.323	10.0[e]	84.3	FhG-ISE (8/16)	Fraunhofer ISE[28]
GaAs/Si (mech. stack)	**32.8 ± 0.5**[c]	**1.003 (da)**	**1.09/0.683**	**28.9/11.1**	**85.0/79.2**	**NREL (12/16)**	**NREL/CSEM/EPFL, 4-term.**[26]
Perovskite/Si (monolithic)	23.6 ± 0.6[f]	0.990 (ap)	1.651	18.09[e]	79.0	NREL (8/16)	Stanford/ASU[29]
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.[30]
a-Si/nc-Si Multijunctions							
a-Si/nc-Si/nc-Si (thin-film)	14.0 ± 0.4[g,c]	1.045 (da)	1.922	9.94[e]	73.4	AIST (5/16)	AIST[31]
a-Si/nc-Si (thin-film cell)	12.7 ± 0.4%[g,c]	1.000(da)	1.342	13.45[h]	70.2	AIST (10/14)	AIST[15,32]

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

[a]Spectral response and current-voltage curve reported in version 42 of these tables.

[b]Spectral response and current-voltage curve reported in version 48 of these tables.

[c]Not measured at an external laboratory.

[d]Spectral response and current-voltage curve reported in the present version of these tables.

[e]Spectral response and current-voltage curve reported in version 49 of these tables.

[f]Not stabilized, initial efficiency. Sasaki et al[24] reviews the stability of similar devices.

[g]Stabilized by 1000 hours exposure to 1 sunlight at 50°C.

[h]Spectral responses and current-voltage curve reported in version 45 of these tables.

TABLE 3 Confirmed terrestrial module efficiencies measured under the global AM1.5 spectrum (1000 W/m^2) at a cell temperature of 25°C (IEC 60904-3: 2008, ASTM G-173-03 global). New entries in bold type

Classification	Effic. (%)	Area (cm^2)	V_{oc} (V)	I_{sc} (A)	FF (%)	Test Centre (date)	Description
Si (crystalline)	24.4 ± 0.5	13177 (da)	79.5	5.04[a]	80.1	AIST (9/16)	Kaneka (108 cells)[5]
Si (multicrystalline)	19.9 ± 0.4	15143 (ap)	78.87	4.795[a]	79.5	FhG-ISE (10/16)	Trina Solar (120 cells)[33]
GaAs (thin film)	**24.8 ± 0.5**	**865.3 (ap)**	**11.07**	**2.288**[b]	**84.7**	**NREL (11/16)**	**Alta Devices**[34]
CIGS (Cd free)	**19.2 ± 0.5**	**841 (da)**	**48.0**	**0.456**[b]	**73.7**	**AIST (1/17)**	**Solar Frontier (70 cells)**[35]
CIGS (large)	15.7 ± 0.5	9703 (ap)	28.24	7.254[c]	72.5	NREL (11/10)	Miasole[36]
CdTe (thin-film)	18.6 ± 0.6	7038.8 (ap)	110.6	1.533[d]	74.2	NREL (4/15)	First Solar, monolithic[37]
a-Si/nc-Si (tandem)	12.3 ± 0.3[e]	14322 (t)	280.1	0.902[f]	69.9	ESTI (9/14)	TEL Solar, Trubbach Labs[38]
Organic	8.7 ± 0.3[g]	802 (da)	17.47	0.569[h]	70.4	AIST (5/14)	Toshiba[22]
Multijunction							
InGaP/GaAs/InGaAs	31.2 ± 1.2	968 (da)	23.95	1.506	83.6	AIST (2/16)	Sharp (32 cells)[39]

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

[a]Spectral response and current-voltage curve reported in version 49 of these tables.

[b]Spectral response and current-voltage curve reported in the present version of these tables.

[c]Spectral response reported in version 37 of these tables.

[d]Spectral response and/or current-voltage curve reported in version 47 of these tables.

[e]Stabilised at the manufacturer to the 2% level following IEC procedure of repeated measurements.

[f]Spectral response and/or current-voltage curve reported in version 46 of these tables.

[g]Initial performance (not stabilized).

[h]Spectral response and current-voltage curve reported in version 45 of these tables.

TABLE 4 "Notable exceptions": "Top dozen" confirmed cell and module results, not class records measured under the global AM1.5 spectrum (1000 Wm^{-2}) at 25°C (IEC 60904-3: 2008, ASTM G-173-03 global). New entries in bold type

Classification	Efficiency (%)	Area (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	Fill Factor (%)	Test Centre (date)	Description
Cells (silicon)							
Si (crystalline)	25.0 ± 0.5	4.00 (da)	0.706	42.7[a]	82.8	Sandia (3/99)[b]	UNSW p-type PERC top/rear contacts[40]
Si (crystalline)	**25.7 ± 0.5**[c]	**4.017 (da)**	**0.7249**	**42.54**[d]	**83.3**	**FhG-ISE (3/17)**	**FhG-ISE, n-type top/rear contacts**[41]
Si (large)	**26.6 ± 0.5**	**179.74 (da)**	**0.7403**	**42.5**[d]	**84.7**	**FhG-ISE (11/16)**	**Kaneka, n-type rear IBC**[5]
Si (multicrystalline)	21.3 ± 0.4	242.74 (t)	0.6678	39.80[e]	80.0	FhG-ISE (11/15)	Trina Solar, large p-type[42]
Cells (III-V)							
GaInP	21.4 ± 0.3	0.2504 (ap)	1.4932	16.31[f]	87.7	NREL (9/16)	LG Electronics, high bandgap[43]
Cells (chalcogenide)							
CIGS (thin-film)	22.6 ± 0.5	0.4092 (da)	0.7411	37.76[f]	80.6	FhG-ISE (2/16)	ZSW on glass[44]
CIGSS (Cd free)	**22.0 ± 0.5**	**0.512 (da)**	**0.7170**	**39.45**[f]	**77.9**	**FhG-ISE (2/16)**	**Solar Frontier on glass**[12]
CdTe (thin-film)	22.1 ± 0.5	0.4798 (da)	0.8872	31.69[g]	78.5	Newport (11/15)	First Solar on glass[45]
CZTSS (thin-film)	12.6 ± 0.3	0.4209 (ap)	0.5134	35.21[h]	69.8	Newport (7/13)	IBM solution grown[46]
CZTS (thin-film)	**11.0 ± 0.2**	**0.2339(da)**	**0.7306**	**21.74**[d]	**69.3**	**NREL (3/17)**	**UNSW on glass**[14]
Cells (other)							
Perovskite (thin-film)	22.1 ± 0.7[i]	**0.0946 (ap)**	1.105	24.97[j]	80.3	Newport (3/16)	KRICT/UNIST[17]
Organic (thin-film)	**12.1 ± 0.3**[k]	**0.0407 (ap)**	**0.8150**	**20.27**[d]	**73.5**	**Newport (2/17)**	**Phillips 66**

Abbreviations: CIGSS, CuInGaSSe; CZTSS, $Cu_2ZnSnS_{4-y}Se_y$; CZTS, Cu_2ZnSnS_4; (ap), aperture area; (t), total area; (da), designated illumination area; AIST, Japanese National Institute of Advanced Industrial Science and Technology; NREL, National Renewable Energy Laboratory; FhG-ISE, Fraunhofer-Institut für Solare Energiesysteme.

[a]Spectral response reported in version 36 of these tables.

[b]Recalibrated from original measurement.

[c]Not measured at an external laboratory.

[d]Spectral response and current-voltage curves reported in the present version of these tables.

[e]Spectral response and current-voltage curves reported in version 47 of these tables.

[f]Spectral response and current-voltage curves reported in version 49 of these tables.

[g]Spectral response and/or current-voltage curves reported in version 46 of these tables.

[h]Spectral response and current-voltage curves reported in version 44 of these tables.

[i]Stability not investigated. Reference[47] documents stability of similar devices.

[j]Spectral response and current-voltage curves reported in version 48 of these tables.

[k]Stability not investigated. Sasaki et al[24] and Kayes et al[25] document stability of similar devices.

for inclusion. Readers who have suggestions of results for inclusion into this table 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 5 shows the best results for concentrator cells and concentrator modules (a smaller number of "notable exceptions" for concentrator cells and modules additionally is included in Table 5).

2 | NEW RESULTS

Seventeen new results are reported in the present version of these tables. Regarding Table 1, in the previous version of these tables,[3] a new efficiency record of 26.3% was reported for a large area (180-cm^2) silicon solar cell fabricated by Kaneka, using an amorphous silicon heterojunction interdigitated back contact (IBC) approach.[5] Three subsequent improvements have been reported for this device structure, all for cells fabricated by Kaneka. An improvement to 26.5% was measured by the Japanese National Institute of Advanced Industrial Science and Technology (AIST) in September 2016, followed by measurement of 26.6% by the Fraunhofer Institute for Solar Energy Systems (FhG-ISE) in November. Finally, an efficiency of 26.7% was measured in March 2017 for a similar but smaller area 79-cm^2 device again fabricated by Kaneka and measured at AIST.

A second new result is a new efficiency record for a multicrystalline silicon cell. An efficiency of 21.9% is reported for a 4-cm^2 cell again using an n-type substrate fabricated by FhG-ISE and measured at the same institution.[6] A third new result in Table 1 has been overlooked in previous versions of these tables (as pointed out by an observant reader). An efficiency of 24.2% has been reported for a 1-cm^2 InP cell fabricated and measured at the US National Renewable Energy Laboratory (NREL).[11]

A fourth new result is a new efficiency record for any reasonably sized thin-film polycrystalline cell, with an efficiency of 21.7% measured for a 1-cm^2 CIGS ($CuIn_{1-x}Ga_xSe_2$) cell fabricated by Solar Frontier and measured at AIST.[12]

TABLE 5 "Direct beam" terrestrial concentrator cell and module efficiencies measured under the ASTM G-173-03 direct AM1.5 spectrum at a cell temperature of 25°C. New entries in bold type

Classification	Effic. (%)	Area (cm^2)	Intensity[a] (suns)	Test Centre (date)	Description
Single cells					
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[48]
CIGS (thin-film)	23.3 ± 1.2[d,e]	0.09902 (ap)	15	NREL (3/14)	NREL[49]
Multijunction cells					
GaInP/GaAs; GaInAsP/GaInAs	46.0 ± 2.2[f]	0.0520 (da)	508	AIST (10/14)	Soitec/CEA/FhG-ISE 4j bonded[50]
GaInP/GaAs/GaInAs/GaInAs	45.7 ± 2.3[d,g]	0.09709 (da)	234	NREL (9/14)	NREL, 4j monolithic[51]
InGaP/GaAs/InGaAs	44.4 ± 2.6[h]	0.1652 (da)	302	FhG-ISE (4/13)	Sharp, 3j inverted metamorphic[52]
GaInP/GaInAs	**35.1 ± 1.1** [d,i]	**0.05376 (da)**	**407**	**FhG-ISE (3/17)**	**Fraunhofer ISE 2j**[53]
Minimodule					
GaInP/GaAs; GaInAsP/GaInAs (wafer bonded)	43.4 ± 2.4[d,j]	18.2 (ap)	340[k]	FhG-ISE (7/15)	Fraunhofer ISE 4j (lens/cell)[54]
Submodule					
GaInP/GaInAs/Ge; Si	40.6 ± 2.0[m]	287 (ap)	365	NREL (4/16)	UNSW 4j split spectrum[55]
Modules					
Si	20.5 ± 0.8[d]	1875 (ap)	79	Sandia (4/89)[k]	Sandia/UNSW/ENTECH (12 cells)[56]
Three junction (3j)	35.9 ± 1.8[m]	1092 (ap)	N/A	NREL (8/13)	Amonix[57]
Four junction (4j)	38.9 ± 2.5[n]	812.3 (ap)	333	FhG-ISE (4/15)	Soitec[58]
"Notable Exceptions"					
Si (large-area cell)	21.7 ± 0.7	20.0 (da)	11	Sandia (9/90)[k]	UNSW laser grooved[59]
Luminescent minimodule	7.1 ± 0.2	25(ap)	2.5[k]	ESTI (9/08)	ECN Petten, GaAs cells[60]

Abbreviations: CIGS, $CuInGaSe_2$; Effic., efficiency; (da), designated illumination area; (ap), aperture area; NREL, National Renewable Energy Laboratory; FhG-ISE, Fraunhofer-Institut für Solare Energiesysteme.

[a]One sun corresponds to direct irradiance of 1000 Wm^{-2}.

[b]Spectral response and current-voltage curve reported in version 49 of these tables.

[c]Measured under a low aerosol optical depth spectrum similar to ASTM G-173-03 direct.[61]

[d]Not measured at an external laboratory.

[e]Spectral response and current-voltage curve reported in version 44 of these tables.

[f]Spectral response and current-voltage curve reported in version 45 of these tables.

[g]Spectral response and current-voltage curve reported in version 46 of these tables.

[h]Spectral response and current-voltage curve reported in version 42 of these tables.

[i]Spectral response and current-voltage curves reported in the present version of these tables.

[j]Determined at IEC 62670-1 CSTC reference conditions.

[k]Geometric concentration.

[l]Recalibrated from original measurement.

[m]Referenced to 1000 W/m^2 direct irradiance and 25°C cell temperature using the prevailing solar spectrum and an in-house procedure for temperature translation.

[n]Measured under IEC 62670-1 reference conditions following the current IEC power rating draft 62670-3.

An additional new result in Table 1 is the achievement of the landmark efficiency of 10% for a 1-cm^2 kesterite solar cell. An efficiency of 10.04% was measured for a 1.1-cm^2 pure sulfide CZTS (Cu_2ZnSnS_4) cell fabricated by the University of New South Wales (UNSW) and measured by NREL.[14] A small increase to 11.9% efficiency is also reported for a 1-cm^2 microcrystalline silicon thin-film cell fabricated and measured by AIST.[16]

Table 1 also reports improved results for perovskite minimodules. An improved efficiency of 12.4% was reported in December 2016 for a 16-cm^2 8-cell minimodule fabricated by IMEC, Belgium, and measured by FhG-ISE. This was surpassed twice in February 2017 with an efficiency of 13.9% measured for a 36-cm^2 minimodule fabricated by SJTU/NIMS[3] and measured at AIST and with 15.2% reported for a 16-cm^2 minimodule fabricated by Microquanta Semiconductor, Hangzhou,[18] with the module measured by the Newport Technology and Applications Center. Finally, in April 2017, an efficiency of 16.0% was measured for a 16-cm^2 perovskite minimodule fabricated by Microquanta and again measured at Newport. All these perovskite results are initial efficiencies, with the stability of these devices not investigated but expected to be poor.

Three new results are reported in Table 2, a table dedicated to one-sun, multijunction cell results. The first new result is for a 3-junction (3j), 4-terminal device consisting of a monolithic

GaInP/GaAs cell mechanically stacked on top of a silicon cell. Two improved results for such 3j devices were measured in February 2017. An efficiency of 33.0% was measured by AIST for a 3.6-cm^2 cell fabricated by Sharp while an efficiency of 35.9% was measured for a 1-cm^2 device fabricated by the combined efforts of the National Renewable Energy Laboratory (NREL), the Swiss Center for Electronics and Microtechnology (CSEM), Neuchatel, and École Polytechnique Fédérale de Lausanne (EPFL), with the stacked device measured by NREL.[26] When connected as a 2-terminal device, the stacked cell efficiency reduced to 30.9% due largely to the lower current output of the silicon cell, although setting a new record for a 2-terminal multijunction cell involving silicon. In March, an improved record was established when 31.3% efficiency was reported for a wafer bonded 2-terminal stack of GaInP/GaAlAs/Si cells fabricated and measured by FhG-ISE.[27]

An additional new entry from the above NREL/CSEM/EPFL team is for a 2-junction (2j), 4-terminal device consisting of a GaAs cell mechanically stacked on a Si cell, with a combined efficiency of 32.8% measured at NREL.[26] Another noteworthy result from the same team is an only slightly lower combined efficiency of 32.5% for a similar 2j, 4-terminal device consisting of a GaInP cell mechanically stacked on a Si cell.

Two new module results are reported in Table 3. An efficiency of 24.8% is reported for an 865-cm^2 GaAs module fabricated by Alta Devices and measured by NREL.[34] Efficiency for an 841-cm^2 CIGS module fabricated by Solar Frontier and measured at AIST was substantially boosted to 19.2%.[35]

Four new results are reported as "notable exceptions" in Table 4. An efficiency of 25.7% has been confirmed for a 4-cm^2 n-type silicon cell with contacts on both top and rear surfaces, fabricated and measured at FhG-ISE, a record for a cell with this traditional type of contacting.[41] As previously noted, an efficiency of 26.6% has been measured for a large-area 180-cm^2 silicon heterojunction IBC cell fabricated by Kaneka and measured at FhG-ISE.[5]

The previous entry for a Pb-free CIGSS ($CuIn_{1-x}Ga_xSe_{2-y}S_y$) cell efficiency is corrected to 22.0% for a small area (0.5-cm^2) cell fabricated by Solar Frontier and measured at FhG-ISE. An efficiency of 11.0% has also been measured for a small area (0.23-cm^2) pure sulfide CZTS cell fabricated by UNSW and measured at NREL.[14] Finally, an efficiency of 12.1% has been measured for a very small area 0.04-cm^2 organic solar cell fabricated by Phillips 66 and also measured at Newport. For the previous 3 cells, cell area is too small for classification as an outright record. Solar cell efficiency targets in

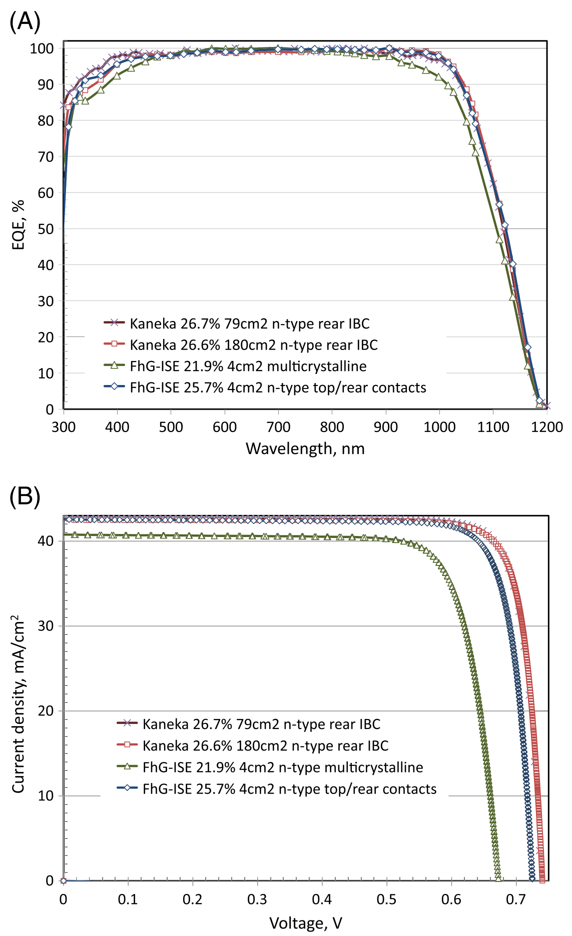

FIGURE 1 A, Normalized external quantum efficiency (EQE) for the new silicon cell results reported in this issue; B corresponding current density-voltage (JV) curves for the same devices. [Colour figure can be viewed at wileyonlinelibrary.com]

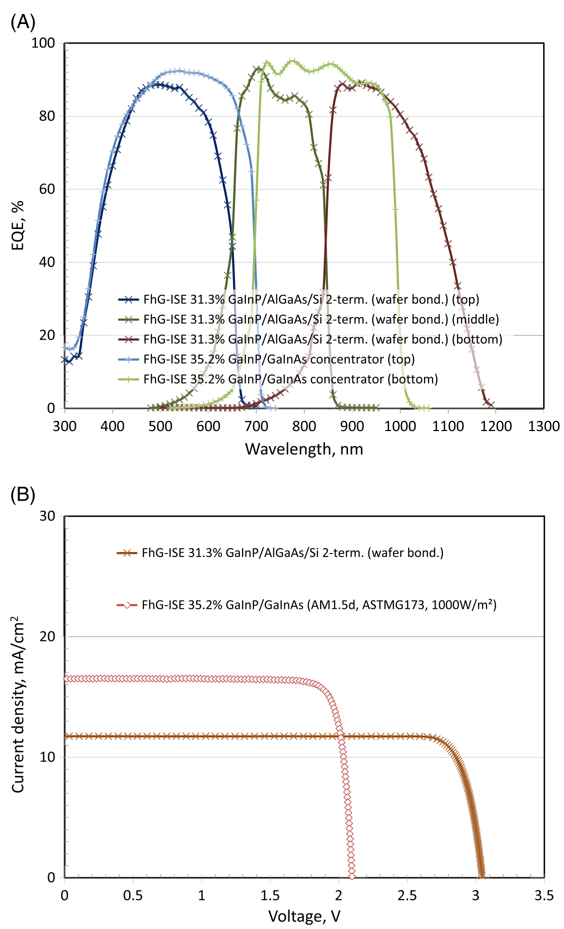

FIGURE 2 A, External quantum efficiency (EQE) for selected multijunction cell results reported in this issue; B, corresponding current density-voltage (JV) curves. [Colour figure can be viewed at wileyonlinelibrary.com]

governmental research programs generally have been specified in terms of a cell area of 1-cm^2 or larger.[62-64]

The final new result is in Table 5 where an improved direct beam efficiency of 35.1% is reported for a small-area, 2-terminal, monolithic GaInP/GaInAs cell under 407 suns concentration with the cell fabricated and measured by FhG-ISE.

The EQE spectra for the new silicon cell results reported in the present issue of these tables are shown in Figure 1A. Figure 1B shows the current density-voltage (JV) curves for the same devices. Figure 2 A,B shows the EQE for the new 2-junction and 3-junction multijunction cell results, respectively, with Figure 2C showing their current density-voltage (JV) curves. Figure 3A,B shows the corresponding EQE and JV curves for the new perovskite minimodule, together with the new CZTS and OPV cell results. Finally, Figure 4A, B shows the corresponding EQE and JV curves for the new CIGS module, together with the new CIGS, CIGSS, InP cell, and GaAs concentrator cell results.

For the case of modules, the measured current-voltage data have been reported on a "per cell" basis (measured voltage has been divided by the known or estimated number of cells in series, while measured current has been multiplied by this quantity and divided by the module area to give current density).

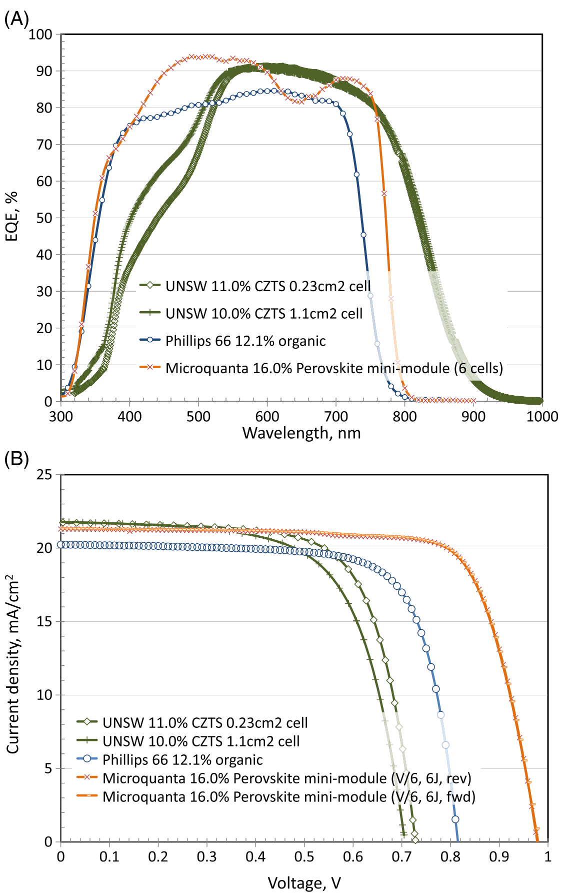

FIGURE 3 A, External quantum efficiency (EQE) for the new perovskite minimodule results reported in this issue together with the new CZTS and organic cell results; B, corresponding current density-voltage (JV) curves [Colour figure can be viewed at wileyonlinelibrary.com]

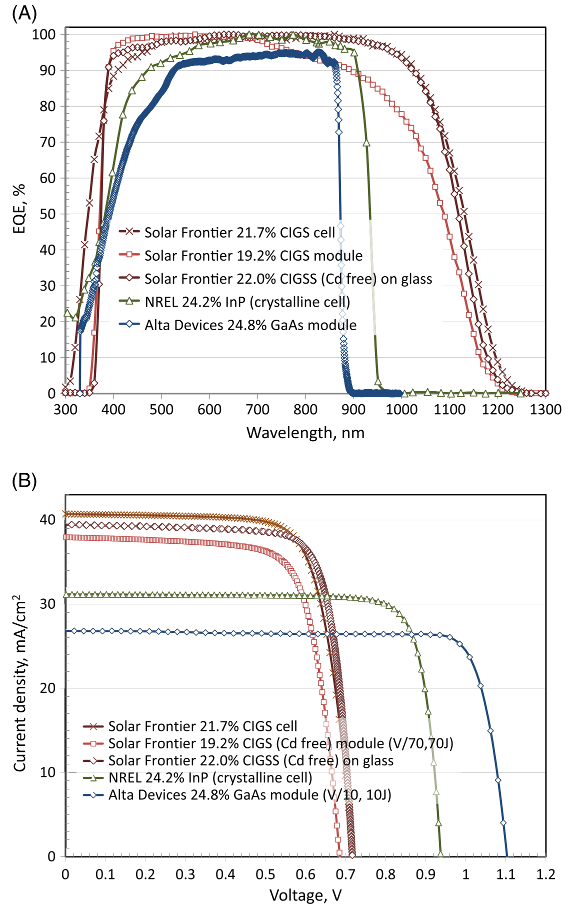

FIGURE 4 A, External quantum efficiency (EQE) for the new CIGS module result reported in this issue together with the new CIGS, CIGSS, InP cell, and GaAs concentrator cell results (mixed normalized and absolute results); B, corresponding current density-voltage (JV) curves. [Colour figure can be viewed at wileyonlinelibrary.com]

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.

ACKNOWLEDGEMENTS

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 by D Levi 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). MAG thanks Tyler Sims for bringing the overlooked InP result to his attention and Bastien Siepchen for corrections to a module entry.

REFERENCES

1. Green MA, Emery K, Hishikawa Y, Warta W, Dunlop ED. Solar cell efficiency tables (version 39). *Progress in Photovoltaics: Research and Applications*. 2012;20:12-20.

2. Green MA, Emery K, Hishikawa Y, Warta W. Solar cell efficiency tables (version 33). *Progress in Photovoltaics: Research and Applications*. 2009;17:85-94.
3. Green MA, Emery K, Hishikawa Y, Warta W, Dunlop ED. Solar cell efficiency tables (version 49). *Progress in Photovoltaics: Research and Applications*. 2017;25:3-13.
4. Green MA. Corrigendum to 'solar cell efficiency tables (version 49)' [Prog. Photovolt: Res. Appl. 2017; 25:3-13]. *Progress in Photovoltaics: Research and Applications*. 2017;25:333-334.
5. Yoshikawa K, Kawasaki H, Yoshida W, et al. Silicon heterojunction solar cell with interdigitated back contacts for a photoconversion efficiency over 26%. *Nature Energy*. 2017;2:17032
6. Benick J, Richter A, Müller R, et al. High-efficiency n-type HP mc silicon solar cells. *IEEE Journal of Photovoltaics*. (submitted)
7. Moslehi MM, Kapur P, Kramer J, Rana V, Seutter S, Deshpande A, Stalcup T, Kommera S, Ashjaee J, Calcaterra A, Grupp D, Dutton D, Brown R. World-record 20.6% efficiency 156 mm x 156 mm full-square solar cells using low-cost kerfless ultrathin epitaxial silicon & porous silicon lift-off technology for industry-leading high-performance smart PV modules. *PV Asia Pacific Conference (APVIA/PVAP)*, 24 October 2012.
8. Keevers MJ, Young TL, Schubert U, Green MA. 10% efficient CSG minimodules. *22nd European Photovoltaic Solar Energy Conference*, Milan, September 2007.
9. Kayes BM, Nie H, Twist R, Spruytte SG, Reinhardt F, Kizilyalli IC, Higashi GS. 27.6% conversion efficiency, a new record for single-junction solar cells under 1 sun illumination. *Proceedings of the 37th IEEE Photovoltaic Specialists Conference*, 2011.
10. Venkatasubramanian R, O'Quinn BC, Hills JS, Sharps PR, Timmons ML, Hutchby JA, Field H, Ahrenkiel A, Keyes B. 18.2% (AM1.5) efficient GaAs solar cell on optical-grade polycrystalline Ge substrate. *Conference Record, 25th IEEE Photovoltaic Specialists Conference*, Washington, May 1997, 31–36.
11. Wanlass M. Systems and methods for advanced ultra-high-performance InP solar cells. US Patent 9,590,131 B2, 7 March 2017.
12. Kato T, Handa A, Yagioka T, Matsuura T, Yamamoto K, Higashi S, Wu J-L, Tai KF, Hiroi H, Yoshiyama T, Sakai T, Sugimoto H. Enhanced efficiency of Cd-free $Cu(In,Ga)(Se,S)_2$ minimodule via (Zn,Mg)O second buffer layer and alkali post treatment. *44th IEEE Photoovltaic Specialists Conference*, Washington DC, 25–30 June 2017.
13. First Solar Press Release, First solar builds the highest efficiency thin film PV cell on record, 5 August 2014.
14. Sun K, Yan C, Liu F, et al. Beyond 9% efficient kesterite Cu_2ZnSnS_4 solar cell: fabricated by using $Zn_{1-x}Cd_xS$ buffer layer. *Advanced Energy Materials*. 2016;6: 1600046. https://doi.org/10.1002/aenm.201600046
15. Matsui T, Sai H, Suezaki T, Matsumoto M, Saito K, Yoshida I, Kondo M. Development of highly stable and efficient amorphous silicon based solar cells. *Proc. 28th European Photovoltaic Solar Energy Conference* 2013; 2213–2217.
16. Sai H, Maejima K, Matsui T, et al. Effect of front TCO layer on properties of substrate-type thin-film microcrystalline silicon solar cells. *IEEE Journal of Photovoltaics*. 2015;5(6):1528-1533.
17. Yang WS, Noh JH, Jeon NJ, et al. High-performance photovoltaic perovskite layers fabricated through intramolecular exchange. *Science*. 2015;348(6240):1234-1237.
18. http://microquanta.com/newsitem/277743967
19. Komiya R, Fukui A, Murofushi N, Koide N, Yamanaka R and Katayama H. Improvement of the conversion efficiency of a monolithic type dye-sensitized solar cell module. *Technical Digest, 21st International Photovoltaic Science and Engineering Conference*, Fukuoka, November 2011; 2C-5O-08.
20. Kawai M. High-durability dye improves efficiency of dye-sensitized solar cells. *Nikkei Electronics* 2013; Feb. 1 (http://techon.nikkeibp.co.jp/english/NEWS_EN/20130131/263532/) (accessed 23 October, 2013)
21. Mori S, Oh-oka H, Nakao H, et al. Organic photovoltaic module development with inverted device structure. *MRS Proceedings*. 2015;1737. https://doi.org/10.1557/opl.2015.540
22. Hosoya M, Oooka H, Nakao H, Gotanda T, Mori S, Shida N, Hayase R, Nakano Y, Saito M. Organic thin film photovoltaic modules. Proceedings of the 93rd annual meeting of the chemical Society of Japan 2013; 21–37.
23. Chiu PT, Law DL, Woo RL, Singer S, Bhusari D, Hong WD, Zakaria A, Boisvert JC, Mesropian S, King RR, Karam NH. 35.8% space and 38.8% terrestrial 5J direct bonded cells. *Proc. 40th IEEE Photovoltaic Specialist Conference*, Denver, June 2014; 11–13.
24. Sasaki K, Agui T, Nakaido K, Takahashi N, Onitsuka R, Takamoto T. Proceedings, 9th international conference on concentrating photovoltaics systems, Miyazaki, Japan 2013.
25. Kayes BM, Zhang L, Twist R, Ding IK, Higashi GS. Flexible thin-film tandem solar cells with >30% efficiency. *IEEE Journal of Photovoltaics*. 2014;4:729-733.
26. Essig S, Allebé C, Remo T, Geisz JF, Steiner MA, Barraud L, Ward JS, Schnabel M, Horowitz K, Descoeudres A, Young DL, Woodhouse M, Despeisse M, Ballif C, Tamboli A. Si-based multi-junction solar cells approaching 36% one-sun efficiency (under review).
27. https://www.ise.fraunhofer.de/content/dam/ise/en/documents/News/2017/0917_News_31_Percent_for-Silicon-based-multi-junction-solar-cell_e.pdf
28. Fraunhofer 19.7%
29. Bush KA, Palmstrom AF, Yu ZJ, et al. 23.6%-efficient monolithic perovskite/silicon tandem solar cells with improved stability. *Nature Energy*. 2017;2:17009
30. Green MA, Keevers MJ, Concha Ramon B, Jiang Y, Thomas I, Lasich JB, Verlinden, PJ, Yang Y, Zhang X, Emery K, Moriarty T, King RR, Bensch W. Improvements in sunlight to electricity conversion efficiency: above 40% for direct sunlight and over 30% for global. Paper 1AP.1.2. *European Photovoltaic Solar Energy Conference 2015*, Hamburg, September 2015.
31. Sai H, Matsui T, Koida T, et al. Triple-junction thin-film silicon solar cell fabricated on periodically textured substrate with a stabilized efficiency of 13.6%. *Appl Phys Lett*. 2015;106:213902. https://doi.org/10.1063/1.4921794
32. Sai H, Maejima K, Matsui T, et al. High-efficiency microcrystalline silicon solar cells on honeycomb textured substrates grown with high-rate VHF plasma-enhanced chemical vapor deposition. *Jpn J Appl Phys*. in press
33. Verlinden PJ, et al. Will we have > 22% efficient multi-crystalline silicon solar cells? *PVSEC 26*, Singapore, 24–28 October, 2016.
34. Mattos LS, Scully SR, Syfu M, Olson E, Yang L, Ling C, Kayes BM, He G. New module efficiency record: 23.5% under 1-sun illumination using thin-film single-junction GaAs solar cells. *Proceedings of the 38th IEEE Photovoltaic Specialists Conference*, 2012.
35. http://www.solar-frontier.com/eng/news/2017/0227_press.html
36. http://www.miasole.com (accessed 22 May, 2015).
37. First Solar Press Release. First solar achieves world record 18.6% thin film module conversion efficiency, 15 June 2015.
38. Cashmore JS, Apolloni M, Braga A, et al. Improved conversion efficiencies of thin-film silicon tandem (MICROMORPH ™) photovoltaic modules. *Solar Energy Materials and Solar Cells*. 2016;144:84-95. https://doi.org/10.1016/j.solmat.2015.08.022
39. Takamoto T. Application of InGaP/GaAs/InGaAs triple junction solar cells to space use and concentrator photovoltaic. *40th IEEE Photovoltaic Specialists Conference*, Denver, June 2014.
40. Zhao J, Wang A, Green MA, Ferrazza F. Novel 19.8% efficient "honeycomb" textured multicrystalline and 24.4% monocrystalline silicon solar cells. *Appl Phys Lett*. 1998;73:1991-1993.

41. Richter A, Benick J, Feldmann F, Fell A, Hermle M, Glunz SW. N-type Si solar cells with passivating electron contact: identifying sources for efficiency limitations by wafer thickness and resistivity variation, *Sol. Energy Mater. Sol. Cells* (Silicon PV proceedings, 2017; submitted)
42. Zhang S, Pan X, Jiao H, et al. 335 watt world record p-type mono-crystalline module with 20.6% efficient PERC solar cells. *IEEE Journal of Photovoltaics*. (to be published)
43. Kim S, Hwang ST, Yoon W, Lee HM. High performance GaAs solar cell using heterojunction emitter and its further improvement by ELO technique. Paper 4CV.1.27, *European Photovoltaic Solar Energy Conference 2016*, Munich, June 2016.
44. https://www.zsw-bw.de/fileadmin/user_upload/PDFs/Pressemitteilungen/2016/pr09-2016-ZSW-WorldRecordCIGS.pdf (accessed 25 October 2016).
45. First solar press release. First Solar Achieves yet Another Cell Conversion Efficiency World Record, 24 February 2016.
46. Wang W, Winkler MT, Gunawan O, et al. Device characteristics of CZTSSe thin-film solar cells with 12.6% efficiency. *Advanced Energy Materials*. 2013. https://doi.org/10.1002/aenm.201301465
47. Krebs FC (Ed). *Stability and Degradation of Organic and Polymer Solar Cells*. Chichester: Wiley; 2012. Jorgensen M, Norrman K, Gevorgyan SA, Tromholt T, Andreasen B, Krebs FC. Stability of polymer solar cells. *Adv Mater*. 2012;24:580-612.
48. Slade A, Garboushian V. 27.6% efficient silicon concentrator cell for mass production. *Technical Digest, 15th International Photovoltaic Science and Engineering Conference*, Shanghai, October 2005; 701.
49. Ward JS, Ramanathan K, Hasoon FS, et al. A 21.5% efficient Cu(In,Ga)Se2 thin-film concentrator solar cell. *Progress in Photovoltaics: Research and Applications*. 2002;10:41-46.
50. Press Release, Fraunhofer Institute for Solar Energy Systems, 1 December 2014 (accessed at http://www.ise.fraunhofer.de/en/press-and-media/press-releases/press-releases-2014/new-world-record-for-solar-cell-efficiency-at-46-percent on 7 December 2014).
51. *NREL Press Release NR-4514*, 16 December 2014.
52. *Press Release, Sharp Corporation*, 31 May 2012 (accessed at http://sharp-world.com/corporate/news/120531.html on 5 June 2013).
53. Ohlmann J, Lackner D, Sanchez JF, Zedda M, Wekkeli A, Steiner M, Fallisch A, Dimroth F. 35.1% efficient dual-junction solar cells optimized for direct hydrogen generation. 44th IEEE PVSC, Washington, 2017.
54. Steiner M, Siefer G, Schmidt T, Wiesenfarth M, Dimroth F, Bett AW. 43% sun light to electricity conversion efficiency using CPV. *IEEE Journal of Photovoltaics*. 2016;6:1020-1024. https://doi.org/10.1109/JPHOTOV.2016.2551460
55. Green MA, Keevers MJ, Thomas I, Lasich JB, Emery K, King RR. 40% efficient sunlight to electricity conversion. *Progress in Photovoltaics: Research and Applications*. 2015;23(6):685-691.
56. Chiang CJ and Richards EH. A 20% efficient photovoltaic concentrator module. *Conf. Record, 21st IEEE Photovoltaic Specialists Conference*, Kissimimee, May 1990: 861–863.
57. http://amonix.com/pressreleases/amonix-achieves-world-record-359-module-efficiency-rating-nrel-4 (accessed 23 October 2013).
58. van Riesen S, Neubauer M, Boos A, Rico MM, Gourdel C, Wanka S, Krause R, Guernard P, Gombert A. New module design with 4-junction solar cells for high efficiencies. *Proceedings of the 11th Conference on Concentrator Photovoltaic Systems*, 2015.
59. Zhang F, Wenham SR, Green MA. Large area, concentrator buried contact solar cells. *IEEE Transactions on Electron Devices*. 1995;42:144-149.
60. Slooff LH, Bende EE, Burgers AR, et al. A luminescent solar concentrator with 7.1% power conversion efficiency. *Physica Status Solidi (RRL)*. 2008;2(6):257-259.
61. Gueymard CA, Myers D, Emery K. Proposed reference irradiance spectra for solar energy systems testing. *Solar Energy*. 2002;73:443-467.
62. Program milestones and decision points for single junction thin films. *Annual Progress Report 1984, Photovoltaics, Solar Energy Research Institute, Report* DOE/CE-0128, June 1985; 7.
63. Sakata I, Tanaka Y, Koizawa K. Japan's new national R&D program for photovoltaics. *Photovoltaic Energy Conversion, Conference Record of the* 2006 *IEEE 4th World Conference*, Vol. 1, May 2008; 1–4.
64. Jäger-Waldau, A (Ed.). *PVNET:* European Roadmap for PV R&D, *EUR 21087 EN*, 2004.
65. Han Y, Meyer S, Dkhissi Y, et al. Degradation observations of encapsulated planar $CH_3NH_3PbI_3$ perovskite solar cells at high temperatures and humidity. *J Mater Chem A*. 2015;8139-8147.
66. Krašovec UO, Bokalič M, Topič M. Ageing of DSSC studied by electroluminescence and transmission imaging. *Solar Energy Materials and Solar Cells*. 2013;117:67-72.
67. Tanenbaum DM, Hermenau M, Voroshazi E, et al. The ISOS-3 interlaboratory collaboration focused on the stability of a variety of organic photovoltaic devices. *RSC Adv*. 2012;2:882-893.

How to cite this article: Green MA, Hishikawa Y, Warta W, et al. Solar cell efficiency tables (version 50). *Prog Photovolt Res Appl*. 2017;25:668–676. https://doi.org/10.1002/pip.2909