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ACCELERATED PUBLICATION

Solar cell efficiency tables (version 49)

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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 June 2016 are reviewed. Copyright © 2016 John Wiley & Sons, Ltd.

KEYWORDS

solar cell efficiency; photovoltaic efficiency; energy conversion efficiency

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

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 three 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 sub-categories within each semiconductor grouping (e.g. 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.

2. NEW RESULTS

Highest confirmed 'one-sun' cell and module results are reported in Tables I–IV. 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

Table I. 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).

Classification	Efficiency (%)	Area (cm^2)	V_{oc} (V)	J_{sc} (mA/ cm^2)	Fill factor (%)	Test centre (date)	Description
Silicon							
Si (crystalline cell)	**26.3 ± 0.5**	**180.43 (da)**	**0.7438**	**42.25**[a]	**83.8**	**FhG-ISE (7/16)**	**Kaneka, rear junction** [4]
Si (multicrystalline cell)	21.3 ± 0.4	242.74 (t)	0.6678	39.80[b]	80.0	FhG-ISE (11/15)	Trina Solar [19]
Si (thin transfer submodule)	21.2 ± 0.4	239.7 (ap)	0.687[c]	38.50[c]	80.3	NREL (4/14)	Solexel (35 μm thick) [20]
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) [21]
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 [22]
GaAs (multicrystalline)	18.4 ± 0.5	4.011 (t)	0.994	23.2	79.7	NREL (11/95)[d]	RTI, Ge substrate [23]
InP (crystalline cell)	22.1 ± 0.7	4.02 (t)	0.878	29.5	85.4	NREL (4/90)[d]	Spire, epitaxial [24]
Thin Film Chalcogenide							
CIGS (cell)	21.0 ± 0.6	0.9927 (ap)	0.757	35.70[g]	77.6	FhG-ISE (4/14)	Solibro, on glass [25]
CIGS (minimodule)	18.7 ± 0.6	15.892 (da)	0.701[c]	35.29[c]	75.6	FhG-ISE (9/13)	Solibro, 4 serial cells [26]
CdTe (cell)	21.0 ± 0.4	1.0623 (ap)	0.8759	30.25[d]	79.4	Newport (8/14)	First Solar, on glass [27]
CZTSSe (cell)	9.8 ± 0.2	1.115 (da)	0.5073	31.95[i]	60.2	Newport (4/16)	IMRA Europe [28]
CZTS (cell)	7.6 ± 0.1	1.067 (da)	0.6585	20.43[i]	56.7	NREL (4/16)	UNSW [14]
Amorphous/Microcrystalline							
Si (amorphous cell)	10.2 ± 0.3[j]	1.001 (da)	0.896	16.36[d]	69.8	AIST (7/14)	AIST [29]
Si (microcrystalline cell)	11.8 ± 0.3[k]	1.044 (da)	0.548	29.39[g]	73.1	AIST (10/14)	AIST [30]
Perovskite							
Perovskite (cell)	19.7 ± 0.6[l]	0.9917 (da)	1.104	24.67[i]	72.3	Newport (3/16)	KRICT/UNIST [31]
Perovskite (minimodule)	**12.1 ± 0.6**[l]	**36.13 (da)**	**0.836**[c]	**20.20**[c]	**71.5**	**AIST (9/16)**	**SJTU/NIMS, 10 serial cells** [5]
Dye sensitised							
Dye (cell)	11.9 ± 0.4[m]	1.005 (da)	0.744	22.47[m]	71.2	AIST (9/12)	Sharp [32]
Dye (minimodule)	10.7 ± 0.4[m]	26.55 (da)	0.754[c]	20.19[c]	69.9	AIST (2/15)	Sharp, 7 serial cells [32]
Dye (submodule)	8.8 ± 0.3[m]	398.8 (da)	0.697[c]	18.42[c]	68.7	AIST (9/12)	Sharp, 26 serial cells [33]
Organic							
Organic (cell)	11.2 ± 0.3[o]	0.992 (da)	0.780	19.30[d]	74.2	AIST (10/15)	Toshiba [34]
Organic (minimodule)	9.7 ± 0.3[o]	26.14 (da)	0.806	16.47[c]	73.2	AIST (2/15)	Toshiba (8 series cells) [35]

Any changes in the tables from those previously published [3] are set in bold type. CIGS, $CuIn_{1-y}Ga_ySe_2$; a-Si, amorphous silicon/hydrogen alloy; nc-Si, nano-crystalline 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, NREL, National Renewable Energy Laboratory.

[a]Spectral response and current–voltage curve reported in the present version of these tables.
[b]Spectral response and current–voltage curve reported in version 47 of these tables.
[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]Spectral response and current–voltage curve reported in version 46 of these tables.
[h]Spectral response and current–voltage curve reported in version 43 of these tables.
[i]Spectral response and current–voltage curve reported in version 48 of these tables.
[j]Stabilised by 1000 h exposure to one sun light at 50 °C.
[k]Not measured at an external laboratory.
[l]Not stabilised, initial efficiency. Reference [36] reviews the stability of similar devices.
[m]Initial performance (not stabilised). Reference [37] reviews the stability of similar devices.
[n]Spectral response and current–voltage curve reported in version 41 of these tables.
[o]Initial performance (not stabilised). References [38] and [39] review the stability of similar devices.
[p]Spectral response and/or current–voltage curve reported in version 42 of these tables.

Table II. 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).

Classification	Efficiency (%)	Area (cm^2)	Voc (V)	Jsc (mA/cm^2)	Fill factor (%)	Test centre (date)	Description
III-V Multijunctions							
Five-junction cell (bonded) (2.17/1.68/1.40/1.06/0.73 eV)	38.8 ± 1.2	1.021 (ap)	4.767	9.564	85.2	NREL (7/13)	Spectrolab [40]
InGaP/GaAs/InGaAs	37.9 ± 1.2	1.047 (ap)	3.065	14.27[a]	86.7	AIST (2/13)	Sharp [41]
GaInP/GaAs (monolithic)	31.6 ± 1.5	0.999 (ap)	2.538	14.18[b]	87.7	NREL (1/16)	Alta Devices [42]
Multijunctions with c-Si							
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 [43]
GaInP/Si (mech. stack)	**30.5 ± 2.0**[c]	**1.005 (da)**	**1.45/0.69**	**15.3/21.5**[d]	**85.1/78.2**	**NREL (9/16)**	**NREL/CSEM, 4-terminal** [6]
GaInP/GaAs/Si (wafer bonded)	**30.2 ± 1.1**[c]	**3.963 (ap)**	**3.046**	**11.9**[d]	**83.0**	**FhG-ISE (6/16)**	**Fraunhofer ISE** [7]
GaInP/GaAs/Si (monolithic)	**19.7 ± 0.7**[c]	**3.943 (ap)**	**2.323**	**10.0**[d]	**84.3**	**FhG-ISE (8/16)**	**Fraunhofer ISE**
Perovskite/Si (monolithic)	**23.6 ± 0.6**[e]	**0.990 (ap)**	**1.651**	**18.09**[d]	**79.0**	**NREL (8/16)**	**Stanford/ASU** [8]
a-Si/nc-Si Multijunctions							
a-Si/nc-Si/nc-Si (thin-film)	**14.0 ± 0.4**[f]	**1.045 (da)**	**1.922**	**9.94**[f]	**73.4**	**AIST (5/16)**	**AIST** [9]
a-Si/nc-Si (thin-film cell)	12.7 ± 0.4%[f]	1.000 (da)	1.342	13.45[g]	70.2	AIST (10/14)	AIST 29,30]

Any changes in the tables from those previously published [3] are set in bold type. 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; NREL, National Renewable Energy Laboratory.

[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] Not stabilised, initial efficiency. Reference 36 reviews the stability of similar devices.

[f] Stabilised by 1000 h exposure to one sun light at 50 °C.

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

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

Classification	Effic. (%)	Area (cm²)	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)	**19.9 ± 0.4**	**15 143 (ap)**	**78.87**	**4.795**[a]	**79.5**	**FhG-ISE (10/16)**	**Trina Solar (120 cells)** [10]
GaAs (thin film)	24.1 ± 1.0	858.5 (ap)	10.89	2.255[b]	84.2	NREL (11/12)	Alta Devices [44]
CdTe (thin-film)	18.6 ± 0.6	7038.8 (ap)	110.6	1.533[c]	74.2	NREL (4/15)	First Solar, monolithic [45]
CIGS (Cd free)	17.5 ± 0.5	808 (da)	47.6	0.408[d]	72.8	AIST (6/14)	Solar Frontier (70 cells) [46]
CIGS (large)	15.7 ± 0.5	9703 (ap)	28.24	7.254[e]	72.5	NREL (11/10)	Miasole [47]
a-Si/nc-Si (tandem)	12.3 ± 0.3[f]	14 322 (t)	280.1	0.902[g]	69.9	ESTI (9/14)	TEL Solar, Trubbach Labs [48]
Organic	8.7 ± 0.3[h]	802 (da)	17.47	0.569[c]	70.4	AIST (5/14)	Toshiba [35]
Multijunction							
InGaP/GaAs/InGa**As**	31.2 ± 1.2	968 (da)	23.95	1.506	**83.6**	AIST (2/16)	Sharp (32 cells) [49]

Any changes in the tables from those previously published [3] are set in bold type. 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; FhG-ISE, Fraunhofer Institut für Solare Energiesysteme; AIST, Japanese National Institute of Advanced Industrial Science and Technology; NREL, National Renewable Energy Laboratory; ESTI, European Solar Test Installation. [a]Spectral response and/or current–voltage curve reported in the present version of these tables.

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

[c]Spectral response and/or current–voltage curve reported in version 48 of these tables.

[d]Spectral response and/or current–voltage curve reported in version 45 of these tables.

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

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

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

[h]Initial performance (not stabilised).

author). Table I summarises the best-reported measurements for ‘one-sun’ (non-concentrator) single-junction cells and submodules. Table II is new to the present issue of these tables and summarises the growing number of cell and submodule results involving high efficiency, one-sun multiple-junction devices, with these previously reported in Table I. Table III shows the best results for one-sun modules. Table IV contains what might be described as ‘notable exceptions’. While not conforming to the requirements to be recognised 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 IV is limited to nominally 10 entries with the present authors having voted for their preferences 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 V 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 V).

Sixteen new results are reported in the present version of these Tables. The first new result in Table I is a new efficiency record for a large area (180 cm² designated illumination area) silicon solar cell. An efficiency of 26.3% has been measured by the Fraunhofer Institute for Solar Energy Systems (FhG-ISE) for a cell fabricated by Kaneka using an amorphous silicon heterojunction interdigitated back contact approach [4]. Efficiency was a creditable 25.6% on a total area basis.

Table I also reports the first certified results for perovskite minimodules. An efficiency of 11.5% was reported in August for a 16-cm² four-cell minimodule fabricated by the University of New South Wales and measured by the Newport Technology and Applications Center. This was surpassed in September with an efficiency of 12.1% reported for a 36-cm² 10-cell minimodule fabricated by Shanghai Jiao Tong University in conjunction with the Japanese National Institute of Materials Science [5] with the module measured by the Japanese National Institute of Advanced Industrial Science and Technology (AIST). This is an initial efficiency in both cases, with the stability of these devices not investigated.

Five new results are reported in the new Table II relating to one-sun, multijunction devices. The first new result is for a two-junction (2j), four-terminal GaInP/Si mechanically stacked device with an efficiency of 30.5% measured for a 1-cm² device with the GaInP cell fabricated by the National Renewable Energy Laboratory (NREL) and the silicon cell by the Swiss Center for Electronics and Microtechnology, Neuchatel, with the stacked device measured by NREL [6].

A similar efficiency of 30.2% has been confirmed for a 4-cm² two-terminal, three-junction, wafer bonded GaInP/GaAs/Si cell fabricated and measured at FhG-ISE [7]. Here, the GaInP/GaAs cells have not been directly grown on the Si but grown inverted on a GaAs substrate and transferred to the Si bottom cell via wafer bonding.

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Table IV. 'Notable Exceptions': 'Top ten' 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).

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 [50]
Si (crystalline)	**25.3 ± 0.3**[c]	**4.014 (da)**	**0.7180**	**42.50**[d]	**82.8**	**FhG-ISE (8/16)**	**FhG-ISE, n-type top/rear contacts** [11]
Cells (III-V)							
GaInP	**21.4 ± 0.3**	**0.2504 (ap)**	**1.4932**	**16.31**[d]	**87.7**	**NREL (9/16)**	**LG Electronics, high bandgap** [12]
Cells (chalcogenide)							
CIGS (thin-film)	**22.6 ± 0.5**	**0.4092 (da)**	**0.7411**	**37.78**[d]	**80.6**	**FhG-ISE (5/16)**	**ZSW on glass** [13]
CIGSS (Cd free)	**22.0 ± 0.5**	**0.512 (da)**	**0.7170**	**39.45**[e]	**77.8**	**FhG-ISE (3/16)**	**Solar Frontier on glass** [51]
CdTe (thin-film)	22.1 ± 0.5	0.4798 (da)	0.8872	31.69[h]	78.5	Newport (11/15)	First Solar on glass [52]
CZTSS (thin-film)	12.6 ± 0.3	0.4209 (ap)	0.5134	35.21[g]	69.8	Newport (7/13)	IBM solution grown [53]
CZTS (thin-film)	**9.5 ± 0.2**	**0.2379 (da)**	**0.6732**	**21.25**[h]	**66.3**	**NREL (9/16)**	**UNSW on glass** [14]
Cells (other)							
Perovskite (thin-film)	22.1 ± 0.7[i]	**0.0946 (ap)**	1.105	24.97[e]	80.3	Newport (3/16)	KRICT/UNIST [31]

Any changes in the tables from those previously published [3] are set in bold type. 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; IBM, International Business Machines Corporation; UNSW, University of New South Wales; ZSW, Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg. [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 of this or similar cell reported in version 48 of these tables.

[f]pectral response and current–voltage curves reported in version 45 of these tables.

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

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

[i]Stability not investigated. Reference 36 documents stability of similar devices.

Table V. 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
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 [54]
CIGS (thin-film)	23.3 ± 1.2[d]	0.09902 (ap)	15	NREL (3/14)	NREL [55]
Multijunction cells					
GaInP/GaAs; GaInAsP/GaInAs	46.0 ± 2.2[f]	0.0520 (da)	508	AIST (10/14)	Soitec/CEA/FhG-ISE 4j bonded [56]
GaInP/GaAs/GaInAs/GaInAs	45.7 ± 2.3[d]	0.09709 (da)	234	NREL (9/14)	NREL, 4j monolithic [57]
InGaP/GaAs/InGaAs	44.4 ± 2.6[h]	0.1652 (da)	302	FhG-ISE (4/13)	Sharp, 3j inverted metamorphic [58]
GaInP/GaInAs	**34.2 ± 1.7**[b]	**0.05361 (da)**	**460**	**FhG-ISE (4/16)**	**Fraunhofer ISE 2j** [18]
Minimodule					
GaInP/GaAs; GaInAsP/GaInAs	43.4 ± 2.4[d]	18.2 (ap)	340[j]	FhG-ISE (7/15)	Fraunhofer ISE 4j (lens/cell) [59]
Submodule					
GaInP/GaInAs/Ge; Si	40.6 ± 2.0[i]	287 (ap)	365	NREL (4/16)	UNSW 4j split spectrum [60]
Modules					
Si	20.5 ± 0.8[d]	1875 (ap)	79	Sandia (4/89)[k]	Sandia/UNSW/ENTECH (12 cells) [61]
Three junction (3j)	35.9 ± 1.8[l]	1092 (ap)	N/A	NREL (8/13)	Amonix [62]
Four junction (4j)	38.9 ± 2.5[m]	812.3 (ap)	333	FhG-ISE (4/15)	Soitec [63]
'Notable exceptions'					
Si (large area)	21.7 ± 0.7	20.0 (da)	11	Sandia (9/90)[k]	UNSW laser grooved [64]
Luminescent minimodule	7.1 ± 0.2	25(ap)	2.5[j]	ESTI (9/08)	ECN Petten, GaAs cells [65]

Any changes in the tables from those previously published [3] are set in bold type. CIGS, $CuInGaSe_2$; Effic., efficiency; (da), designated illumination area; (ap), aperture area; NREL, National Renewable Energy Laboratory; FhG-ISE, Fraunhofer-Institut für Solare Energiesysteme; AIST, Japanese National Institute of Advanced Industrial Science and Technology; UNSW, University of New South Wales; ESTI, European Solar Test Installation; ECN, Energy Research Centre of the Netherlands.

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

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

[c]Measured under a low aerosol optical depth spectrum similar to ASTM G-173-03 direct [66].

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

[j]Geometric concentration.

[k]Recalibrated from original measurement.

[l]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.

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

An efficiency of 19.7% also has been confirmed for a 4-cm^2 monolithic GaInP/GaAs/Si cell again fabricated and measured at FhG-ISE, with the GaInP/GaAs cells directly grown on the Si.

The fourth new result in Table II is for a 1-cm^2, 23.6% efficient monolithic perovskite-on-silicon tandem cell fabricated by combining an infrared-tuned silicon heterojunction bottom cell developed at Arizona State University with a $Cs_{0.17}FA_{0.83}Pb(Br_{0.17}I_{0.83})_3$ perovskite top cell deposited at Stanford University with the final device measured at NREL [8]. Finally, 14.0% efficiency for a 1-cm^2 thin-film a-Si/nc-Si/nc-Si triple junction cell fabricated and measured at AIST is reported [9].

Two significant new module results are reported in Table III. Following the battle for supremacy for a large area crystalline-Si module reported in the previous versions of these tables [3], two groups reported confirmed large-area module efficiencies above 24% during the reporting period. First, SunPower reported an efficiency of 24.1% in June exceeded by Kaneka in September with an aperture area efficiency of 24.4% reported for a 1.3-m^2 interdigitated back contact module measured by AIST [4].

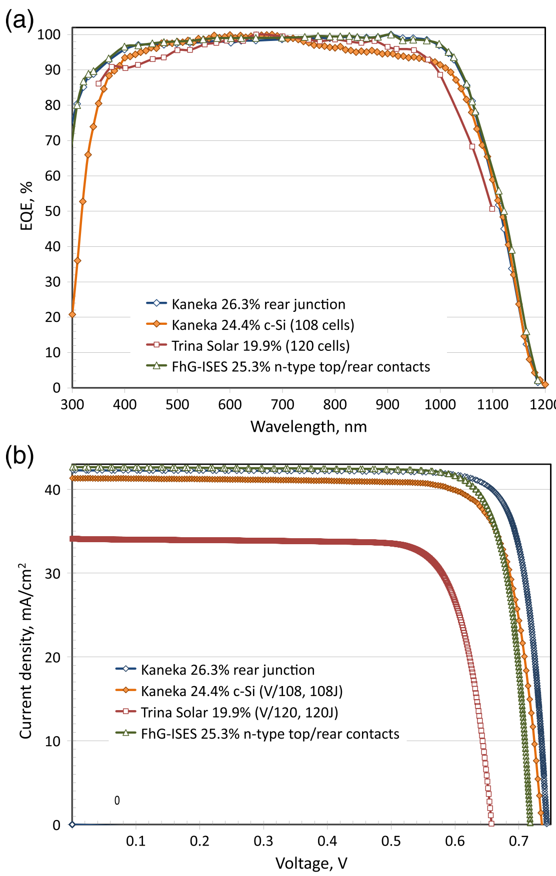

Figure 1. (a) Normalised external quantum efficiency (EQE) for the new silicon cell and module results reported in this issue and (b) corresponding current density–voltage (JV) curves for the same devices. FhG-ISES, Fraunhofer-Institut für Solare Energiesysteme.

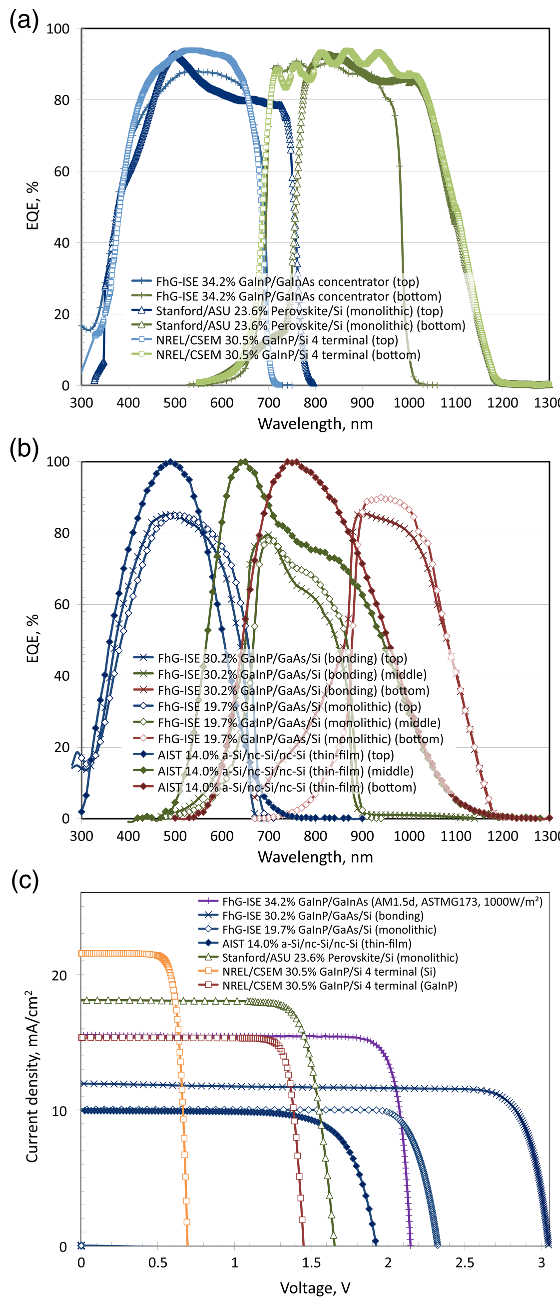

Figure 2. (a) External quantum efficiency (EQE) for the new two-junction multijunction cell results reported in this issue; (b) external quantum efficiency (EQE) for the new three-junction multijunction cell results reported in this issue (mixed normalised and absolute results); and (c) corresponding current density–voltage (JV) curves. AIST, Japanese National Institute of Advanced Industrial Science and Technology; CSEM, Swiss Center for Electronics and Microtechnology; FhG-ISE, Fraunhofer-Institut für Solare Energiesysteme; NREL, National Renewable Energy Laboratory.

An increase to 19.9% aperture area efficiency is also reported for a larger (1.5 m^2) multicrystalline module fabricated by Trina Solar [10] and measured at the FhG-ISE. This module included a number of advanced cell and module technologies, including half-cell, high-performance multi-crystalline silicon wafers with a high minority carrier lifetime, high-efficiency passivated emitter and rear cell technology and highly efficient light trapping.

Five new results are reported as 'notable exceptions' in Table IV. An efficiency of 25.3% has been confirmed for a 4-cm^2 n-type silicon cell with both top and rear contacts, fabricated and measured at FhG-ISE, a record for a cell with this traditional type of contacting [11]. The efficiency of a wide bandgap GaInP cell has been increased to 21.4% for a small area (0.25 cm^2) cell fabricated by LG Electronics and measured at NREL [12]. Yet another increase in CIGS ($CuIn_{1-x}Ga_xSe_2$) cell efficiency to 22.6% is reported for a small area (0.4 cm^2) cell fabricated by Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg and measured at FhG-ISE [13]. For a Cd-free CIGSS device of similar area, efficiency was increased to 22.0% for a cell fabricated by Solar Frontier and also measured at FhG-ISE. Finally, an efficiency of 9.5% has also been measured for a small (0.24 cm^2) pure sulfide CZTS (Cu_2ZnSnS_4) cell fabricated by the University of New South Wales and measured at Newport [14]. For the previous four cells, cell area is too small for classification as an outright record. Solar cell efficiency targets in governmental research programmes generally have been specified in terms of a cell area of 1 cm^2 or larger [15–17].

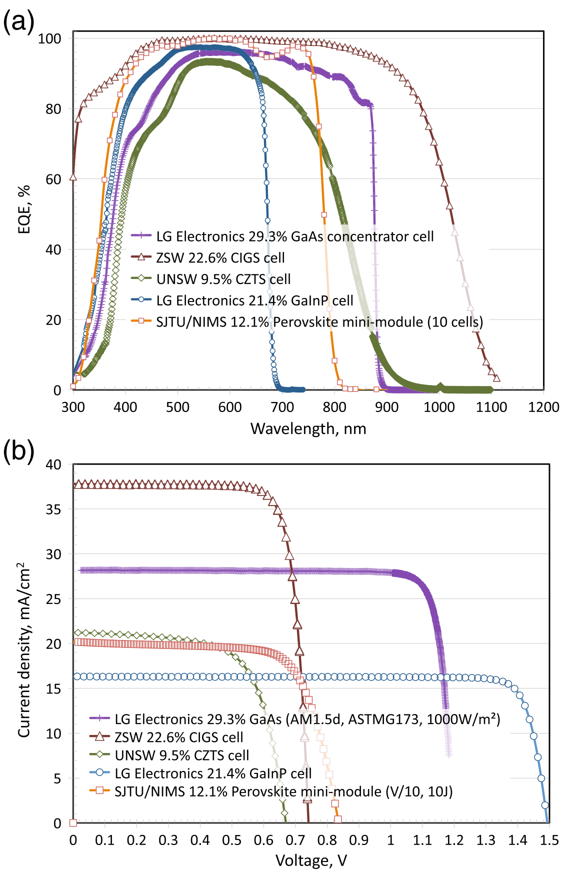

Figure 3. (a) External quantum efficiency (EQE) for the new perovskite minimodule results reported in this issue together with the new GaInP, CIGS, CZTS and GaAs concentrator cell results (mixed normalised and absolute results) and (b) corresponding current density–voltage (JV) curves. CIGS, $CuIn_{1-y}Ga_ySe_2$; CZTS, Cu_2ZnSnS_4; UNSW, University of New South Wales; ZSW, Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg; SJTU, Shanghai Jiao Tong University; NIMS, ,Japanese National Institute of Materials Science.

Two new concentrator cell results are reported in Table V. The first is improvement in efficiency to 29.3% for a small area (0.09 cm^2) cell fabricated by LG Electronics and measured at NREL. The final new result in Table V is a new efficiency level of 34.2% for a small area (0.05 cm^2), two-junction GaInP/GaInAs concentrator cell fabricated and measured by FhG-ISE [18], slightly higher in measured efficiency than a similar device fabricated and measured at NREL in 2014.

The EQE spectra for the new silicon cell and module results reported in the present issue of these Tables are shown in Figure 1(a). Figure 1(b) shows the current density–voltage (JV) curves for the same devices. Figure 2(a) and (b) shows the EQE for the new two-junction and three-junction multijunction cell results, respectively with Figure 2(c) showing their current density–voltage (JV) curves. Figure 3(a) and (b) shows the corresponding EQE and JV curves for the new perovskite minimodule, together with the new GaInP, CIGS, CZTS 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).

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.

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