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ACCELERATED PUBLICATION

Solar cell efficiency tables (version 44)

Martin A. Green[1]*, Keith Emery[2], Yoshihiro Hishikawa[3], Wilhelm Warta[4] and Ewan D. Dunlop[5]

[1] Australian Centre for Advanced Photovoltaics, University of New South Wales, Sydney, 2052, Australia
[2] National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, CO, 80401, USA
[3] Research Center for Photovoltaic Technologies (RCPVT), National Institute of Advanced Industrial Science and Technology (AIST), Central 2, Umezono 1-1-1, Tsukuba, Ibaraki, 305-8568, JAPAN
[4] Department of Materials and Technology, Solar Cells, Fraunhofer Institute for Solar Energy Systems, Heidenhofstr. 2; D-79110 Freiburg, Germany
[5] Joint Research Centre, Renewable Energy Unit, Institute for Energy, European Commission, Via E. Fermi 2749, IT-21027 Ispra (VA), Italy

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 2014 are reviewed. Copyright © 2014 John Wiley & Sons, Ltd.

KEYWORDS
solar cell efficiency; photovoltaic efficiency; energy conversion efficiency

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

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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 (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 (*I*–*V*) curves have also been included where possible from Version 38 onwards.

2. NEW RESULTS

The highest confirmed 'one-sun' cell and module results are reported in Tables I and II. 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 I summarises the best measurements for cells and submodules, whereas Table II shows the best results for modules. Table III contains what might be described as 'notable exceptions'. Whilst not conforming to the requirements to be recognised as a class record, the cells and modules in this Table have notable characteristics that will be of interest to sections of the

Table I. Confirmed 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[a]	Efficiency (%)	Area[b] (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	Fill factor (%)	Test centre[c] (date)	Description
Silicon							
Si (crystalline)	**25.6 ± 0.5**	**143.7 (da)**	**0.740**	**41.8**[d]	**82.7**	**AIST (2/14)**	**Panasonic HIT, rear-junction** [4]
Si (multicrystalline)	20.4 ± 0.5	1.002 (ap)	0.664	38.0	80.9	NREL (5/04)[e]	FhG-ISE [21]
Si (thin film transfer)	20.1 ± 0.4	242.6 (ap)	0.682	38.14[f]	77.4	NREL (10/12)	Solexel (43 μm thick) [22]
Si (thin film minimodule)	10.5 ± 0.3	94.0 (ap)	0.492[g]	29.7[g]	72.1	FhG-ISE (8/07)[e]	CSG Solar (<2 μm on glass; 20 cells) [23]
III–V Cells							
GaAs (thin film)	28.8 ± 0.9	0.9927 (ap)	1.122	29.68[h]	86.5	NREL (5/12)	Alta Devices [24]
GaAs (multicrystalline)	18.4 ± 0.5	4.011 (t)	0.994	23.2	79.7	NREL (11/95)[e]	RTI, Ge substrate [25]
InP (crystalline)	22.1 ± 0.7	4.02 (t)	0.878	29.5	85.4	NREL (4/90)[e]	Spire, epitaxial [26]
Thin film chalcogenide							
CIGS (cell)	**20.5 ± 0.6**	**0.9882 (ap)**	**0.752**	**35.3**[d]	**77.2**	**NREL (3/14)**	**Solibro, on glass** [5]
CIGS (minimodule)	18.7 ± 0.6	15.892 (da)	0.701[g]	35.29[g,i]	75.6	FhG-ISE (9/13)	Solibro, four serial cells [27]
CdTe (cell)	19.6 ± 0.4	1.0055 (ap)	0.8573	28.59[j]	80.0	Newport (6/13)	GE Global Research [28]
Amorphous/microcrystalline Si							
Si (amorphous)	10.1 ± 0.3[k]	1.036 (ap)	0.886	16.75[l]	67.8	NREL (7/09)	Oerlikon Solar Lab, Neuchatel [29]
Si (microcrystalline)	**11.0 ± 0.3**[m]	**1.045 (da)**	**0.542**	**27.44**[d]	**73.8**	**AIST (1/14)**	**AIST** [9]
Dye sensitised							
Dye sensitised	11.9 ± 0.4[n]	1.005 (da)	0.744	22.47[f]	71.2	AIST (9/12)	Sharp [30]
Dye sensitised (minimodule)	29.9 ± 0.4[n]	17.11 (ap)	0.719[g]	19.4[g,i]	71.4	AIST (8/10)	Sony, eight parallel cells [31]
Dye (submodule)	8.8 ± 0.3[n]	398.8 (da)	0.697[g]	18.42[g,i]	68.7	AIST (9/12)	Sharp, 26 serial cells [32]
Organic							
Organic thin film	10.7 ± 0.3[o]	1.013 (da)	0.872	17.75[f]	68.9	AIST (10/12)	Mitsubishi Chemical (4.4 × 23.0 mm) [33]
Organic (minimodule)	**9.1 ± 0.3**[o]	**25.04 (da)**	**0.794**[g]	**17.06**[g,d]	**67.5**	**AIST (2/14)**	**Toshiba (four series cells)** [10]
Organic (submodule)	6.8 ± 0.2[o]	395.9 (da)	0.798[g]	13.50[f,g]	62.8	AIST (10/12)	Toshiba (15 series cells) [10]
Multijunction devices							
InGaP/GaAs/InGaAs	37.9 ± 1.2	1.047 (ap)	3.065	14.27[j]	86.7	AIST (2/13)	Sharp [34]
a-Si/nc-Si/nc-Si (thin film)	13.4 ± 0.4[p]	1.006 (ap)	1.963	9.52[f]	71.9	NREL (7/12)	LG Electronics [35]

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a-Si/nc-Si (thin film cell)	12.3 ± 0.3%[q]	0.962(ap)	1.365	12.93[r]	69.4	AIST (7/11)	Kaneka [36]
a-Si/nc-Si (thin film minimodule)	**11.8 ± 0.6[s]**	**40.26 (ap)**	**1.428[g]**	**12.27[g,d]**	**67.5**	**FhG-ISE (4/14)**	**TEL Solar, Trubbach Labs [13](10 serial cells)**

[a]CIGS, CuInGaSe2; a-Si, amorphous silicon/hydrogen alloy; nc-Si, nanocrystalline or microcrystalline silicon.

[b]ap, aperture area; t, total area; da, designated illumination area.

[c]FhG-ISE, Fraunhofer Institut für Solare Energiesysteme; AIST, Japanese National Institute of Advanced Industrial Science and Technology.

[d]Spectral response and current–voltage curve reported in present version of these Tables.

[e]Recalibrated from original measurement.

[f]Spectral response and current–voltage curve reported in Version 41 of these Tables.

[g]Reported on a 'per cell' basis.

[h]Spectral response and current–voltage curve reported in Version 40 of these Tables.

[i]Spectral response and current–voltage curve reported in Version 43 of these Tables.

[j]Spectral response and/or current–voltage curve reported in Version 42 of these Tables.

[k]Light soaked at Oerlikon prior to testing at NREL (1000 h, 1 sun, 50°C)

[l]Spectral response reported in Version 36 of these Tables.

[m]Not measured at an external laboratory.

[n]Stability not investigated. References 37 and 38 review the stability of similar devices.

[o]Stability not investigated. References 11 and 12 review the stability of similar devices.

[p]Light soaked under 100 mW/cm2 white light at 50°C for over 1000 h.

[q]Stabilised by manufacturer.

[r]Spectral response and current–voltage curve reported in Version 39 of these Tables.

[s]Stabilised at test centre for 132 h to the 2% IEC criteria.

Table II. 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).

Classification[a]	Effic.[b] (%)	Area[c] (cm^2)	V_{oc} (V)	I_{sc} (A)	FF[d] (%)	Test centre (date)	Description
Si (crystalline)	22.9 ± 0.6	778 (da)	5.60	3.97	80.3	Sandia (9/96)[e]	UNSW/Gochermann [39]
Si (large crystalline)	22.4 ± 0.6	15775 (ap)	69.57	6.341[f]	80.1	NREL (8/12)	SunPower [40]
Si (multicrystalline)	18.5 ± 0.4	14661 (ap)	38.97	9.149[g]	76.2	FhG-ISE (1/12)	Q-Cells (60 serial cells) [41]
Si (thin film polycrystalline)	8.2 ± 0.2	661(ap)	25.0	0.320	68.0	Sandia (7/02)[e]	Pacific Solar (<2 m on glass) [42]
GaAs (thin film)	24.1 ± 1.0	858.5 (ap)	10.89	2.255[h]	84.2	NREL (11/12)	Alta Devices [43]
CdTe (thin film)	**17.5 ± 0.7**	**7021 (ap)**	**103.1**	**1.553**[i]	**76.6**	**NREL (2/14)**	**First Solar, monolithic** [14]
CIGS (thin film)	15.7 ± 0.5	9703 (ap)	28.24	7.254[j]	72.5	NREL (11/10)	Miasole [44]
CIGSS (Cd free)	13.5 ± 0.7	3459 (ap)	31.2	2.18	68.9	NREL (8/02)[e]	Showa Shell [45]
a-Si/nc-Si (tandem)	**11.6 ± 0.5**[k]	**14250 (t)**	**198.5**	**1.254**[i]	**66.2**	**ESTI (12/13)**	**TEL Solar, Trubbach Labs** [13]

[a]CIGSS, CuInGaSSe; a-Si, amorphous silicon/hydrogen alloy; a-SiGe, amorphous silicon/germanium/hydrogen alloy; nc-Si, nanocrystalline or microcrystalline silicon.
[b]Effic., efficiency.
[c]t, total area; ap, aperture area; da, designated illumination area.
[d]FF, fill factor.
[e]Recalibrated from original measurement.
[f]Spectral response and current–voltage curve reported in Version 42 of these Tables.
[g]Spectral response and/or current–voltage curve reported in Version 40 of these Tables.
[h]Spectral response and current–voltage curve reported in Version 41 of these Tables.
[i]Current–voltage curve reported in the present version of these Tables.
[j]Spectral response reported in Version 37 of these Tables.
[k]Stabilised at the manufacturer under the light-soaking conditions of IEC61646.

photovoltaic community, with entries based on their significance and timeliness.

To encourage discrimination, Table III is limited to nominally ten 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 IV 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 IV).

Fourteen new results are reported in the present version of these Tables. The first new result in Table I displaces one of the longest standing entries, that for the highest efficiency for a crystalline silicon cell. An improved efficiency of 25.6% has been measured by the Japanese National Institute of Advanced Industrial Science and Technology (AIST) for a large area (144 cm^2) n-type crystalline silicon cell fabricated by Panasonic [4]. This cell uses the company's heterojuction cell technology (using a thin p-type amorphous silicon layer as the cell emitter a similar n-type layer as the rear contact) but, unlike earlier such heterojunction entries in these Tables, is a rear-junction cell with both positive and negative contacts made to the unilluminated rear cell surface. The former long-established 25.0% cell result is displaced to Table III as a 'notable exception', representing the highest efficiency reported for a silicon cell with conventional contacts to both front and rear surfaces.

The second new result in Table I also represents a significant landmark, the first 1-cm^2 thin film polycrystalline cell to exceed 20% efficiency. An efficiency of 20.5% has been measured by the US National Renewable Energy Laboratory (NREL) for a 1-cm^2 copper indium diselenide (CIGS) cell fabricated by Solibro [5]. Although higher efficiencies have been reported for smaller area cells, solar cell efficiency targets in governmental research programs generally have been specified in terms of a cell area of 1 cm^2 or larger, for example, in US [6], Japanese [7] and European [8] programs.

The third new result in Table I documents a slight improvement in microcrystalline (also referred to as nanocrystalline) silicon cell technology. An efficiency of 11.0% has been confirmed for a 1-cm^2 cell fabricated and measured at AIST [9]. The fourth new result records an improvement in the performance of a small area 25-cm^2 organic cell submodule ('minimodule') to 9.1%. The four-cell minimodule was fabricated by Toshiba [10] and measured at AIST. Along with other emerging technology devices, the stability of this device was not investigated, although the stability of related devices is reported elsewhere [11,12]. The fourth and final new result in Table I is also for a small submodule, with an improved efficiency of 11.7% measured for a 40-cm^2 amorphous silicon/nanocrystalline silicon (a-Si/nc-Si) minimodule fabricated by TEL Solar, Trubbach Labs [13] and measured at the Fraunhofer Institute for Solar Energy Systems (FhG-ISE). The minimodule consisted of 10 multijunction cells in series and was stablised at the test centre.

A significant new result in Table II is a new performance record for a large area CdTe module. An aperture area efficiency of 17.5% is reported for a 0.7-m^2 module fabricated by the First Solar [14] and measured at

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Table III. '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[a]	Efficiency (%)	Area[b] (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[d]**	**82.8**	**Sandia (3/99)[e]**	**UNSW PERL top/rear contacts** [15]
Si (large crystalline)	**25.0 ± 0.7**	**120.94 (t)**	**0.726**	**41.5[f]**	**82.8**	**FhG-ISE (2/14)**	**SunPower rear junction** [16]
Si (large multicrystalline)	19.5 ± 0.4	242.7 (t)	0.652	39.0[g]	76.7	FhG-ISE (3/11)	Q-Cells, laser-fired contacts [46]
Cells (III–V)							
GaInP	20.8 ± 0.6	0.2491 (ap)	1.4550	16.04[h]	89.3	NREL (5/13)	NREL, high bandgap [47]
Cells (chalcogenide)							
CIGSS (Cd free)	**20.9 ± 0.7**	**0.5192 (ap)**	**0.6858**	**39.91[f]**	**76.4**	**FhG-ISE (3/14)**	**Showa Shell on glass** [17,48]
CIGSS (Cd free module)	**16.6 ± 0.8**	**660.3 (ap)**	**26.7**	**0.895[f]**	**69.5**	**NREL (1/14)**	**Avancis (monolithic)**
CdTe (thin film)	**20.4 ± 0.5**	**0.4778 (da)**	**0.8717**	**29.47[f]**	**79.5**	**Newport (12/13)**	**First Solar on glass** [18]
CZTSS (thin film)	**12.6 ± 0.3**	**0.4209 (ap)**	**0.5134**	**35.21[f]**	**69.8**	**Newport (7/13)**	**IBM solution grown** [19]
CZTS (thin film)	8.5 ± 0.2[i]	0.2382 (da)	0.708	16.83[h]	70.9	AIST (1/13)	Toyota Central R&D Labs [49]
Cells (other)							
Perovskite (thin film)	**17.9 ± 0.8[i]**	**0. 0937 (ap)**	**1.1142**	**21.8[f]**	**73.6**	**Newport (4/14)**	**KRICT[j]** [20]
Organic (thin film)	11.1 ± 0.3[g]	0.159 (ap)	0.867	17.81[k]	72.2	AIST (10/12)	Mitsubishi Chemical [33]

[a]CIGSS, CuInGaSSe; CZTSS, $Cu_2ZnSnS_{4-y}Se_y$; CZTS, Cu_2ZnSnS_4.

[b]ap, aperture area; t, total area; da, designated illumination area.

[c]AIST, Japanese National Institute of Advanced Industrial Science and Technology; NREL, National Renewable Energy Laboratory; FhG-ISE, Fraunhofer Institut für Solare Energiesysteme; ESTI, European Solar Test Installation.

[d]Spectral response reported in Version 36 of these Tables.

[e]Recalibrated from original measurement.

[f]Spectral response and/or current–voltage curves reported in present version of these Tables.

[g]Spectral response reported in Version 37 of these Tables.

[h]Spectral response and current–voltage curves reported in Version 42 of these Tables.

[i]Stability not investigated.

[j]Korean Research Institute of Chemical Technology.

[k]Spectral response and current–voltage curves reported in Version 41 of these Tables.

NREL. This is the highest confirmed efficiency reported for any thin film polycrystalline module. Notably, the total area efficiency, the figure chosen as the basis for reporting by the company, is not significantly lower at 17.0%. Another new result in Table II is a significant improvement in the performance of an amorphous silicon based module to a stabilised 11.6% total area efficiency for a a-Si/nc-Si tandem cell module fabricated by TEL Solar, Trubbach Labs [13] and measured at the European Solar Test Installation (ESTI). Light soaking was performed by the manufacturer prior to testing.

In Table III, 'notable exceptions', the first new entry is the conventionally contacted silicon cell result displaced from Table I, with 25.0% efficiency (under present standards) demonstrated in 1999 [15]. The first new result is also for a 25.0% efficient silicon cell, in this case, for a large area (121 cm^2) rear-junction cell fabricated by SunPower [16] and measured at FhG-ISE. This is the highest reported efficiency for a large area silicon-diffused junction device.

An additional new result in Table III documents a small increase to 20.9% efficiency for a small area 0.5-cm^2 CIGSS Cd-free cell fabricated by Showa Shell [17] and measured by FhG-ISE. The cell area is too small for classification of this result as an outright record for a CIGS or CIGSS cell, with this recently increased to 20.5% efficiency (Table I), as previously noted. A related new result is for a Cd-free $CuIn_xGa_{1-x}S_ySe_{2-y}$ (CIGSS) module, with 16.6% reported for a 660-cm^2 monolithic module fabricated by Avancis and measured at NREL. Although this is the highest confirmed efficiency reported for any CIGS or CIGSS module, the area is marginally too small to displace the much larger area CIGS/CIGSS module results from Table II.

The next new result in Table III is 20.4% efficiency for a small area of 0.5-cm^2 CdTe cell fabricated by the First Solar [18] and measured at Newport Technology and Applications Center. Again, cell area is too small for classification as an outright record. Another new result is 12.6% efficiency for a small area 0.4-cm^2 $Cu_2ZnSnS_xSe_{4-x}$

Table IV. 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.[a] (%)	Area[b] (cm^2)	Intensity[c] (suns)	Test Centre (date)	Description
Single cells					
GaAs	29.1 ± 1.3[d,e]	0.0505 (da)	117	FhG-ISE (3/10)	Fraunhofer ISE
Si	27.6 ± 1.2[f]	1.00 (da)	92	FhG-ISE (11/04)	Amonix back-contact [50]
CIGS (thin film)	**23.3 ± 1.2[d,g]**	**0.09902 (ap)**	**15**	**NREL (3/14)**	**NREL**[51]
Multijunction cells (monolithic)					
InGaP/GaAs/InGaAs	44.4 ± 2.6[h]	0.1652 (da)	302	FHG-ISE (4/13)	Sharp, inverted metamorphic [52]
Submodule					
GaInP/GaAs; GaInAsP/GaInAs	38.5 ± 1.9[i]	0.202 (ap)	20	NREL (8/08)	DuPont *et al.*, split spectrum [53]
Modules					
Si	20.5 ± 0.8[d]	1875 (ap)	79	Sandia (4/89)[j]	Sandia/UNSW/ENTECH (12 cells) [54]
Triple junction	35.9 ± 1.8[k]	1092 (ap)	N/A	NREL (8/13)	Amonix [55]
'Notable exceptions'					
Si (large area)	21.7 ± 0.7	20.0 (da)	11	Sandia (9/90)[j]	UNSW laser grooved [56]
Luminescent submodule	**7.1 ± 0.2**	**25(ap)**	**2.5**[l]	**ESTI**[m] **(9/08)**	**ECN Petten, GaAs cells** [57]

[a] Effic., efficiency.
[b] da, designated illumination area; ap, aperture area.
[c] One sun corresponds to direct irradiance of 1000 Wm^{-2}.
[d] Not measured at an external laboratory
[e] Spectral response reported in Version 36 of these Tables.
[f] Measured under a low aerosol optical depth spectrum similar to ASTM G-173-03 direct [58].
[g] Spectral response and current–voltage curve reported in present version of these Tables.
[h] Spectral response and current–voltage curve reported in Version 42 of these Tables.
[i] Spectral response reported in Version 37 of these Tables.
[j] Recalibrated from original measurement.
[k] 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.
[l] Geometric concentration.
[m] European Solar Test Installation.

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cell fabricated at IBM T.J. Watson Research Center [19] and also measured at Newport.

The final new result in Table III is 17.9% for a very small area (0.1 cm^2) perovskite cell fabricated by the Korea Research Institute of Chemical Technology [20] and again measured at Newport. Its performance represents a significant advance beyond the 14.1% result reported in Version 42 of these Tables and a 16.2% result measured in December 2013.

Table IV reports one new result for concentrator cells and systems. A new record of 23.3% is documented for a 0.1-cm^2 thin film CIGS cell operating at a concentration of 14.7 suns (direct irradiance of 14.7 kW/m^2). The cell was fabricated and measured at the US NREL. An earlier luminescent concentrator result has also been moved from Table III to the 'Notable Exceptions' category of Table IV, because a geometric concentration of 2.5 is involved in its operation.

The EQE spectra for the new CIGS/CIGSS and perovskite cell and module results reported in the present issue of these Tables are shown in Figure 1(a). Figure 1(b) shows the EQE for the new silicon cell and a-Si/nc-Si and organic minimodule results.

Figure 2 shows the current density–voltage (*J–V*) curves for the corresponding devices. 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, whereas measured current has been multiplied by this quantity and divided by the module area). For the concentrator cell, the current density has been normalised to 1000-W/m^2 irradiance by dividing the sunlight concentration ratio.

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.

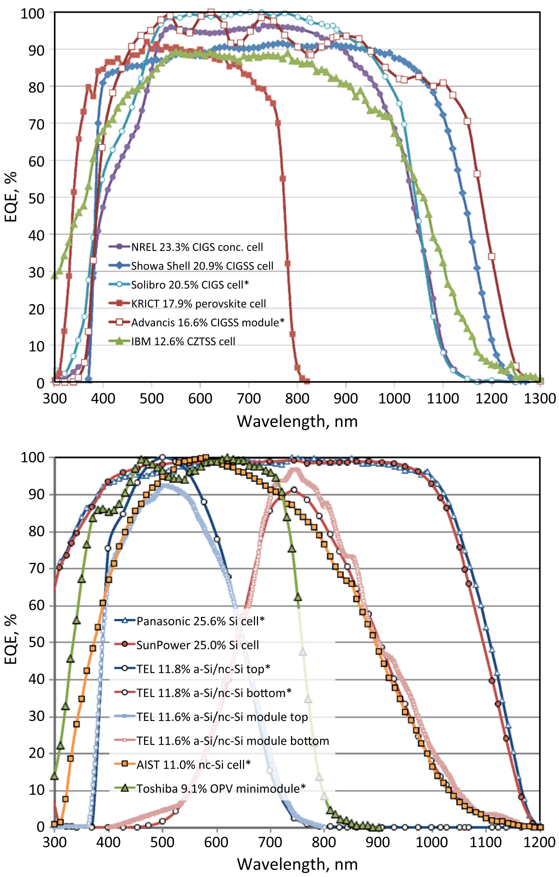

Figure 1. (a) External quantum efficiency (EQE) for the new chalcogenide (CIGS, CZTS, CdTe, etc.) and perovskite cell and module results in this issue; (b) EQE for the new silicon cell plus a-Si/nc-Si and organic module and minimodule entries (*asterisk indicates normalised value; other values are absolute values).

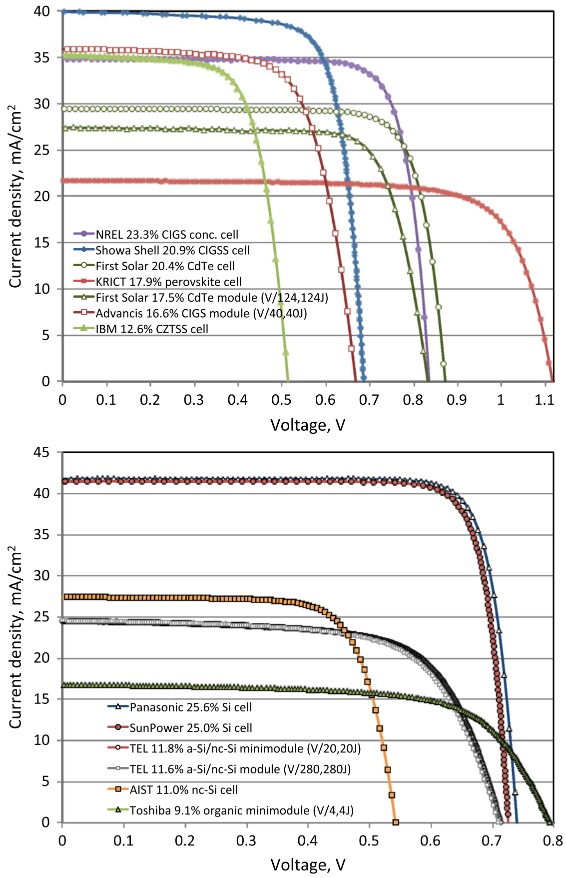

Figure 2. (a) Current density–Voltage (*J–V*) curves for the new chalcogenide (CIGS, CZTS, CdTe, etc.) and perovskite cell and module results in this issue; (b) *J–V* curves for the new silicon cell plus a-Si/nc-Si and organic module and minimodule entries (for the concentrator cell, the current density is normalised to an irradiance of 1 kW/m^2).

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