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ACCELERATED PUBLICATION

Solar cell efficiency tables (version 41)

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] National Institute of Advanced Industrial Science and Technology (AIST), Research Center for Photovoltaics (RCPV), Central 2, Umezono 1-1-1, Tsukuba, Ibaraki, 305-8568, Japan
[4] Fraunhofer-Institute for Solar Energy Systems, Department: Solar Cells - Materials and Technology, Heidenhofstr. 2, D-79110 Freiburg, Germany
[5] European Commission – Joint Research Centre, Renewable Energy Unit, Institute for Energy, 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 June 2012 are reviewed. Copyright © 2012 John Wiley & Sons, Ltd.

KEYWORDS
solar cell efficiency; photovoltaic efficiency; energy conversion efficiency

***Correspondence**
Martin A. Green, ARC Photovoltaics Centre of Excellence, 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 the 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 areas: 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

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

To encourage discrimination, Table III 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

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

Classification [a]	Effic. [b] (%)	Area [c] (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	*FF* [d] (%)	Test centre [e] (and date)	Description
Silicon							
Si (crystalline)	25.0 ± 0.5	4.00 (da)	0.706	42.7 [f]	82.8	Sandia (3/99) [g]	UNSW PERL [18]
Si (multicrystalline)	20.4 ± 0.5	1.002 (ap)	0.664	38.0	80.9	NREL (5/04) [g]	FhG-ISE [19]
Si (thin film transfer)	**20.1 ± 0.4**	**242.6 (ap)**	**0.682**	**38.14** [h]	**77.4**	**NREL (10/12)**	**Solexel (43 μm thick)** [4]
Si (thin film submodule)	10.5 ± 0.3	94.0 (ap)	0.492 [i]	29.7 [i]	72.1	FhG-ISE (8/07) [g]	CSG Solar (1–2 μm on glass; 20 cells) [20]
III–V Cells							
GaAs (thin film)	28.8 ± 0.9	0.9927 (ap)	1.122	29.68 [j]	86.5	NREL (5/12)	Alta Devices [21]
GaAs (multicrystalline)	18.4 ± 0.5	4.011 (t)	0.994	23.2	79.7	NREL (11/95) [g]	RTI, Ge substrate [22]
InP (crystalline)	22.1 ± 0.7	4.02 (t)	0.878	29.5	85.4	NREL (4/90) [g]	Spire, epitaxial [23]
Thin Film Chalcogenide							
CIGS (cell)	19.6 ± 0.6 [k]	0.996 (ap)	0.713	34.8 [l]	79.2	NREL (4/09)	NREL, on glass [24]
CIGS (submodule)	17.4 ± 0.5	15.993 (da)	0.6815 [i]	33.84 [i]	75.5	FhG-ISE (10/11)	Solibro, 4 serial cells [25]
CdTe (cell)	**18.3 ± 0.5**	**1.005 (ap)**	**0.857**	**26.95** [h]	**77.0**	**NREL (10/12)**	**GE Global Research** [5]
Amorphous/ Nanocrystalline Si							
Si (amorphous)	10.1 ± 0.3 [m]	1.036 (ap)	0.886	16.75 [f]	67.8	NREL (7/09)	Oerlikon Solar Lab, Neuchatel [26]
Si (nanocrystalline)	10.1 ± 0.2 [n]	1.199 (ap)	0.539	24.4	76.6	JQA (12/97)	Kaneka (2 μm on glass) [27]
Photochemical							
Dye sensitised	11.9 ± 0.4 [o]	1.005 (da)	0.744	22.47 [h]	71.2	AIST (9/12)	Sharp [6]
Dye sensitised (submodule)	9.9 ± 0.4 [o]	17.11 (ap)	0.719 [i]	19.4 [i]	71.4	AIST (8/10)	Sony, 8 parallel cells [28]
Organic							
Organic thin-film	10.7 ± 0.3 [o]	1.013 (da)	0.872	17.75 [h]	68.9	AIST (10/12)	Mitsubishi Chemical (4.4 mm × 23.0 mm) [10]
Organic (submodule)	**6.8 ± 0.2** [o]	**395.9 (da)**	**0.798** [i]	**13.50** [i]	**62.8**	**AIST (10/12)**	**Toshiba (15 series cells)** [13]
Multijunction Devices							
InGaP/GaAs/InGaAs	**37.7 ± 1.2**	**1.047 (ap)**	**3.014**	**14.57** [h]	**86.0**	**AIST (9/12)**	**Sharp** [14]
a-Si/nc-Si/nc-Si (thin film)	13.4 ± 0.4 [p]	1.006 (ap)	1.963	9.52 [h]	71.9	NREL (7/12)	LG Electronics [15]
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 [29]
a-Si/nc-Si (thin film submodule)	11.7 ± 0.4 [n,s]	14.23 (ap)	5.462	2.99	71.3	AIST (9/04)	Kaneka [30]

Any changes in the tables from those previously published [3] are set in bold type.

[a] CIGS, $CuInGaSe_2$; a-Si, amorphous silicon/hydrogen alloy; nc-Si, nanocrystalline or microcrystalline silicon.

[b] Effic., efficiency.

[c] (ap), aperture area; (t), total area; (da), designated illumination area.

[d] FF, fill factor.

[e] FhG-ISE, Fraunhofer Institut für Solare Energiesysteme; JQA, Japan Quality Assurance; AIST, Japanese National Institute of Advanced Industrial Science and Technology.

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

[g] Recalibrated from original measurement.

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

[i] Reported on a ‘per cell’ basis.

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

[k] Not measured at an external laboratory.

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

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

[n] Measured under IEC 60904–3 Ed. 1: 1989 reference spectrum.

[o] Stability not investigated. References 9, 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 by 174 h, 1 sun illumination after 20 h, 5 sun illumination at a sample temperature of 50 °C.

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 (and date)	Description
Si (crystalline)	22.9 ± 0.6	778 (da)	5.60	3.97	80.3	Sandia (9/96)[e]	UNSW/Gochermann [31]
Si (large crystalline)	21.4 ± 0.6	15780 (ap)	68.6	6.293	78.4	NREL (10/09)	SunPower [32]
Si (multicrystalline)	18.5 ± 0.4	14661 (ap)	38.97	9.149[f]	76.2	FhG-ISE (1/12)	Q-Cells (60 serial cells) [33]
Si (thin-film polycrystalline)	8.2 ± 0.2	661(ap)	25.0	0.320	68.0	Sandia (7/02)[e]	Pacific Solar (1–2 μm on glass) [34]
GaAs (thin film)	**24.1 ± 1.0**	**858.5 (ap)**	**10.89**	**2.255**[g]	**84.2**	**NREL (11/12)**	**Alta Devices** [35]
CIGS	15.7 ± 0.5	9703 (ap)	28.24	7.254[h]	72.5	NREL (11/10)	Miasole [36]
CIGSS (Cd free)	13.5 ± 0.7	3459 (ap)	31.2	2.18	68.9	NREL (8/02)[e]	Showa Shell [37]
CdTe	15.3 ± 0.5	6750.9 (ap)	64.97	2.183[f]	72.9	NREL (1/12)	First Solar [38]
a-Si/a-SiGe/nc-Si (tandem)	**10.5 ± 0.4**[i]	**14316** (t)	**224.3**	**0.991**	**67.9**	**AIST (9/12)**[g]	**LG Electronics** [15]

Any changes in the tables from those previously published [3] are set in bold type.

[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/or current–voltage curve reported in Version 40 of these Tables.

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

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

[i]Stabilised at the manufacturer under the light-soaking conditions of IEC61646.

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]	Effic.[b] (%)	Area[c] (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	*FF* (%)	Test centre (and date)	Description
Cells (silicon)							
Si (MCZ crystalline)	24.7 ± 0.5	4.0 (da)	0.704	42.0	83.5	Sandia (7/99)[d]	UNSW PERL, SEH MCZ substrate [39]
Si (large crystalline)	24.2 ± 0.7	155.1(t)	0.721	40.5[e]	82.9	NREL (5/10)	Sunpower *n*-type CZ substrate [40]
Si (large crystalline)	23.9 ± 0.6	102.7(t)	0.748	38.89[f]	82.2	AIST (2/12)	Panasonic HIT, *n*-type [41]
Si (large multicrystalline)	19.5 ± 0.4	242.7(t)	0.652	39.0[e]	76.7	FhG ISE (3/11)	Q-Cells, laser fired contacts [42]
Cells (other)							
CIGS (thin film)	20.3 ± 0.6	0.5015 (ap)	0.740	35.4[e]	77.5	FhG-ISE (6/10)	ZSW Stuttgart, CIGS on glass [43]
CZTSS (thin film)	11.1 ± 0.3	0.4496 (ap)	0.4598	34.54[g]	69.8	Newport (2/12)	IBM solution grown [44]
CZTS (thin film)	**8.4 ± 0.2**	**0.4463 (ap)**	**0.661**	**19.5**[h]	**65.8**	**Newport (4/11)**	**IBM, thermal evaporation** [16]
Organic (thin film)	**11.1 ± 0.3**[i]	**0.159 (ap)**	**0.867**	**17.81**[f]	**72.2**	**AIST (10/12)**	**Mitsubishi Chemical** [10]
Luminescent submodule	7.1 ± 0.2	25(ap)	1.008	8.84[e]	79.5	ESTI (9/08)	ECN Petten, GaAs cells [45]

Any changes in the tables from those previously published [3] are set in bold type.

[a] CIGS, $CuInGaSe_2$; CZTSS, $Cu_2ZnSnS_{4-y}Se_y$; CZTS, Cu_2ZnSnS_4.

[b] Effic., efficiency.

[c] (ap), aperture area; (t), total area; (da), designated illumination area.

[d] Recalibrated from original measurement.

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

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

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

[h] Spectral response and current–voltage curves reported in the present version of these Tables.

[i] Stability not investigated.

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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 (and date)	Description
Single Cells					
GaAs	29.1 ± 1.3[d]	0.0505 (da)	117	FhG-ISE (3/10)	Fraunhofer ISE
Si	27.6 ± 1.0[f]	1.00 (da)	92	FhG-ISE (11/04)	Amonix back-contact [46]
Multijunction cells (monolithic)					
GaInP/GaAs/GaInNAs	**44.0 ± 3**[g]	**0.3104 (ap)**	**942**	**NREL (10/12)**	**Solar Junction** [17]
InGaP/GaAs/InGaAs	**43.5 ± 2.6**[h]	**0.167 (da)**	**306**	**FhG-ISE (4/12)**	**Sharp, inverted metamorphic** [14]
GaInP/GaInAs/Ge	41.6 ± 2.5[e]	0.3174(da)	364	NREL (8/09)	Spectrolab, lattice-matched [47]
Submodule					
GaInP/GaAs; GaInAsP/GaInAs	38.5 ± 1.9[i]	0.202 (ap)	20	NREL (8/08)	DuPont *et al.*, split spectrum [48]
Modules					
Si	20.5 ± 0.8[d]	1875 (ap)	79	Sandia (4/89)[j]	Sandia/UNSW/ENTECH (12 cells) [49]
Triple Junction	33.5 ± 0.5[k]	10,674.8 (ap)	N/A	NREL (5/12)	Amonix [50]
'Notable Exceptions'					
Si (large area)	21.7 ± 0.7	20.0 (da)	11	Sandia (9/90)[j]	UNSW laser grooved [51]

Any changes in the tables from those previously published [3] are set in bold type.

[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 [52].

[g]Current–voltage curve reported in the present version of these Tables.

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

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

[j]Recalibrated from original measurement.

[k]Based on ASTM E2527 rating, May 2012 (850 W/m^2 direct irradiance, 20 °C ambient, 4 m/s wind speed).

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).

Thirteen new results are reported in the present version of these Tables. The first new result in Table I is a new record for a large (156 mm × 156 mm) but thin (43 micron) silicon cell transferred from a reusable template. An efficiency of 20.1% has been measured at the National Renewable Energy Laboratory (NREL) for a 243-cm^2 device fabricated by Solexel, Inc. (Milpitas, CA, USA) [4].

The second new result is for a 1-cm^2 CdTe cell with 18.3% efficiency reported for a cell fabricated by GE Global Research [5] and measured by NREL. This improves upon the 17.3% cell result from First Solar reported in the previous version of these Tables [3] (Note: The current–density J_{sc} for the 17.3% result was incorrectly reported as 28.99 mA/cm^2 [3] rather than the correct value of 27.20 mA/cm^2).

A third new result in Table I is an improvement in the performance of a 1-cm^2 dye-sensitised solar cell to 11.9%. The cell was fabricated by Sharp [6] and measured at the Japanese National Institute of Advanced Industrial Science and Technology (AIST). Although slightly higher values for smaller area dye-sensitised cells have been reported in the journal *Science* [7], these higher values appear to be based solely on 'in-house' measurements [8], with such measurements known to be notably unreliable (editors of, and reviewers for, reputable journals are encouraged to ensure that any published cell result claiming to be the best in its field has been independently certified by an appropriately qualified laboratory). Along with other emerging technology devices, the stability of this device was not investigated, although the stability of earlier devices is reviewed elsewhere [9].

A fourth new result in Table I is an improvement of a 1-cm^2 organic solar cell efficiency to a new high of 10.7%. The rectangular cell (4.4 mm × 23.0 mm) was fabricated by the Mitsubishi Chemical Group Science and Technology Research Center, Inc. [10] and measured at AIST. Again, the stability of this device was not investigated, although that of earlier devices is reviewed elsewhere [11,12].

A fifth new result in Table I is an improvement in the efficiency to 6.8% for a 396-cm^2 organic cell submodule fabricated by Toshiba [13] and measured by AIST. The stability of this device also was not investigated.

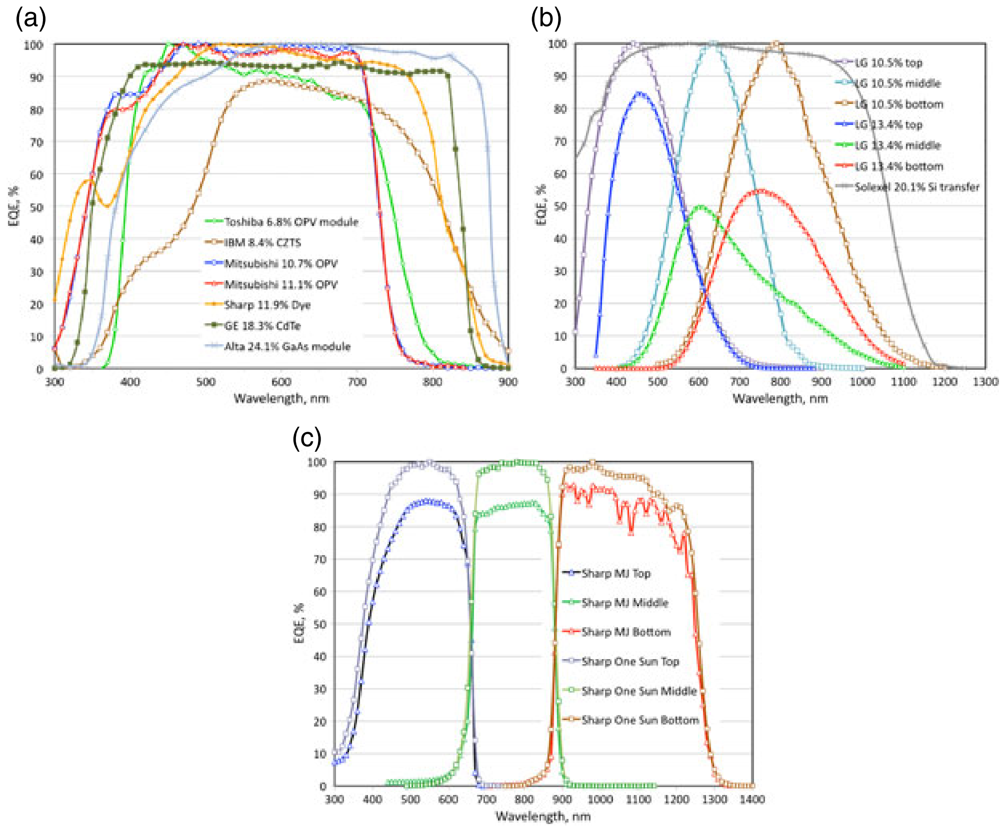

Figure 1. (a) External quantum efficiency (EQE) for the new CdTe and CZTS cell (absolute values) as well as normalised values for the GaAs module and dye-sensitised and organic cell and submodule results in this issue; (b) EQE for the new silicon cell (normalised values) and a-Si/nc-Si/nc-Si cell (absolute values) and a-Si/a-SiGe/nc-Si module (normalised values) entries in this issue; (c) EQE for two new III–V multijunction cells in this issue (normalised and absolute values).

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A sixth major new result in Table I is a new record for energy conversion efficiency for any photovoltaic converter that does not use sunlight concentration. An efficiency of 37.7% is reported for a 1-cm^2 InGaP/GaAs/InGaAs monolithic multijunction cell fabricated by Sharp [14] and again measured at AIST.

The final new result in Table I is an improvement in the stabilised efficiency of a 1-cm^2 a-Si/nc-Si/nc-Si triple junction cell to 13.4%. The cell was fabricated by the LG Electronics Advanced Research Institute [15] and measured at NREL. Related to this result, in Table II, a new efficiency record of 10.5% is reported for a large (1.4 m^2 total area) a-Si/a-SiGe/nc-Si module again fabricated by LG Electronics [15] but measured at AIST. Another new result in Table II is a new record reported for independently confirmed global solar module performance. An efficiency of 24.1% was measured for a 860-cm2 GaAs module fabricated by Alta Devices and measured by NREL.

The first new result in Table III relates to an efficiency increase to 8.4% for a small area (0.45 cm^2) pure sulphide CZTS solar cell fabricated by the IBM T.J. Watson Research Center [16] using thermal evaporation and measured at the Newport Technology and Application Center's Photovoltaic Lab.

The second new result in Table III relates to an efficiency increase to 11.1% for a small area (0.159 cm^2) organic solar cell again fabricated by Mitsubishi Chemical [10] and measured at AIST. This cell is much smaller than the 1-cm^2 size required for classification as an outright record.

Table IV reports two new results for concentrator cells. A new record of 44.0% for the conversion of sunlight by any means is reported for a 0.3 cm^2 MJ cell operating at a concentration of 942 suns (direct irradiance of 942 kW/m^2). The cell was a GaInP/GaAs/GaInNAs triple junction device fabricated by Solar Junction [17] and measured at NREL. Demonstrating that such high efficiencies are not unique to a specific fabrication approach or measurement centre, a new efficiency of 43.5% is also reported for a 0.167-cm^2 inverted metamorphic triple-junction cell (InGaP/GaAs/InGaAs) fabricated by Sharp [14] and measured at the Fraunhofer Institute for Solar Energy Systems (FhG-ISE).

The EQEs for the new CdTe and CZTS cell and GaAs module results as well as for the dye-sensitised and organic cell and submodule results of Table I are shown in Figure 1 (a). Figure 1(b) shows the EQE of the new silicon cell and a-Si/a-SiGe/nc-Si cell and module results reported in the present issue of these Tables. Figure 1(c) shows the EQE of two of the new III–V multijunction cell results.

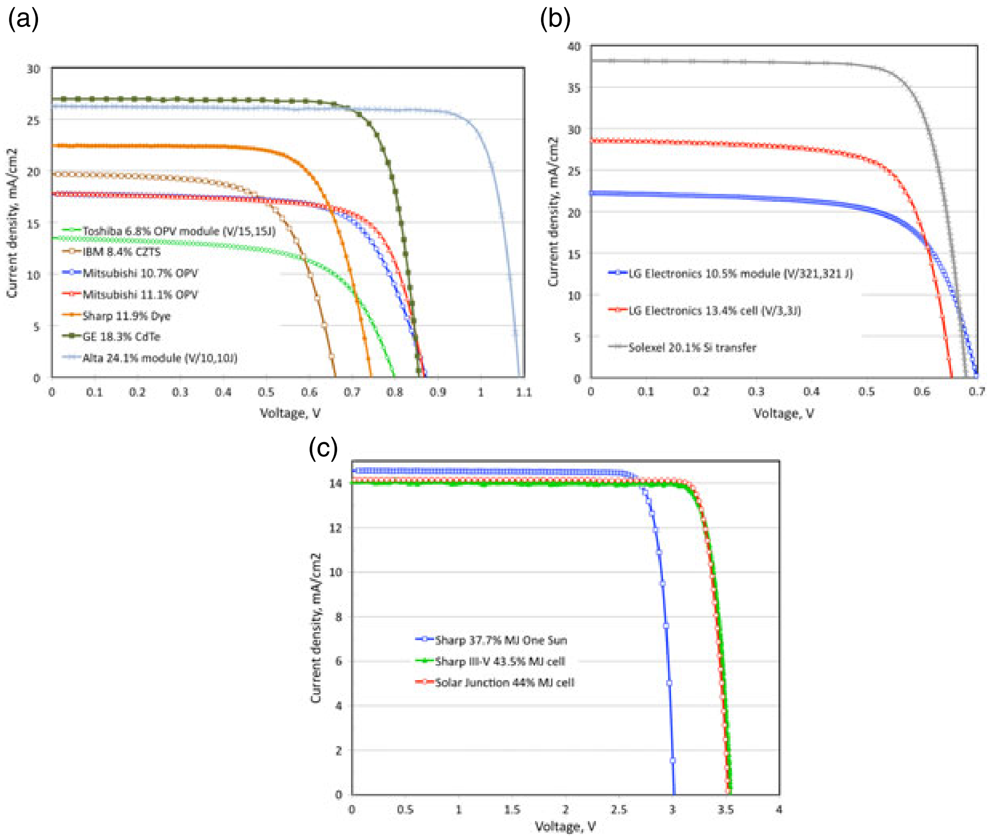

Figure 2. (a) Current density–Voltage (*J–V*) curve for the new CdTe and CZTS cell and GaAs module results, as well as for the dye-sensitised and organic cell and submodule results in this issue; (b) *J–V* curves for the new silicon and a-Si/nc-Si/nc-Si cell and a-Si/a-SiGe/nc-Si module entries in this issue; (c) *J–V* curves for the new multijunction cells in this issue (for the concentrator cells, the current density is normalised to an irradiance of 1 kW/m^2).

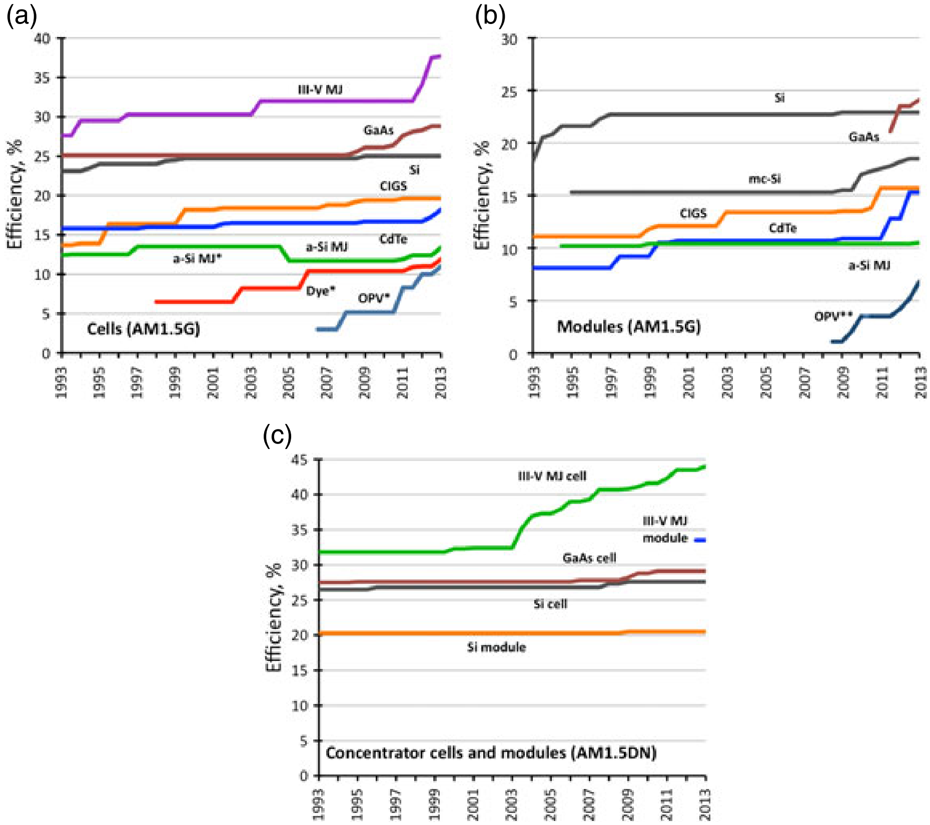

Figure 3. Twenty years of progress: (a) Highest confirmed efficiencies for ≥1-cm^2 area cells fabricated using the different technologies shown (*the results for the OPV and dye-sensitised results are unstabilised results as are those for a-Si multi-junction cells prior to 2005); (b) highest confirmed module results for modules sizes ≥800-cm^2, except for OPV where the module results are unstabilised and module sizes range from 200–400 cm^2; (c) highest confirmed concentrator cell and module results.

Figure 2 shows the current density–voltage (*J–V*) curves for the corresponding devices and for one additional device for which the EQE is not reported. For the case of modules and some tandem devices, the measured *I–V* data has been reported on a 'per cell' basis (measured voltage has been divided by the number of cells in series, whereas measured current has been multiplied by this quantity and divided by the module area).

Figure 3 reports 20 years of progress in confirmed cell and module efficiencies since the first version of these Tables was published in 1993. Figure 3(a) shows progress with 'one-sun' cells of ≥1-cm^2 area. Recent progress with OPV, GaAs and MJ III–V cells has been most notable. Figure 3(b) shows similar progress with photovoltaic modules with OPV, CdTe and the mainstream multicrystalline-Si (mc-Si) being the recent standouts. Figure 3 (c) shows the results for concentrator cells and modules. Impressive progress has been made with monolithic III–V MJ cells where efficiency has been improved from 31.8% to 44.0% over the 20-year period (efficiency in this case is boosted relative to Figure 3(a) and (b) by being based on only the direct normal component of the solar spectrum).

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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