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ACCELERATED PUBLICATION

Solar cell efficiency tables (version 43)

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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 July 2013 are reviewed. Copyright © 2013 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 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 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 (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 (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’. Although not conforming to 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] (and date)	Description
Silicon							
Si (crystalline)	25.0 ± 0.5	4.00 (da)	0.706	42.7[d]	82.8	Sandia (3/99)[e]	UNSW PERL [20]
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)	**19.8 ± 0.6**[i]	**0.9974 (ap)**	**0.716**	**34.91**[k]	**79.2**	**NREL (11/13)**	**NREL, on glass** [27]
CIGS (minimodule)	**18.7 ± 0.6**	**15.892 (da)**	**0.701**[g]	**35.29**[g]	**75.6**	**FhG-ISE (9/13)**	**Solibro, four serial cells** [4]
CdTe (cell)	19.6 ± 0.4	1.0055 (ap)	0.8573	28.59[l]	80.0	Newport (6/13)	GE Global Research [28]
Amorphous/microcrystalline Si							
Si (amorphous)	10.1 ± 0.3[m]	1.036 (ap)	0.886	16.75[d]	67.8	NREL (7/09)	Oerlikon Solar Lab, Neuchatel [29]
Si (microcrystalline)	**10.8 ± 0.3**[i]	**1.045 (da)**	**0.523**	**28.24**[k]	**73.2**	**AIST (9/13)**	**AIST** [5]
Perovskite/dye sensitised							
Dye sensitised	11.9 ± 0.4[n]	1.005 (da)	0.744	22.47[f]	71.2	AIST (9/12)	Sharp [6]
Dye sensitised (minimodule)	9.9 ± 0.4[n]	17.11 (ap)	0.719[g]	19.4[g]	71.4	AIST (8/10)	Sony, eight parallel cells [30]
Dye (submodule)	**8.8 ± 0.3**[n]	**398.9 (da)**	**0.697**[g]	**18.42**[g]	**68.7**	**AIST (9/12)**	**Sharp, 26 serial cells** [6,7]
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) [31]
Organic (minimodule)	**8.5 ± 0.3**[o]	**25.02 (da)**	**0.800**[g]	**15.81**[g]	**67.3**	**AIST (8/13)**	**Toshiba (four series cells)** [10]
Organic (submodule)	**6.8 ± 0.2**[o]	**395.9 (da)**	**0.798**[g]	**13.50**[f]	**62.8**	**AIST (10/12)**	**Toshiba (15 series cells)** [10]
Multijunction devices							
5J GaAs/InP bonded	**38.8 ± 1.9**	**1.021 (ap)**	**4.767**	**9.56**	**85.2**	**NREL(7/13)**	**Spectrolab 5 junction** [32]
InGaP/GaAs/InGaAs	37.9 ± 1.2	1.047 (ap)	3.065	14.27[l]	86.7	AIST (2/13)	Sharp [33]
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 [34]
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 [35]
a-Si/nc-Si (thin-film minimodule)	11.7 ± 0.4[s]	14.23 (ap)	5.462	2.99	71.3	AIST (9/04)	Kaneka [36]

UNSW, University of New South Wales; PERL, Passivated Emitter and Rear Locally-diffused; NREL, National Renewable Energy Laboratory.

[a] CIGS, $CuInGaSe_2$; 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 reported in version 36 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] Not measured at an external laboratory.

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

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

[l] Spectral response and/or current–voltage curve reported in version 42 of these tables.

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

[n] Stability not investigated. References [8] and [9] 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/cm^2 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.

[t] Measured under IEC 60904-3 Ed. 1: 1989 reference spectrum.

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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 [37]
Si (large crystalline)	22.4 ± 0.6	15775 (ap)	69.57	6.341[f]	80.1	NREL (8/12)	SunPower [38]
Si (multicrystalline)	18.5 ± 0.4	14661 (ap)	38.97	9.149[g]	76.2	FhG-ISE (1/12)	Q-Cells (60 serial cells) [39]
Si (thin-film polycrystalline)	8.2 ± 0.2	661(ap)	25.0	0.320	68.0	Sandia (7/02)[e]	Pacific Solar (<2 μm on glass) [40]
GaAs (thin film)	24.1 ± 1.0	858.5 (ap)	10.89	2.255[h]	84.2	NREL (11/12)	Alta Devices [41]
CdTe (thin film)	16.1 ± 0.5	7200 (t)	68.68	2.252[f]	74.8	NREL (2/13)	First Solar, monolithic [42]
CIGS (thin film)	15.7 ± 0.5	9703 (ap)	28.24	7.254[i]	72.5	NREL (11/10)	Miasole [43]
CIGSS (Cd free)	13.5 ± 0.7	3459 (ap)	31.2	2.18	68.9	NREL (8/02)[e]	Showa Shell [44]
a-Si/a-SiGe/nc-Si (triple)	**10.9 ± 0.4**[j]	**14305 (t)**	**224.3**	**1.015**[k,g]	**68.3**	**AIST (9/13)**	**LG Electronics** [13]

UNSW, University of New South Wales; NREL, National Renewable Energy Laboratory.

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

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

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

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 (large crystalline)	24.7 ± 0.5	101.8(t)	0.750	39.5[c]	83.2	AIST (12/12)	Panasonic HIT, n-type [45]
Si (large crystalline)	24.2 ± 0.7	155.1(t)	0.721	40.5[d]	82.9	NREL (5/10)	Sunpower n-type CZ substrate [46]
Si (large multicrystalline)	19.5 ± 0.4	242.7(t)	0.652	39.0[d]	76.7	FhG ISE (3/11)	Q-Cells, laser fired contacts [47]
Cells (other)							
GaInP	20.8 ± 0.6	0.2491 (ap)	1.4550	16.04[c]	89.3	NREL (5/13)	NREL, high bandgap [48]
CIGS (thin film)	**20.8 ± 0.6**	**0.5005 (ap)**	**0.7574**	**34.77**[e]	**79.2**	**FhG-ISE (10/13)**	**ZSW on glass** [14]
CIGSS (Cd free)	19.7 ± 0.5	0.496 (da)	0.683	37.06[c]	77.8	AIST (11/12)	Showa Shell/Tokyo University of Science [49]
CZTSS (thin film)	**12.0 ± 0.3**	**0.4348 (ap)**	**0.4982**	**34.80**[e]	**69.4**	**Newport (7/13)**	**IBM solution grown** [50]
CZTS (thin film)	8.5 ± 0.2[f]	0.2382 (da)	0.708	16.83[c]	70.9	AIST (1/13)	Toyota Central R&D Labs [51]
Perovskite (thin film)	14.1 ± 0.3[f]	0.2090 (ap)	1.007	21.34[c]	65.7	Newport (5/13)	EPFL [52]
Organic (thin film)	11.1 ± 0.3[f]	0.159 (ap)	0.867	17.81[g]	72.2	AIST (10/12)	Mitsubishi Chemical [31]
Luminescent submodule	7.1 ± 0.2	25 (ap)	1.008	8.84[d]	79.5	ESTI (9/08)	ECN Petten, GaAs cells [53]

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.

[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]Spectral response and current–voltage curves reported in version 42 of these tables.

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

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

[f]Stability not investigated.

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

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,e]	0.0505 (da)	117	FhG-ISE (3/10)	FhG-ISE
Si	27.6 ± 1.0[f]	1.00 (da)	92	FhG-ISE (11/04)	Amonix back-contact [54]
CIGS (thin film)	**22.8 ± 0.9**[d,g]	**0.100 (ap)**	**15**	**NREL (8/13)**	**NREL** [18]
Multijunction cells (monolithic)					
InGaP/GaAs/InGaAs	44.4 ± 2.6[h]	0.1652 (da)	302	FHG-ISE (4/13)	Sharp, inverted metamorphic [55]
Submodule					
GaInP/GaAs; GaInAsP/GaInAs	38.5 ± 1.9[i]	0.202 (ap)	20	NREL (8/08)	DuPont *et al.*, split spectrum [56]
Modules					
Si	20.5 ± 0.8[d]	1875 (ap)	79	Sandia (4/89)[j]	Sandia/UNSW/ENTECH (12 cells) [57]
Triple Junction	**35.9 ± 1.8**[k]	**1092 (ap)**	**N/A**	**NREL (8/13)**	**Amonix** [19]
Notable exceptions					
Si (large area)	21.7 ± 0.7	20.0 (da)	11	Sandia (9/90)[j]	UNSW laser grooved [58]

FhG-ISE, Fraunhofer-Institut für Solare Energiesysteme; NREL, National Renewable Energy Laboratory; N/A, not applicable.
[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 [59].
[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.

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 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 are included in Table IV).

Eleven new results are reported in the present version of these tables. The first new result in Table I documents a small improvement in the performance of a 1-cm^2 $CuIn_xGa_{1-x}Se_2$ (CIGS) cell to 19.8%. The cell was fabricated and measured at the US National Renewable Energy Laboratory (NREL). This also represents an outright record for any polycrystalline thin-film cell, slightly better than the 19.6% result reported for a CdTe cell in the previous version of these Tables. A second new result in Table I represents a significant improvement in the performance of a small CIGS submodule (minimodule) to 18.7%. The four-cell minimodule was fabricated by Solibro [4] and measured at the Fraunhofer Institute for Solar Energy Systems. The third new result in Table I records a slight improvement in efficiency to 10.8% for a 1-cm^2 microcrystalline silicon cell fabricated and measured by the Japanese National Institute of Advanced Industrial Science and Technology (AIST) [5].

The fourth new result in Table I represents a new record for energy conversion efficiency for a reasonably large-area 399-cm^2 dye-sensitised submodule fabricated by Sharp [7], with an efficiency of 8.8% 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 [8,9]. The fifth new result in Table I is for a small submodule, with an improved efficiency of 8.5% measured for a 25-cm^2 four-cell organic minimodule cell fabricated by Toshiba [10] and measured at AIST. Again, the stability of this device was not investigated, although the stability of earlier devices is also reviewed elsewhere [11,12]. An earlier 6.8% result for a much larger organic cell submodule (396 cm^2) fabricated by Toshiba, first appearing in version 41 of these tables, is also reinstated.

The final new result in Table I represents a new outright record for the conversion of the global solar spectrum by any photovoltaic device. An efficiency of 38.8% has been measured by NREL for a five junction cell fabricated by Spectrolab. The details of an earlier device demonstrating 37.8% efficiency are to be reported in an upcoming issue of the IEEE Journal of Photovoltaics. The top three higher bandgap subcells were grown inverted on a GaAs substrate while the bottom two subcells were grown upright

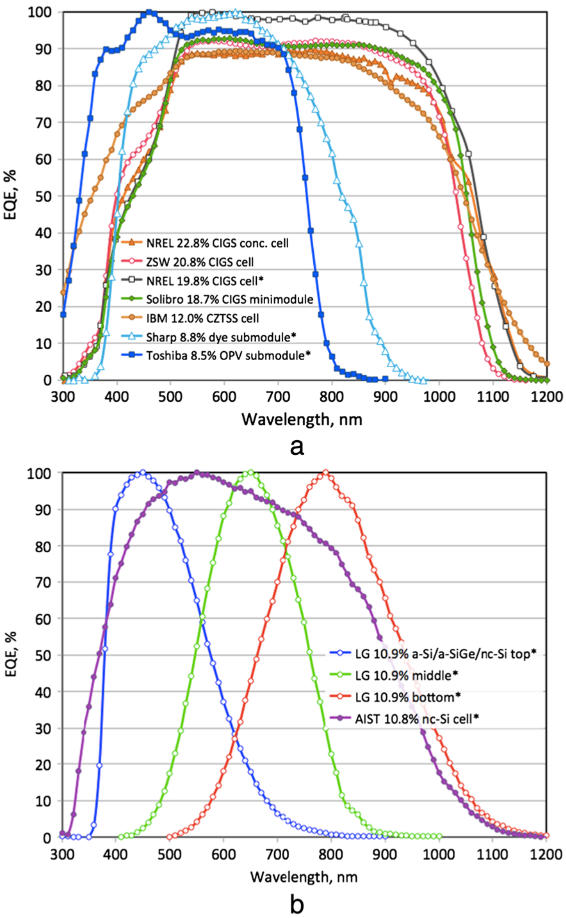

Figure 1. (a) External quantum efficiency (EQE) for the new dye and organic submodule and CIGS and CZTSS cell results in this issue. (b) EQE for the new nc-Si cell and a-Si/a-SiGe/nc-Si module entries (*normalised value; other values are absolute values).

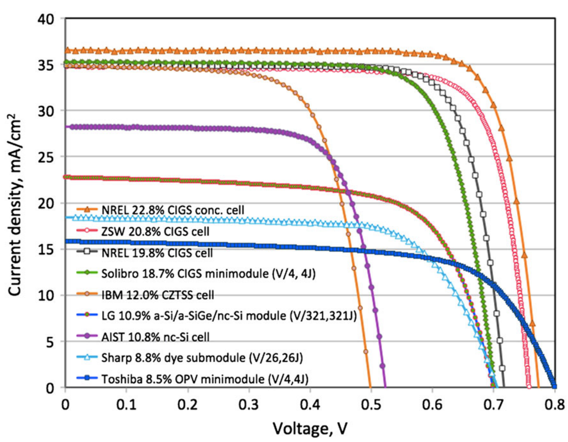

Figure 2. Current density–voltage (*J–V*) curve for nine of the new results in this issue (for the concentrator cell, the current density is normalised to an irradiance of 1 kW/m^2).

on an InP substrate. After polishing and bonding, the GaAs substrate was removed.

A new result in Table II is a new record for a large-area a-Si/a-SiGe/nc-Si module (a, amorphous; nc, nanocrystalline, also referred to as microcrystalline). A stabilised efficiency of 10.9% is reported for a 1.4-m^2 module of this type fabricated by LG Electronics [13] and measured at AIST.

An additional new result in Table III is an increase to 20.8% efficiency for a small-area 0.5-cm^2 CIGS cell fabricated by the Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg [14] and measured by the Fraunhofer Institute for Solar Energy Systems. The cell area is too small for classification of this result as an outright record for a CIGS cell, with this now at 19.8% efficiency (Table I). Research solar cell efficiency targets in US [15], Japanese [16] and European [17] programs, for example, generally have been specified in terms of a minimum cell area of greater than 1 cm^2. The 20.8% result is only slightly higher in efficiency than a 20.65% result also reported for a CIGS cell of similar size fabricated and measured at NREL.

A second new result in Table III is an improvement to 12.0% efficiency for a small area copper-zinc-tin-sulphide/selenide (CZTSS) cell fabricated by IBM and measured at the Newport Technology and Application Center, improving upon the 11.1% result reported earlier by the same group.

Table IV reports two new results for concentrator cells and systems. A new record of 22.8% is reported for a 0.1-cm^2 thin-film CIGS cell operating at a concentration of 15.4 suns (direct irradiance of 15.4 kW/m^2). The cell was fabricated and measured at NREL, improving upon an earlier 21.5% result for a similar cell from the same group [18]. The final new result in Table IV is the confirmed measurement of a concentrator photovoltaic module with energy conversion efficiency above 35%. An efficiency of 35.9% was measured by NREL for a 1092-cm^2 aperture area concentrator module fabricated by Amonix [19], under conditions approximating draft IEC standard 62670-1 'Concentrator Standard Test Conditions' (1000 W/m^2 direct irradiance, 25 °C cell temperature).

The EQE spectra for the new dye and organic submodule results as well as for the four new CIGS cell results and the CZTSS cell result reported in the present issue of these tables are shown in Figure 1(a). Figure 1(b) shows the EQE for the new nc-Si cell and a-Si/a-SiGe/nc-Si module 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 by the sunlight concentration ratio.

3. DISCLAIMER

Although 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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