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Research ***SHORT COMMUNICATION***

Solar Cell Efficiency Tables (Version 33)

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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 2008 are reviewed. Efficiencies are updated to the new reference solar spectrum tabulated in IEC 60904-3 Ed. 2 revised in April 2008 and an updated list of recognised test centres is also included. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS: solar cell efficiency; photovoltaic efficiency; energy conversion efficiency

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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[1,2]. 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 the present paper, new results since July 2008 are briefly reviewed and old results are updated to the new internationally accepted reference spectrum (IEC 60904-3, Ed. 2, 2008).

The most important criterion for inclusion of results into the tables is that they must have been measured by a recognised test centre listed in the Appendix. A distinction is made between three different eligible areas: total area, aperture area and designated illumination area[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)[1].

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).

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REFERENCE SPECTRA CHANGES

Results reported in these Efficiency Tables from January 1993 to August 2008 (Version 1–Version 32) were reported under reference spectra tabulated in American Society for Testing Materials Standard ASTM E891-87 (direct normal) and ASTM E892-87 (global) which formed the basis of various other national and international standards including IEC 60904-3 Ed. 1: 1989, ISO 9845-1: 1992, JIS C8910: 2001, etc. In April 2008, the global reference spectrum tabulated in international standard IEC 60904-3 was revised from Ed. 1 to Ed. 2 to become IEC 60904-3 Ed. 2: 2008 (referred to as IEC 60904-3: 2008)[3,4].

The new global reference spectrum is identical to the global spectrum tabulated in ASTM G-173-03 which also tabulates a direct normal spectrum. It is not unlikely that this direct normal spectrum will also become an international standard. This direct normal reference spectrum is similar to, but not identical to, the 'low aerosol optical depth' (low-AOD) direct-beam spectrum[5] introduced in Version 22 of these tables in mid-2003. Several key concentrator cell results have since been referenced to this spectrum both in the literature and in Versions 22–32 (including, importantly, recent 40%-plus efficiency results for triple-junction concentrator cells).

To reflect the acceptance of the tabulated global spectrum of ASTM G-173-03 as the international standard IEC 60904-3: 2008, the tables will convert to this new global reference spectrum for its one-sun efficiency measurements from the present issue. Furthermore, to reflect that concentrator measurements published in previous issues are referenced to spectra not likely to remain standards in the future, the tables will convert to the direct normal spectrum tabulated in ASTM G-173-03, also from the present issue.

Previously published results will be updated to the new reference spectra where this is possible.

NEW GLOBAL SPECTRUM AND IMPACT

The tabulated spectral energy content of the new IEC 60904-3, Ed. 2: 2008 global spectrum is compared to the previous Ed. 1: 1989 in Figure 1. The new spectrum has a much higher spectral density of data points with differences in energy content clearly apparent over some spectral ranges.

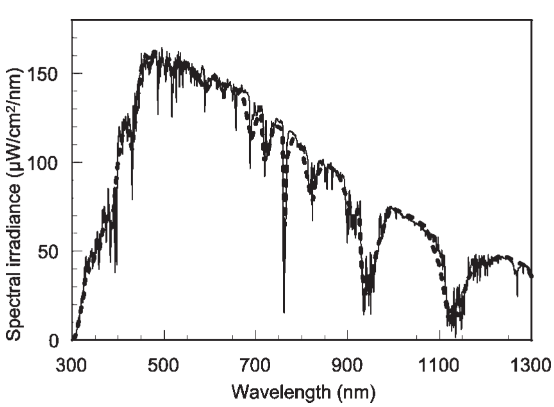

Figure 1. Comparison of spectral irradiance of IEC 60904-3 Ed. 1 (dashed line) and Ed. 2 (continuous line)

The solid line in Figure 2 shows the relative difference between the photon flux of the new spectrum integrated up to the wavelength indicated and the correspondingly integrated flux for the old spectrum. This difference equals the relative increase in current for an idealised cell that has 100% external quantum efficiency (EQE) from 280 nm (first tabulated wavelength) to the wavelength indicated, at which the idealised EQE then drops abruptly to 0.

A positive slope of this solid line corresponds to a spectral range where the new spectrum has a higher photon content; negative slope to a lower content. It can be seen that photon content is higher for the new spectrum in the 400–450 nm spectral range, slightly less in the 450–550 nm range, more over the 550–900 nm range, less from 900–1050 nm and more again from 1050–1100 nm.

Figure 2 is useful in providing a first-order estimate of the recalibrated value of the short-circuit current (Isc) of a cell originally calibrated under the old spectrum[3]. The discrete data points in Figure 2 represent the actual percentage increase in the new calibrated current for several different cell types plotted as a function of the wavelength where the cell's EQE drops to half its peak value in its long wavelength tail[3]. As can be seen, the solid line provides an excellent estimate of the size of the correction for any individual cell, except when the cell is a middle or bottom cell in a multi-cell tandem stack. A simple method for estimating the change for such cells is also given elsewhere[3].

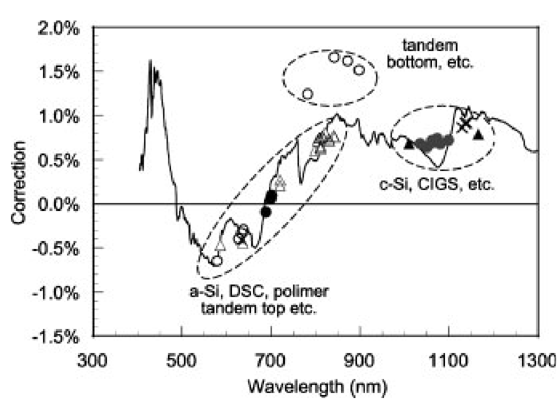

Figure 2. Relative difference between integrated photon flux to wavelength indicated for IEC 60904-3 Ed. 2 compared to Ed. 1. This difference gives first order estimates of corrections to calibrated current values for various cell technologies[3]

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As these data points indicate, the correction generally ranges from a few tenths of a per cent to about 1% for single junction or top junction cells. Conventional bulk silicon cells have their Isc boosted by about 0.6–1.0% under the new spectrum, typically by 0.8%. A similar boost applies to CdTe and CIGS (copper indium gallium diselenide or disulphide) cells. Present organic and dye-sensitised cells give almost no change in Isc while amorphous silicon cells give slightly lower Isc under the new spectrum.

NEW AND REVISED RESULTS

Highest confirmed cell and module results are reported in Tables I, II and IV. Any changes in the tables from

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]	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)	0.705	**42.7**	82.8	Sandia (3/99)[f]	UNSW PERL[12]
Si (multicrystalline)	**20.4 ± 0.5**	1.002 (ap)	0.664	**38.0**	80.9	NREL (5/04)[f]	FhG-ISE[13]
Si (thin film transfer)	**16.7 ± 0.4**	4.017 (ap)	0.645	**33.0**	78.2	FhG-ISE (7/01)[f]	U. Stuttgart (45 μm thick)[14]
Si (thin film submodule)	**10.5 ± 0.3**	94.0 (ap)	0.492[g]	**29.7**[g]	72.1	FhG-ISE (8/07)[f]	CSG Solar (1-2 μm on glass; 20 cells)[15]
III-V cells							
GaAs (crystalline)	**26.1 ± 0.8**	0.998 (ap)	1.038	**29.7**	84.7	FhG-ISE (12/07)[f]	Radboud U. Nijmegen[6]
GaAs (thin film)	**26.1 ± 0.8**	**1.001 (ap)**	**1.045**	**29.5**	**84.6**	**FhG-ISE (07/08)**[f]	**Radboud U. Nijmegen**[6]
GaAs (multicrystalline)	**18.4 ± 0.5**	4.011 (t)	0.994	**23.2**	79.7	NREL (11/95)[f]	RTI, Ge substrate[16]
InP (crystalline)	**22.1 ± 0.7**	4.02 (t)	0.878	**29.5**	85.4	NREL (4/90)[f]	Spire, epitaxial[17]
Thin film chalcogenide							
CIGS (cell)	**19.4 ± 0.6**[h]	0.994 (ap)	0.716	**33.7**	80.3	NREL (1/08)[f]	NREL, CIGS on glass[18]
CIGS (submodule)	**16.7 ± 0.4**	16.0 (ap)	0.661[g]	**33.6**[g]	75.1	FhG-ISE (3/00)[f]	U. Uppsala, 4 serial cells[19]
CdTe (cell)	**16.7 ± 0.5**[h]	1.032 (ap)	0.845	**26.1**	75.5	NREL (9/01)[f]	NREL, mesa on glass[20]
Amorphous/nanocrystalline Si							
Si (amorphous)	9.5 ± 0.3[i]	1.070 (ap)	0.859	17.5	63.0	NREL (4/03)[f]	U. Neuchatel[21]
Si (nanocrystalline)	10.1 ± 0.2[j]	1.199 (ap)	0.539	24.4	76.6	JQA (12/97)	Kaneka (2 μm on glass)[22]
Photochemical							
Dye sensitised	10.4 ± 0.3[k]	1.004 (ap)	0.729	**22.0**	65.2	AIST (8/05)[f]	Sharp[23]
Dye sensitised (submodule)	8.2 ± 0.3[k]	25.45 (ap)	**0.705**[g]	**19.1**[g]	61.1	AIST (12/07)[f]	Sharp, 9 serial cells[24]
Dye sensitised (submodule)	8.2 ± 0.3[k]	18.50	0.659[g]	**19.9**[g]	62.9	AIST (6/08)[f]	Sony, 8 serial cells[25]
Organic							
Organic polymer	5.15 ± 0.3[k]	1.021 (ap)	0.876	**9.39**	62.5	NREL (12/06)[f]	Konarka[26]
Organic (submodule)	1.1 ± 0.3[k]	232.8 (ap)	29.3	0.072	51.2	NREL (3/08)[f]	Plextronics (P3HT/PCBM)[27]
Multijunction devices							
GaInP/GaAs/Ge	32.0 ± 1.5[j]	3.989 (t)	2.622	14.37	85.0	NREL (1/03)	Spectrolab (monolithic)
GaInP/GaAs	30.3[j]	4.0 (t)	2.488	14.22	85.6	JQA (4/96)	Japan Energy (monolithic)[28]
GaAs/CIS (thin film)	25.8 ± 1.3[j]	4.00 (t)	—	—	—	NREL (11/89)	Kopin/Boeing (4 terminal)[29]
a-Si/μc-Si (thin submodule)[j,l]	11.7 ± 0.4[j,l]	14.23 (ap)	5.462	2.99	71.3	AIST (9/04)	Kaneka (thin film)[30]

[a]CIGS = CuInGaSe2; a-Si = amorphous silicon/hydrogen alloy.
[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]Recalibrated from original measurement.
[g]Reported on a 'per cell' basis.
[h]Not measured at an external laboratory.
[i]Stabilised by 800 h, 1 sun AM1.5 illumination at a cell temperature of 50°C.
[j]Measured under IEC 60904-3 Ed. 1: 1989 reference spectrum.
[k]Stability not investigated.
[l]Stabilised by 174 h, 1 sun illumination after 20 h, 5 sun illumination at a sample temperature of 50°C.

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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[31]
Si (large crystalline)	**20.3 ± 0.6**	16300 (ap)	66.1	**6.35**	78.7	Sandia (8/07)[e]	SunPower[32]
Si (multicrystalline)	**15.5 ± 0.4**[f]	1017 (ap)	14.6	**1.37**	78.6	Sandia (10/94)[e]	Sandia/HEM[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]
CIGSS	**13.5 ± 0.7**	3459 (ap)	31.2	**2.18**	68.9	NREL (8/02)[e]	Showa shell (Cd free)[35]
CdTe	**10.9 ± 0.5**	4874 (ap)	26.21	**3.24**	62.3	NREL (4/00)[e]	BP solarex[36]
a-Si/a-SiGe/a-SiGe (tandem)[g]	10.4 ± 0.5[h]	905 (ap)	4.353	3.285	66.0	NREL (10/98)[e]	USSC[37]

[a]CIGSS = CuInGaSSe; a-Si = amorphous silicon/hydrogen alloy; a-SiGe = amorphous silicon/germanium/hydrogen alloy.
[b]Effic. = efficiency.
[c](ap) = aperture area; (da) = designated illumination area.
[d]FF = fill factor.
[e]Recalibrated from original measurement.
[f]Not measured at an external laboratory.
[g]Light soaked at NREL for 1000 hours at 50°C, nominally 1-sun illumination.
[h]Measured under IEC 60904-3 Ed. 1: 1989 reference spectrum.

those previously published[2] 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, Table II shows the best results for modules and Table IV shows the best results for concentrator cells and concentrator modules. Table III contains what might be described as 'notable exceptions'. While 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 ensure 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. (A smaller number of 'notable exceptions' for concentrator cells and modules additionally is included in Table IV).

Many revised results are reported in the present versions of the Tables, due to recalibration against the new reference spectrum, together with three completely new results.

One new result in Table I is the achievement of 26.1% efficiency referenced to the new spectrum for a 1 cm^2 thin-film GaAs cell fabricated by Radboud University, Nijmegen[6] and measured by the Fraunhofer Institute for Solar Energy Systems (FhG-ISE). This cell was transferred from its native GaAs substrate. Interestingly, the result equals the best result from the same group for a bulk GaAs cell.

Of the revised results in Table I, most notable as a result of the recalibration has been the increase in confirmed silicon cell efficiency to 25%, that of GaAs to beyond 26%, that of InP to beyond 22% and the increase in CIGS cells to 19.4%, reducing the gap to the 20% milestone for a 1 cm^2 cell based on this technology (a revised value of 20% is reported in Table III for a small area 0.4 cm^2 CIGS cell as a 'notable exception' but the cell area is considered too small to be accepted as an outright class record; research cell efficiency targets in US[7], Japanese[8] and European[9] programs, for example, have been generally specified in terms of a minimum cell area of greater than 1 cm^2).

All silicon, III–V, CIGS and CdTe cells in Table I showed improved efficiency referenced to the new spectrum by values in the 0.7–1.0% range, apart from the amorphous silicon cell tabulated that showed little change. Dye-sensitised and organic cells also showed little change. The same trend prevailed in Table II for module efficiency and in Table III for 'notable exceptions'.

A completely new result in Table III is achievement of 18.7% efficiency in a large 150 cm^2 multicrystalline silicon cell with honeycomb texture fabricated by Mitsubishi Electric and measured by the Japanese National Institute of Advanced Industrial Science and

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Table III. 'Notable exceptions': 'top 10' 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[38]
Si (moderate area)	**23.9 ± 0.5**	22.1 (da)	0.704	**41.9**	81.0	Sandia (8/96)[d]	UNSW PERL, FZ substrate[31]
Si (large FZ crystalline)	**22.0 ± 0.7**	147.4 (t)	0.677	**40.3**	80.6	FhG-ISE (3/06)[d]	Sunpower FZ substrate[39]
Si (large CZ crystalline)	**22.5 ± 0.6**	100.5 (t)	0.725	**39.2**	79.1	AIST (7/07)[d]	Sanyo HIT, n-type CZ substrate[40]
Si (large multicrystalline)	**18.7 ± 0.6**	**217.4 (t)**	**0.639**	**37.7**	**77.6**	**AIST (2/08)[d]**	**Mitsubishi Electric, honeycomb[10]**
Cells (other)							
GaInP/GaInAs/GaInAs (tandem)	33.8 ± 1.5[e,h]	0.25 (ap)	2.960	13.1	86.8	NREL (1/07)	NREL, monolithic[41]
CIGS (thin film)	**20.0 ± 0.6[e]**	0.419 (ap)	0.692	**35.7**	81.0	NREL (10/07)[d]	NREL, CIGS on glass[42]
a-Si/a-Si/a-SiGe (tandem)	12.1 ± 0.7[h]	0.27 (da)	2.297	7.56	69.7	NREL (10/96)	USSC stabilised (monolithic)[43]
Dye-sensitised	11.2 ± 0.3[f]	0.219 (ap)	0.737	**21.0**	72.2	AIST (3/06)[d]	Sharp[44]
Organic	5.4 ± 0.3[f]	0.096 (ap)	0.856	**9.67**	65.3	NREL (7/07)[d]	Plextronics[27]

[a]CIGS = $CuInGaSe_2$.
[b]Effic. = efficiency.
[c](ap) = aperture area; (t) = total area; (da) = designated illumination area.
[d]Recalibrated from original measurement.
[e]Not measured at an external laboratory.
[f]Stability not investigated.
[h]Measured under IEC 60904-3 Ed. 1: 1989 reference spectrum.

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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	**28.2 ± 1.0**	0.203 (da)	**213**	Sandia (8/88)[d]	Varian, Entech cover[45]
Si	27.6 ± 1.0	1.00 (da)	92	FhG-ISE (11/04)	Amonix back-contact[46]
CIGS (thin film)	**21.8 ± 1.5**[f]	0.102 (da)	14	NREL (2/01)[d]	NREL
Multijunction cells					
GaInP/GaAs/Ge (2-terminal)	40.7 ± 2.4[e]	0.267 (da)	240	NREL (9/06)	Spectrolab, Lattice-mismatched[47]
GaInP/GaAs/GaInAs (2-terminal)	**40.8 ± 2.4**[e,f]	**0.0976 (da)**	**140**	**NREL (7/08)**	**NREL, inverted monolithic**[11]
Submodules					
GaInP/GaAs/Ge	27.0 ± 1.5[g]	34 (ap)	10	NREL (5/00)	ENTECH[48]
Modules					
Si	**20.5 ± 0.8**[f]	1875 (ap)	**79**	Sandia (4/89)[d]	Sandia/UNSW/ENTECH (12 cells)[49]
Notable exceptions					
GaAs/GaSb (4-terminal)	32.6 ± 1.7[g]	0.053 (da)	100	Sandia (10/89)[d]	Boeing, mechanical stack[50]
InP/GaInAs (3-terminal)	**31.7 ± 1.6**[f]	0.063 (da)	50	NREL (8/90)[d]	NREL, monolithic[51]
GaInP/GaInAs (2-terminal)	30.2 ± 1.2[g]	0.1330 (da)	300	NREL/FhG-ISE (6/01)	Fraunhofer, monolithic[52]
GaAs (high concentration)	**26.6 ± 1.0**	0.203 (da)	1000	Sandia (8/88)[d]	Varian[53]
Si (large area)	**21.7 ± 0.7**	20.0 (da)	11	Sandia (9/90)[d]	UNSW laser grooved[54]

[a]Effic. = efficiency.
[b](da) = designated illumination area; (ap) = aperture area.
[c]One sun corresponds to direct irradiance of 1000 Wm^{-2}.
[d]Recalibrated from original measurement.
[e]Measured under a low aerosol optical depth spectrum similar to ASTM G-173-03 direct[5].
[f]Not measured at an external laboratory.
[g]Measured under old ASTM E891-87 reference spectrum.

Technology (AIST) (this result was reported as 18.6% efficiency under the old spectrum[10]).

As previously mentioned, all concentrator cell and module results are now referenced against the direct normal spectrum tabulated in ASTM G173-03 (except where otherwise noted). This generally has the effect of improving results previously reported referenced to ASTM G891-87. For the subset of results previously reported referenced to an interim 'low aerosol optical depth' (low-AOD) spectrum[5], performance differences due to recalibration have been smaller.

A significant new result in Table IV has been a new record for cell performance under concentrated sunlight. An efficiency of 40.8% is reported[11] for an inverted, monolithic GaInP/GaAs/GaInAs cell fabricated by and measured at the National Renewable Energy Laboratory (NREL) under the low-AOD spectrum (multijunction cells present additional challenges in converting between spectra).

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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APPENDIX

List of Recognised Test Centres

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