

Research

SHORT COMMUNICATION

Solar Cell Efficiency Tables (Version 31)

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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. Copyright © 2007 John Wiley & Sons, Ltd.

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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.^{1–3} 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 the present article, new results since July, 2007 are briefly reviewed.

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 an earlier issue.² 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 cm² for a concentrator cell, 1 cm² for a one-sun cell and 800 cm² 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).

NEW RESULTS

Highest confirmed cell and module results are reported in Tables I, II and IV. Any changes in the tables from those previously published³ 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

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Table I. Confirmed terrestrial cell and submodule efficiencies measured under the global AM1.5 spectrum (1000 W/m²) at 25°C

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)	24.7 ± 0.5	4.00 (da)	0.706	42.2	82.8	Sandia (3/99)	UNSW PERL ¹³
Si (multicrystalline)	20.3 ± 0.5	1.002 (ap)	0.664	37.7	80.9	NREL (5/04)	FhG-ISE ¹⁴
Si (thin film transfer)	16.6 ± 0.4	4.017 (ap)	0.645	32.8	78.2	FhG-ISE (7/01)	U. Stuttgart (45 µm thick) ¹⁵
Si (thin film submodule)	10.4 ± 0.3	94.0 (ap)	0.492^f	29.5^f	72.1	FhG-ISE (8/07)	CSG Solar (1–2 µm on glass; 20 cells)⁵
III–V Cells							
GaAs (crystalline)	25.1 ± 0.8	3.91 (t)	1.022	28.2	87.1	NREL (3/90)	Kopin, AlGaAs window ¹⁶
GaAs (thin film)	24.5 ± 0.5	1.002 (t)	1.029	28.8	82.5	FhG-ISE (5/05)	Radboud U., NL ¹⁷
GaAs (multicrystalline)	18.2 ± 0.5	4.011 (t)	0.994	23.0	79.7	NREL (11/95)	RTI, Ge substrate ¹⁸
InP (crystalline)	21.9 ± 0.7	4.02 (t)	0.878	29.3	85.4	NREL (4/90)	Spire, epitaxial ¹⁹
Thin Film Chalcogenide							
CIGS (cell)	18.8 ± 0.6	1.00 (ap)	0.703	34.0	78.7	FhG-ISE (8/06)	NREL, CIGS on glass ²⁰
CIGS (submodule)	16.6 ± 0.4	16.0 (ap)	0.661 ^f	33.4 ^f	75.1	FhG-ISE (3/00)	U. Uppsala, 4 serial cells ²¹
CdTe (cell)	16.5 ± 0.5 ^g	1.032 (ap)	0.845	25.9	75.5	NREL (9/01)	NREL, mesa on glass ²²
Amorphous/Nanocrystalline Si							
Si (amorphous) ^h	9.5 ± 0.3	1.070 (ap)	0.859	17.5	63.0	NREL (4/03)	U. Neuchatel ²³
Si (nanocrystalline)	10.1 ± 0.2	1.199 (ap)	0.539	24.4	76.6	JQA (12/97)	Kaneka (2 µm on glass) ²⁴
Photochemical							
Dye sensitised	10.4 ± 0.3	1.004 (ap)	0.729	21.8	65.2	AIST (8/05)	Sharp ²⁵
Dye sensitised (submodule)	7.9 ± 0.3	26.48 (ap)	6.27	2.01	62.4	AIST (6/07)	Sharp⁶
Organic							
Organic polymerⁱ	5.15 ± 0.3	1.021 (ap)	0.876	9.40	62.5	NREL(12/06)	Konarka⁷
Multijunction Devices							
GaInP/GaAs/Ge	32.0 ± 1.5	3.989 (t)	2.622	14.37	85.0	NREL (1/03)	Spectrolab (monolithic)
GaInP/GaAs	30.3	4.0 (t)	2.488	14.22	85.6	JQA (4/96)	Japan energy (monolithic) ²⁶
GaAs/CIS (thin film)	25.8 ± 1.3	4.00 (t)	—	—	—	NREL (11/89)	Kopin/Boeing (4 terminal) ²⁷
a-Si/µc-Si (thin submodule) ^j	11.7 ± 0.4	14.23(ap)	5.462	2.99	71.3	AIST (9/04)	Kaneka (thin film) ²⁸

^aCIGS = CuInGaSe₂; a-Si = amorphous silicon/hydrogen alloy.

^bEffic. = Efficiency.

^c(ap) = Aperture area; (t) = Total area; (da) = Designated illumination area.

^dFF = Fill factor.

^eFhG-ISE = Fraunhofer Institut für Solare Energiesysteme; JQA = Japan Quality Assurance; AIST = Japanese National Institute of Advanced Industrial Science and Technology.

^fReported on a 'per cell' basis.

^gNot measured at an external laboratory.

^hStabilised by 800 h, 1 sun AM1.5 illumination at a cell temperature of 50°C.

ⁱStability not investigated.

^jStabilised by 174 h, 1 sun illumination after 20 h, 5 sun illumination at a sample temperature of 50°C.

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, as are results under a relatively new low aerosol optical depth direct-beam spectrum).⁴

Eight new results are reported in the present versions of the Tables, something of a record in its own right.

The first new result appears in Table I where landmark efficiency has been reported for a thin-film crystalline silicon submodule, with 10.4% confirmed on an aperture area basis for a 94 cm² submodule fabricated by CSG Solar⁵ and measured by the Fraunhofer Institute for Solar Energy Systems (FhG-ISE).

The second new result also appears in Table I where an efficiency of 7.9% is reported on an aperture area basis for a 26 cm² dye sensitised submodule⁶

Table II. Confirmed terrestrial module efficiencies measured under the global AM1.5 spectrum (1000 W/m²) at a cell temperature of 25°C

Classification ^a	Effic. ^b (%)	Area ^c (cm ²)	V _{oc} (V)	I _{sc} (A)	FF ^d (%)	Test centre (and date)	Description
Si (crystalline)	22.7 ± 0.6	778 (da)	5.60	3.93	80.3	Sandia (9/96)	UNSW/Gochermann ²⁹
Si (large crystalline)	20.1 ± 0.6	16300 (ap)	66.1	6.30	78.7	Sandia (8/07)	SunPower⁸
Si (multicrystalline)	15.3 ± 0.4 ^e	1017 (ap)	14.6	1.36	78.6	Sandia (10/94)	Sandia/HEM ³⁰
Si (thin-film polycrystalline)	8.2 ± 0.2	661 (ap)	25.0	0.318	68.0	Sandia (7/02)	Pacific Solar (1–2 μm on glass) ³¹
CIGSS	13.4 ± 0.7	3459 (ap)	31.2	2.16	68.9	NREL (8/02)	Showa Shell (Cd free) ³²
CdTe	10.7 ± 0.5	4874 (ap)	26.21	3.205	62.3	NREL (4/00)	BP Solarex ³³
a-Si/a-SiGe/a-SiGe (tandem) ^f	10.4 ± 0.5	905 (ap)	4.353	3.285	66.0	NREL (10/98)	USSC (a-Si/a-Si/a-Si:Ge) ³⁴

^aCIGSS = CuInGaSSe; a-Si = amorphous silicon/hydrogen alloy; a-SiGe = amorphous silicon/germanium/hydrogen alloy.

^bEffic. = Efficiency.

^c(ap) = Aperture area; (da) = Designated illumination area.

^dFF = Fill factor.

^eNot measured at an external laboratory.

^fLight soaked at NREL for 1000 h at 50°C, nominally 1-sun illumination.

fabricated by Sharp and measured by the Japanese National Institute of Advanced Industrial Science and Technology (AIST).

The third new result again appears in Table I where 5.15% efficiency is reported for a 1 cm² organic cell⁷ fabricated by Konarka Technologies and measured by the National Renewable Energy Laboratory (NREL). This is a significant improvement in performance for an organic cell of this size.

The fourth new result is reported in Table II where a landmark 20.1% aperture area efficiency is reported for a large area (1.63 m²) silicon module fabricated by SunPower⁸ and measured at Sandia National Laboratories.

The fifth new result is reported in Table III, 'notable exceptions'. An efficiency of 22.3% is reported for a large area (100 cm²) silicon cell fabricated on n-type Czochralski-grown (CZ) silicon by Sanyo⁹ and

Table III. 'Notable Exceptions': 'Top ten' confirmed cell and module results, not class records (Global AM1.5 spectrum, 1000 W/m², 25°C)

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)	24.5 ± 0.5	4.0 (da)	0.704	41.6	83.5	Sandia (7/99)	UNSW PERL, SEH MCZ substrate ³⁵
Si (moderate area)	23.7 ± 0.5	22.1 (da)	0.704	41.5	81.0	Sandia (8/96)	UNSW PERL, FZ substrate ²⁹
Si (large FZ crystalline)	21.8 ± 0.7	147.4 (t)	0.677	40.0	80.6	FhG-ISE (3/06)	Sunpower FZ substrate ³⁶
Si (large CZ crystalline)	22.3 ± 0.6	100.5 (t)	0.725	39.1	79.1	AIST (7/07)	Sanyo HIT, n-type CZ substrate⁹
Si (large multicrystalline)	18.1 ± 0.5	137.7 (t)	0.636	36.9	77.0	FhG-ISE (8/05)	U. Konstanz, laser grooved ³⁷
Cells (other)							
GaInP/GaInAs/GaInAs (tandem)	33.8 ± 1.5 ^e	0.25 (ap)	2.960	13.1	86.8	NREL (1/07)	NREL, monolithic ³⁸
CIGS (thin film)	19.9 ± 0.6^e	0.419 (ap)	0.692	35.5	81.0	NREL (10/07)	NREL, CIGS on glass¹⁰
a-Si/a-Si/a-SiGe (tandem)	12.1 ± 0.7	0.27 (da)	2.297	7.56	69.7	NREL (10/96)	USSC stabilised (monolithic) ³⁹
Photoelectrochemical	11.1 ± 0.3	0.219 (ap)	0.736	20.9	72.2	AIST (3/06)	Sharp, dye sensitised ²³
Organic	5.4 ± 0.3^d	0.096 (ap)	0.856	9.70	65.3	NREL (7/07)	Plextronics¹¹

^aCIGS = CuInGaSe₂.

^bEffic. = Efficiency.

^c(ap) = Aperture area; (t) = Total area; (da) = Designated illumination area.

^dStability not investigated.

^eNot measured at an external laboratory.

Table IV. Terrestrial concentrator cell and module efficiencies measured under the 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	27.8 ± 1.0	0.203 (da)	216	Sandia ^d (8/88)	Varian, Entech cover ⁴⁰
Si	27.3 ± 1.0	1.00 (da)	93	FhG-ISE (9/07)	Amonix back-contact¹⁰
CIGS (thin film)	21.5 ± 1.5 ^c	0.102 (da)	14	NREL (2/01)	NREL
Multijunction cells					
GaInP/GaAs/Ge (2-terminal)	34.7 ± 1.7	0.267 (da)	333	NREL (9/03)	Spectrolab, monolithic
Submodules					
GaInP/GaAs/Ge	27.0 ± 1.5	34 (ap)	10	NREL (5/00)	ENTECH ⁴¹
Modules					
Si	20.3 ± 0.8 ^c	1875 (ap)	80	Sandia (4/89)	Sandia/UNSW/ENTECH (12 cells) ⁴²
Low-AOD spectrum					
GaInP/GaInAs/Ge (2-terminal)	40.7 ± 2.4 ^f	0.267 (da)	240	NREL (9/06)	Spectrolab, lattice-mismatched ⁴³
Si	27.6 ± 1.0 ^f	1.00 (da)	92	FhG-ISE (11/04)	Amonix back-contact ⁴⁴
'Notable Exceptions'					
GaAs/GaSb (4-terminal)	32.6 ± 1.7	0.053 (da)	100	Sandia ^d (10/89)	Boeing, mechanical stack ⁴⁵
InP/GaInAs (3-terminal)	31.8 ± 1.6 ^c	0.063 (da)	50	NREL (8/90)	NREL, monolithic ⁴⁶
GaInP/GaInAs (2-terminal)	30.2 ± 1.2	0.1330 (da)	300	NREL/FhG-ISE (6/01)	Fraunhofer, monolithic ⁴⁷
GaAs (high concentration)	26.2 ± 1.0	0.203 (da)	1000	Sandia ^d (8/88)	Varian ⁴⁸
Si (large area)	21.6 ± 0.7	20.0 (da)	11	Sandia ^d (9/90)	UNSW laser grooved ⁴⁹

^aEffic. = Efficiency.

^b(da) = Designated illumination area; (ap) = Aperture area.

^cOne sun corresponds to direct irradiance of 1000 W/m².

^dMeasurements corrected from originally measured values due to Sandia recalibration in January, 1991.

^eNot measured at an external laboratory.

^fLow aerosol optical depth direct beam AM1.5 spectrum.

measured by AIST. Particularly striking is the very high open-circuit voltage of 725 mV measured for this silicon cell.

The sixth new result is also reported in Table III. An efficiency of 19.9% is reported for a small area (0.4 cm²) copper indium gallium diselenide (CIGS) polycrystalline thin-film solar cell fabricated by and measured at NREL.¹⁰ The device area is too small for consideration as an outright record.

The seventh new result is also reported in Table III. An efficiency of 5.4% has been measured for a small area (0.1 cm²) organic cell fabricated by Plextronics¹¹ and measured at NREL. The device area is too small for consideration of this result as an outright record.

The eighth new result is reported in Table IV where one of the longer-standing efficiency milestones has been displaced. An efficiency of 27.3% has been measured at 93 suns concentration (more precisely, 93 kW/m² direct irradiance) for a silicon concentrator cell fabricated by Amonix.¹²

Figure 1 reports 15 years of progress in confirmed efficiency since the first version of these Tables was published in 1993. Notable recent improvements have

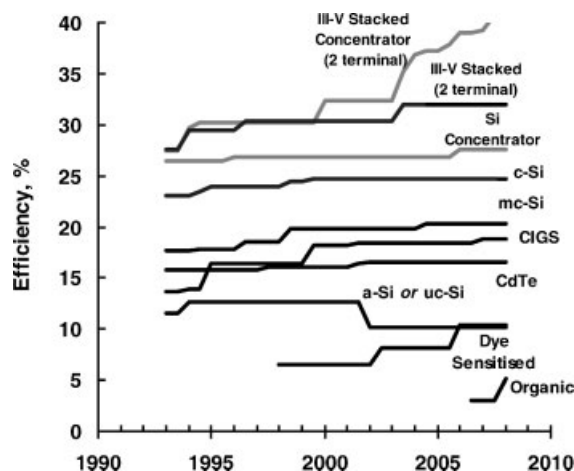


Figure 1. 15 years of progress: Confirmed cell efficiencies for a range of technologies since the first version of these Tables was issued in 1993 (the apparent decrease in performance in the 'a-Si or uc-Si' category arises from a change to reporting stabilised values)

been in the stacked triple-junction III–V tandem concentration cell field where 40.7% efficiency was confirmed last year (concentrator results are shown as the lighter coloured lines since not directly comparable to non-concentrator cell results). Good recent progress has also been shown with the ‘newer’ dye sensitised and organic cells.

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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