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Solar cell efficiency tables (version 51)

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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 2017 are reviewed, together with progress over the last 25 years. Appendices are included documenting area definitions and also listing recognised test centres.

KEYWORDS

energy conversion efficiency, photovoltaic efficiency, solar cell efficiency

1 | INTRODUCTION

Since January 1993, *Progress in Photovoltaics* has published 6 monthly listings of the highest confirmed efficiencies for a range of photovoltaic cell and module technologies.[1,2] 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 (International Electrotechnical Commission IEC 60904-3, Ed. 2, 2008).

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 in Appendix A (note 2 recent additions). A distinction is made between 3 different eligible definitions of cell area: total area, aperture area, and designated illumination area, as defined in Appendix B. "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 1-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 (eg, 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 (IV) curves have also been included where possible from version 38 onwards. The present version also includes a graphical summary of progress over the past 25 years during which the tables have been published.

Highest confirmed "1-sun" cell and module results are reported in Tables 1–4. Any changes in the tables from those previously published[1] 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 1 summarises the best-reported measurements for 1-sun (nonconcentrator) single-junction cells and submodules. Table 2 was first introduced in version 49 of these tables and summarises the growing number of cell and submodule results involving high efficiency, 1-sun multiple-junction devices (previously reported in Table 1). Table 3 shows the best results for 1-sun modules. Table 4 contains what might be described as "notable exceptions." While not conforming to the requirements to be recognised as a class record, the 1-sun cells and modules in this table have notable characteristics that will be of interest to sections

TABLE 1 Confirmed single-junction 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	Efficiency, %	Area, cm^2	V_{oc}, V	J_{sc}, mA/cm^2	Fill Factor, %	Test Centre (date)	Description
Silicon							
Si (crystalline cell)	26.7 ± 0.5	79.0 (da)	0.738	42.65[a]	84.9	AIST (3/17)	Kaneka, n-type rear IBC[3]
Si (multicrystalline cell)	**22.3 ± 0.4**[b]	**3.923 (ap)**	**0.6742**	**41.08**[c]	**80.5**	**FhG-ISE (8/17)**	**FhG-ISE, n-type**[4]
Si (thin transfer submodule)	21.2 ± 0.4	239.7 (ap)	0.687[d]	38.50[d,e]	80.3	NREL (4/14)	Solexel (35 μm thick)[5]
Si (thin film minimodule)	10.5 ± 0.3	94.0 (ap)	0.492[d]	29.7[d,f]	72.1	FhG-ISE (8/07)	CSG solar (<2 μm on glass)[6]
III-V cells							
GaAs (thin film cell)	28.8 ± 0.9	0.9927 (ap)	1.122	29.68[g]	86.5	NREL (5/12)	Alta Devices[7]
GaAs (multicrystalline)	18.4 ± 0.5	4.011 (t)	0.994	23.2	79.7	NREL (11/95)	RTI, Ge substrate[8]
InP (crystalline cell)	24.2 ± 0.5[b]	1.008 (ap)	0.939	31.15[a]	82.6	NREL (3/13)	NREL[9]
Thin film chalcogenide							
CIGS (cell)	21.7 ± 0.5	1.044 (da)	0.718	40.70[a]	74.3	AIST (1/17)	Solar Frontier[10]
CdTe (cell)	21.0 ± 0.4	1.0623 (ap)	0.8759	30.25[e]	79.4	Newport (8/14)	First Solar, on glass[11]
CZTS (cell)	10.0 ± 0.2	1.113 (da)	0.7083	21.77[a]	65.1	NREL (3/17)	UNSW[12]
Amorphous/microcrystalline							
Si (amorphous cell)	10.2 ± 0.3[h,b]	1.001 (da)	0.896	16.36[e]	69.8	AIST (7/14)	AIST[13]
Si (microcrystalline cell)	11.9 ± 0.3[b]	1.044 (da)	0.550	**28.72**[a]	75.0	AIST (2/17)	AIST[14]
Perovskite							
Perovskite (cell)	**20.9 ± 0.7**[i,j]	**0.991 (da)**	**1.125**	**24.92**[c]	**74.5**	**Newport (7/17)**	**KRICT**[15]
Perovskite (minimodule)	16.0 ± 0.4[i]	16.29 (ap)	0.978[d]	**21.44**[d,a]	76.1	Newport (4/17)	Microquanta, 6 serial cells[16]
Dye sensitised							
Dye (cell)	11.9 ± 0.4[k]	1.005 (da)	0.744	22.47[l]	71.2	AIST (9/12)	Sharp[17]
Dye (minimodule)	10.7 ± 0.4[k]	26.55 (da)	0.754[d]	20.19[d,m]	69.9	AIST (2/15)	Sharp, 7 serial cells[17]
Dye (submodule)	8.8 ± 0.3[k]	398.8 (da)	0.697[d]	18.42[d,n]	68.7	AIST (9/12)	Sharp, 26 serial cells[18]
Organic							
Organic (cell)	11.2 ± 0.3[o]	0.992 (da)	0.780	19.30[e]	74.2	AIST (10/15)	Toshiba[19]
Organic (minimodule)	9.7 ± 0.3[o]	26.14 (da)	0.806[d]	16.47[d,m]	73.2	AIST (2/15)	Toshiba (8 series cells)[20]

Abbreviations: (ap), aperture area; (da), designated illumination area; (t), total area; a-Si, amorphous silicon/hydrogen alloy; AIST, Japanese National Institute of Advanced Industrial Science and Technology; CIGS, $CuIn_{1-y}Ga_ySe_2$; CZTS, Cu_2ZnSnS_4; CZTSS, $Cu_2ZnSnS_{4-y}Se_y$; FhG-ISE, Fraunhofer Institut für Solare Energiesysteme; nc-Si, nanocrystalline or microcrystalline silicon.

[a]Spectral response and current-voltage curve reported in version 50 of these tables.

[b]Not measured at an external laboratory.

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

[d]Reported on a "per cell" basis.

[e]Spectral responses and current-voltage curve reported in version 45 of these tables.

[f]Recalibrated from original measurement.

[g]Spectral response and current-voltage curve reported in version 40 of these tables.

[h]Stabilised by 1000 h exposure to 1-sun light at 50°C.

[i]Initial performance (not stabilised). Reference 21 reviews the stability of similar devices.

[j]Certified parameters are average of forward and reverse sweeps performed at 150 mV/s. Efficiency hysteresis of ±0.26% of the certified value was observed at this sweep rate.

[k]Not stabilised, initial efficiency. Reference 22 reviews the stability of similar devices.

[l]Spectral response and current-voltage curve reported in version 41 of these tables.

[m]Spectral response and current-voltage curve reported in version 46 of these tables.

[n]Spectral response and current-voltage curve reported in version 43 of these tables.

[o]Initial performance (not stabilised).

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

To encourage discrimination, Table 4 is limited to nominally 12 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 5 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 5).

TABLE 2 Confirmed multiple-junction 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	Efficiency, %	Area, cm^2	V_{oc}, V	J_{sc}, mA/cm^2	Fill Factor, %	Test Centre (date)	Description
III-V multijunctions							
5 junction cell (bonded)	38.8 ± 1.2	1.021 (ap)	4.767	9.564	85.2	NREL (7/13)	Spectrolab, 2-terminal[23]
(2.17/1.68/1.40/1.06/0.73 eV)							
InGaP/GaAs/InGaAs	37.9 ± 1.2	1.047 (ap)	3.065	14.27[a]	86.7	AIST (2/13)	Sharp, 2-term[24]
GaInP/GaAs (monolithic)	**32.8 ± 1.4**	**1.000 (ap)**	**2.568**	**14.56[b]**	**87.7**	**NREL (9/17)**	**LG Electronics, 2-term**
Multijunctions with c-Si							
GaInP/GaAs/Si (mech. Stack)	35.9 ± 0.5[c]	1.002 (da)	2.52/0.681	13.6/11.0	87.5/78.5	NREL (2/17)	NREL/CSEM/EPFL, 4-term[25]
GaInP/GaAs/Si (wafer bonded)	**33.3 ± 1.2[c]**	**3.984 (ap)**	**3.127**	**12.7[b]**	**83.8**	**FhG-ISE (8/17)**	**Fraunhofer ISE, 2-term[26]**
GaInP/GaAs/Si (monolithic)	19.7 ± 0.7[c]	3.943 (ap)	2.323	10.0[e]	84.3	FhG-ISE (8/16)	Fraunhofer ISE
GaInP/Si (mech. stack)	32.8 ± 0.5[c]	1.003 (da)	1.09/0.683	28.9/11.1[d]	85.0/79.2	NREL (12/16)	NREL/CSEM/EPFL, 4-term[25]
Perovskite/Si (monolithic)	23.6 ± 0.6[f]	0.990 (ap)	1.651	18.09[e]	79.0	NREL (8/16)	Stanford/ASU[27]
GaInP/GaInAs/Ge; Si (spectral split minimodule)	34.5 ± 2.0	27.83 (ap)	2.66/0.65	13.1/9.3	85.6/79.0	NREL (4/16)	UNSW/Azur/Trina, 4-term[28]
a-Si/nc-Si multijunctions							
a-Si/nc-Si/nc-Si (thin-film)	14.0 ± 0.4%[g,c]	1.045 (da)	1.922	9.94[e]	73.4	AIST (5/16)	AIST[29]
a-Si/nc-Si (thin-film cell)	12.7 ± 0.4%[g,c]	1.000(da)	1.342	13.45[h]	70.2	AIST (10/14)	AIST[13,14]

Abbreviations: (ap), aperture area; a-Si, amorphous silicon/hydrogen alloy; (da), designated illumination area; (t), total area; AIST, Japanese National Institute of Advanced Industrial Science and Technology; FhG-ISE, Fraunhofer Institut für Solare Energiesysteme; nc-Si, nanocrystalline or microcrystalline silicon.

[a]Spectral response and current-voltage curve reported in version 42 of these tables.

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

[c]Not measured at an external laboratory.

[d]Spectral response and current-voltage curve reported in version 50 of these tables.

[e]Spectral response and current-voltage curve reported in version 49 of these tables.

[f]Not stabilised, initial efficiency. Reference 21 reviews the stability of similar devices.

[g]Stabilised by 1000 h exposure to 1-sun light at 50°C.

[h]Spectral responses and current-voltage curve reported in version 45 of these tables.

TABLE 3 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	Effic. (%)	Area (cm^2)	V_{oc} (V)	I_{sc} (A)	FF (%)	Test Centre (date)	Description
Si (crystalline)	24.4 ± 0.5	13177 (da)	79.5	5.04[a]	80.1	AIST (9/16)	Kaneka (108 cells)[3]
Si (multicrystalline)	19.9 ± 0.4	15143 (ap)	78.87	4.795[a]	79.5	FhG-ISE (10/16)	Trina solar (120 cells)[30]
GaAs (thin film)	**25.1 ± 0.8**	**866.45 (ap)**	**11.08**	**2.303[b]**	**85.3**	**FhG-ISE (11/17)**	**Alta Devices[31]**
CIGS (Cd free)	19.2 ± 0.5	841 (da)	48.0	0.456[c]	73.7	AIST (1/17)	Solar frontier (70 cells)[32]
CdTe (thin-film)	18.6 ± 0.5	7038.8 (ap)	110.6	1.533[d]	74.2	NREL (4/15)	First solar, monolithic[33]
CIGS (large)	15.7 ± 0.5	9703 (ap)	28.24	7.254[e]	72.5	NREL (11/10)	Miasole[34]
a-Si/nc-Si (tandem)	12.3 ± 0.3[f]	14322 (t)	280.1	0.902[g]	69.9	ESTI (9/14)	TEL solar, Trubbach Labs[35]
Organic	8.7 ± 0.3[h]	802 (da)	17.47	0.569[i]	70.4	AIST (5/14)	Toshiba[20]
Multijunction							
InGaP/GaAs/InGaAs	31.2 ± 1.2	968 (da)	23.95	1.506	83.6	AIST (2/16)	Sharp (32 cells)[36]

CIGSS = CuInGaSSe; a-Si = amorphous silicon/hydrogen alloy; a-SiGe = amorphous silicon/germanium/hydrogen alloy; nc-Si = nanocrystalline or microcrystalline silicon; Effic. = efficiency; (t) = total area; (ap) = aperture area; (da) = designated illumination area; FF = fill factor

[a]Spectral response and current voltage curve reported in version 49 of these tables.

[b]pectral response and current-voltage curve reported in the present version of these tables.

[c]Spectral response and current-voltage curve reported in version 50 of these tables.

[d]Spectral response and/or current-voltage curve reported in version 47 of these tables.

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

[f]Stabilised at the manufacturer to the 2% level following IEC procedure of repeated measurements.

[g]Spectral response and/or current-voltage curve reported in version 46 of these tables.

[h]Initial performance (not stabilised).

[i]Spectral response and current-voltage curve reported in version 45 of these tables.

TABLE 4 "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	Efficiency, %	Area, 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[a]	82.8	Sandia (3/99)[b]	UNSW p-type PERC top/rear contacts[37]
Si (crystalline)	**25.8 ± 0.5**[c]	**4.008 (da)**	**0.7241**	**42.87**[d]	**83.1**	**FhG-ISE (7/17)**	**FhG-ISE, n-type top/rear contacts**[38]
Si (large)	26.6 ± 0.5	179.74 (da)	0.7403	42.5[e]	84.7	FhG-ISE (11/16)	Kaneka, n-type rear IBC[3]
Si (multicrystalline)	**22.0 ± 0.4**	**245.83 (t)**	**0.6717**	**40.55**[d]	**80.9**	**FhG-ISE (9/17)**	**Jinko solar, large p-type**[39]
GaInP	21.4 ± 0.3	0.2504 (ap)	1.4932	16.31[f]	87.7	NREL (9/16)	LG electronics, high bandgap[40]
GaInAsP/GaInAs	**32.6 ± 1.4**[c]	**0.248 (ap)**	**2.024**	**19.51**[d]	**82.5**	**NREL (10/17)**	**NREL, monolithic tandem**
Cells (chalcogenide)							
CIGS (thin-film)	22.6 ± 0.5	0.4092 (da)	0.7411	37.76[f]	80.6	FhG-ISE (2/16)	ZSW on glass[41]
CIGSS (cd free)	22.0 ± 0.5	0.512 (da)	0.7170	39.45[f]	77.9	FhG-ISE (2/16)	Solar frontier on glass[10]
CdTe (thin-film)	22.1 ± 0.5	0.4798 (da)	0.8872	31.69[g]	78.5	Newport (11/15)	First solar on glass[42]
CZTSS (thin-film)	12.6 ± 0.3	0.4209 (ap)	0.5134	35.21[h]	69.8	Newport (7/13)	IBM solution grown[43]
CZTS (thin-film)	11.0 ± 0.2	0.2339(da)	0.7306	21.74[e]	69.3	NREL (3/17)	UNSW on glass[12]
Cells (other)							
Perovskite (thin-film)	**22.7 ± 0.8**[i]	**0.0935 (ap)**	**1.144**	**24.92**[d]	**79.6**	**Newport (7/17)**	**KRICT**[15]
Organic (thin-film)	12.1 ± 0.3[k]	0.0407 (ap)	0.8150	20.27[e]	73.5	Newport (2/17)	Phillips 66

Abbreviations: (ap), aperture area; (da), designated illumination area; (t), total area; AIST, Japanese National Institute of Advanced Industrial Science and Technology; CIGSS = CuInGaSSe; CZTS = Cu_2ZnSnS_4; CZTSS = $Cu_2ZnSnS_{4-y}Se_y$; FhG-ISE, Fraunhofer-Institut für Solare Energiesysteme; NREL, National Renewable Energy Laboratory.

[a]Spectral response reported in version 36 of these tables.

[b]Recalibrated from original measurement.

[c]Not measured at an external laboratory.

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

[e]Spectral response and current-voltage curves reported in version 50 of these tables.

[f]Spectral response and current-voltage curves reported in version 49 of these tables.

[g]Spectral response and/or current-voltage curves reported in version 46 of these tables.

[h]Spectral response and current-voltage curves reported in version 44 of these tables.

[i]Stability not investigated. Reference 21 documents stability of similar devices. Certified parameters are average of forward and reverse sweeps performed at 150 mV/s. Efficiency hysteresis of ±0.51% of the certified value was observed at this sweep rate.

[j]Spectral response and current-voltage curves reported in version 48 of these tables.

[k]Stability not investigated.

2 | NEW RESULTS

Ten new results are reported in the present version of these tables. The first new result in Table 1 is a new efficiency record for a multicrystalline silicon (mc-Si) cell. An efficiency of 22.3% is reported for a 4-cm^2 cell using an n-type mc-Si wafer as substrate, fabricated by Fraunhofer Institute for Solar Energy Systems (FhG-ISE), and measured at the same institution.[4]

A second new result in Table 1 documents achievement of the landmark efficiency of 20% for a 1-cm^2 lead halide perovskite solar cell. An efficiency of 20.9% was measured for a 1.0-cm^2 perovskite cell fabricated by the Korean Research Institute of Chemical Technology[15] and measured at the Newport PV Laboratory. These perovskite results represent initial efficiencies, with the long-term stability of these devices not investigated.

Two new results are reported in Table 2 for 1-sun, multijunction devices. An efficiency of 32.8% was measured for a 1-cm^2 GaInP/GaAs monolithic 2-junction, 2-terminal device fabricated by LG Electronics and measured at the US National Renewable Energy Laboratory (NREL). Efficiency for a 2-terminal, triple-junction GaInP/GaInAs cell wafer-bonded to a Si cell was increased to 33.3% for a cell fabricated and measured at FhG-ISE.

One new module result is reported in Table 3. An efficiency of 25.1% is reported for a 866-cm2 GaAs module fabricated by Alta Devices and measured at FhG-ISE.

Four new cell results are reported as notable exceptions in Table 4. An efficiency of 25.8% has been confirmed for a 4-cm^2 n-type crystalline silicon cell with contacts on both top and rear surfaces, fabricated and measured at FhG-ISE,[38] a record for a cell with this traditional type of contacting. An efficiency of 22.0% has

TABLE 5 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., %	Area, cm^2	Intensity[a], suns	Test Centre (date)	Description
Single cells					
GaAs	29.3 ± 0.7[b]	0.09359 (da)	49.9	NREL (10/16)	LG Electronics
Si	27.6 ± 1.2[c]	1.00 (da)	92	FhG-ISE (11/04)	Amonix back-contact[44]
CIGS (thin film)	23.3 ± 1.2[d,e]	0.09902 (ap)	15	NREL (3/14)	NREL[45]
Multijunction cells					
GaInP/GaAs; GaInAsP/GaInAs	46.0 ± 2.2[f]	0.0520 (da)	508	AIST (10/14)	Soitec/CEA/FhG-ISE 4j bonded[46]
GaInP/GaAs/GaInAs/GaInAs	45.7 ± 2.3[d,g]	0.09709 (da)	234	NREL (9/14)	NREL, 4j monolithic[47]
InGaP/GaAs/InGaAs	44.4 ± 2.6[h]	0.1652 (da)	302	FhG-ISE (4/13)	Sharp, 3j inverted metamorphic[48]
GaInAsP/GaInAs	**35.5 ± 1.2[i,d]**	**0.10031 (da)**	**38**	**NREL (10/17)**	**NREL 2-junction (2j)**
Minimodule					
GaInP/GaAs; GaInAsP/GaInAs	43.4 ± 2.4[d,j]	18.2 (ap)	340[k]	FhG-ISE (7/15)	Fraunhofer ISE 4j (lens/cell)[49]
Submodule					
GaInP/GaInAs/Ge; Si	40.6 ± 2.0[j]	287 (ap)	365	NREL (4/16)	UNSW 4j split spectrum[50]
Modules					
Si	20.5 ± 0.8[d]	1875 (ap)	79	Sandia (4/89)[l]	Sandia/UNSW/ENTECH (12 cells)[51]
Three junction (3j)	35.9 ± 1.8[m]	1092 (ap)	N/A	NREL (8/13)	Amonix[52]
Four junction (4j)	38.9 ± 2.5[n]	812.3 (ap)	333	FhG-ISE (4/15)	Soitec[53]
"Notable exceptions"					
Si (large area)	21.7 ± 0.7	20.0 (da)	11	Sandia (9/90)[k]	UNSW laser grooved[54]
Luminescent minimodule	7.1 ± 0.2	25(ap)	2.5[k]	ESTI (9/08)	ECN Petten, GaAs cells[55]

Abbreviations: (ap), aperture area; (da), designated illumination area; CIGS, $CuInGaSe_2$; Effic., efficiency; FhG-ISE, Fraunhofer-Institut für Solare Energiesysteme; NREL, National Renewable Energy Laboratory.

[a]One sun corresponds to direct irradiance of 1000 Wm^{-2}.

[b]Spectral response and current-voltage curve reported in version 50 of these tables.

[c]Measured under a low aerosol optical depth spectrum similar to ASTM G-173-03 direct.[56]

[d]Not measured at an external laboratory.

[e]Spectral response and current-voltage curve reported in version 44 of these tables.

[f]Spectral response and current-voltage curve reported in version 45 of these tables.

[g]Spectral response and current-voltage curve reported in version 46 of these tables.

[h]Spectral response and current-voltage curve reported in version 42 of these tables.

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

[j]Determined at IEC 62670-1 CSTC reference conditions.

[k]Geometric concentration.

[l]Recalibrated from original measurement.

[m]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.

[n]Measured under IEC 62670-1 reference conditions following the current IEC power rating draft 62670-3.

also been confirmed for a large area 246-cm^2 p-type multicrystalline cell fabricated by Jinko Solar using Passivated Emitter and Rear Cell technology,[39] with the cell also measured at FhG-ISE.

A third new result in Table 4 is 32.6% efficiency for a small area (0.25 cm^2) GaInAsP/GaInAs monolithic, 2-junction, 2-terminal, 1-sun cell fabricated by and measured at NREL.[57] An efficiency of 22.7% has also been measured for a small area (0.09 cm^2) lead halide perovskite cell fabricated by Korean Research Institute of Chemical Technology and measured at Newport.[15] For the previous 2 cells, cell area is too small for classification as an outright record. Solar cell efficiency targets in governmental research programs generally have been specified in terms of a cell area of 1 cm^2 or larger.[58-60] Additionally, the certificate for the perovskite cell advises that the results "apply at the time of the test and do not imply future performance."

The final new result in Table 5 is improvement in the efficiency of a small area, 2-junction, 2-terminal tandem GaInAsP/GaInAs concentrator cell to 35.5% under 38-suns concentration (direct irradiance of 38 kW/m^2). The cell was fabricated by and measured at NREL.

The EQE spectra for the new silicon cell results reported in the present issue of these tables are shown in Figure 1A, with Figure 1B showing the current density-voltage (JV) curves for the

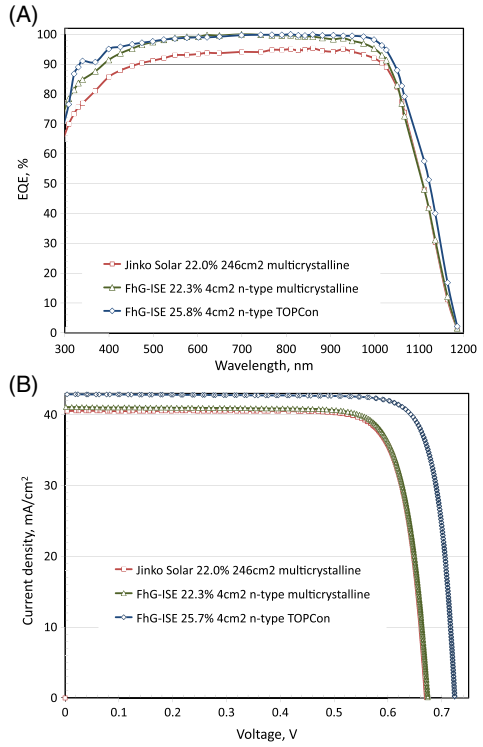

FIGURE 1 A, Normalised external quantum efficiency (EQE) for the new silicon cell results reported in this issue (some results normalised). B, Corresponding current density-voltage curves for the same devices. FhG-ISE, Fraunhofer Institute for Solar Energy Systems [Colour figure can be viewed at wileyonlinelibrary.com]

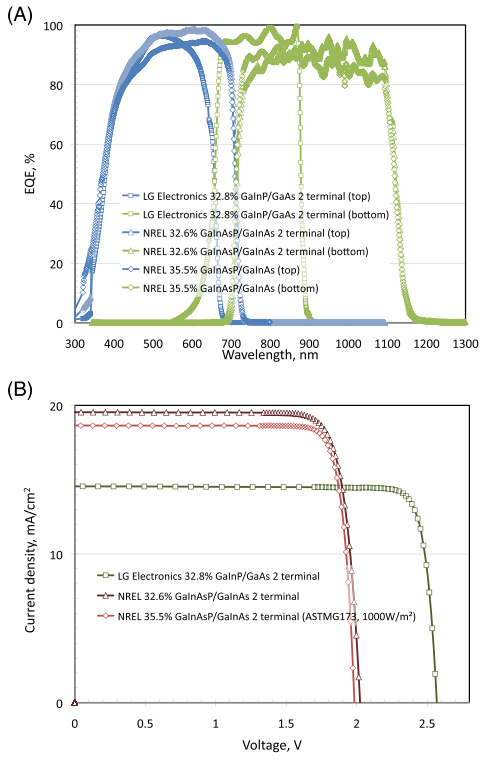

FIGURE 2 A, External quantum efficiency (EQE) for the new 2-junction multijunction cell results reported in this issue (some results normalised). B, Corresponding current density-voltage curves. NREL, National Renewable Energy Laboratory [Colour figure can be viewed at wileyonlinelibrary.com]

same devices. Figure 2A shows the EQE for the new 2-junction multijunction cell results with Figure 2B showing their current JV curves. Figure 3A,B shows the corresponding EQE and JV curves for the new perovskite and GaAs cell results.

3 | PROGRESS OVER THE LAST 25 YEARS

Figure 4 reports 25 years of progress in confirmed cell and module efficiencies since the first version of these tables was published in 1993. Figure 4A shows progress with 1-sun cells of ≥1-cm^2 area. Recent progress with perovskite and CdTe cells has been most notable, with good progress also with CIGS and both crystalline and mc-Si. Figure 4B shows similar progress with photovoltaic modules with CdTe, CIGS, and the mainstream mc-Si being the recent standouts. Figure 4C 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 46.0% over the 25-year period (efficiency in this case is boosted relative to results in Figure 4A,B since based on only the direct normal component of the solar spectrum, with the diffuse component neglected in the efficiency calculation).

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.

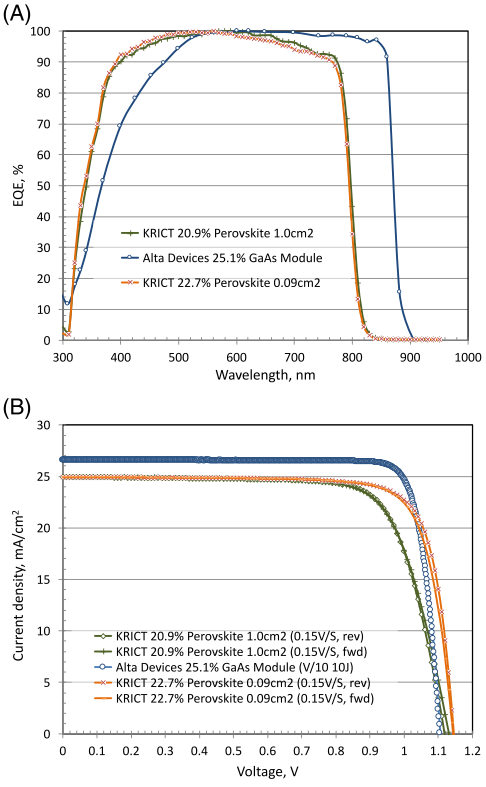

FIGURE 3 A, External quantum efficiency (EQE) for the new perovskite and GaAs cell results reported in this issue (all results normalised). B, Corresponding current density-voltage curves. KRICT, Korean Research Institute of Chemical Technology [Colour figure can be viewed at wileyonlinelibrary.com]

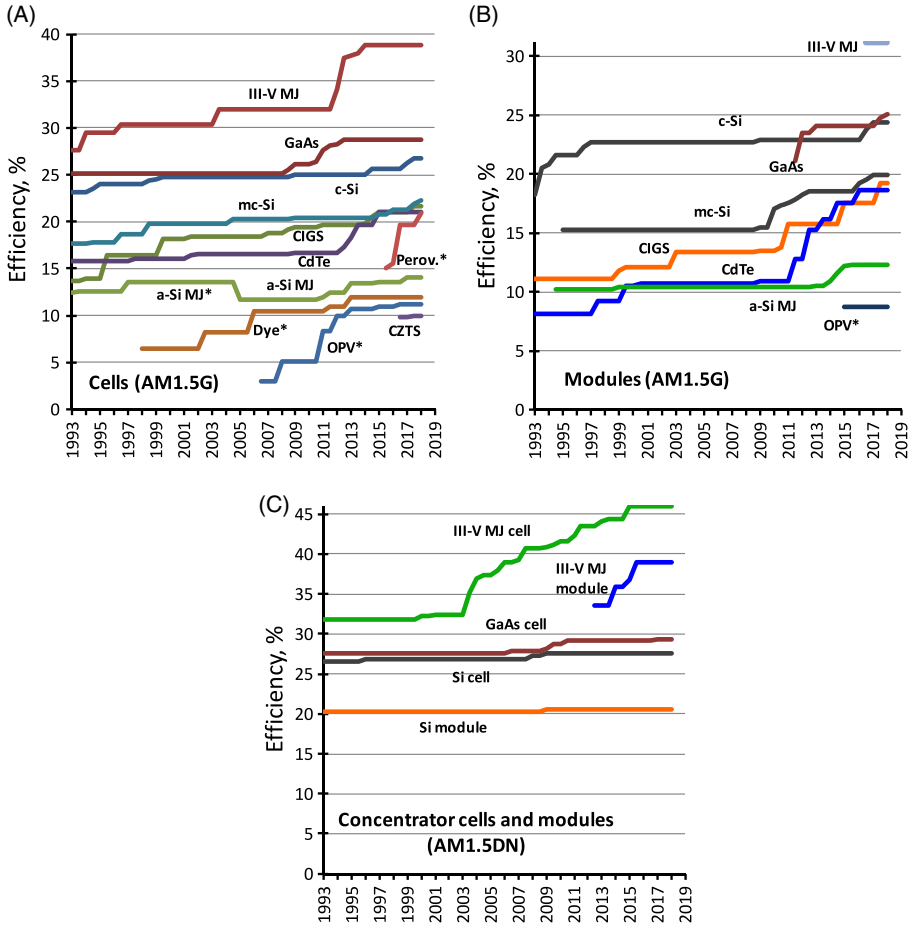

FIGURE 4 Twenty-five years of progress: A, highest confirmed efficiencies for ≥1-cm^2 area cells fabricated using the different technologies shown (*the results for the OPV, dye-sensitised and perovskite cells are unstabilised results as are those for a-Si multijunction cells prior to 2005). B, highest confirmed module results for modules sizes ≥800-cm^2. C, highest confirmed concentrator cell and module results [Colour figure can be viewed at wileyonlinelibrary.com]

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APPENDIX A
LIST OF DESIGNATED TEST CENTRES

A list of designated test centres follows. Results from additional ISO/IEC17025 certified centres participating in international round robins involving cells of a similar type to those being reported will also be considered on a case-by-case basis.

European Solar Test Installation (ESTI),
CEC Joint Research Centre,
Via E. Fermi 2749, 21020 Ispra (Varese), Italy.
Contact: Dr Ewan Dunlop
Telephone: +39 332–789090
Facsimile: +39 332-789-268
Email: esti.services@jrc.ec.europa.eu
(cells and modules)

Fraunhofer-Institut für Solare Energiesysteme ISE,
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Contact (CalLab PV Cells): Dr Jochen Hohl-Ebinger
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Email: jochen.hohl-ebinger@ise.fraunhofer.de
Contact (CalLab PV Modules): Frank Neuberger,
Phone: +49 (0) 761 4588-5280
Facsimile: +49 (0) 761 4588-9280
Email: frank.neuberger@ise.fraunhofer.de
(terrestrial, space, and concentrator cells and modules)

Institut für Solarenergieforschung GmbH (ISFH),
Calibration and Test Center (CalTeC), Solar Cells Laboratory
Am Ohrberg 1, D-31860 Emmerthal, Germany.
Contact: Dr Karsten Bothe
Phone: +49 (0) 5151 999 425
Facsimile: +49 (0) 5151 999 400
Mobile: +49 (0) 176 151 999 02
Email: k.bothe@isfh.de
(terrestrial cells)

Japan Electrical Safety & Environment Technology Laboratories (JET),
1-12-28 Motomiya Tsurumi-ku, Yokohama-shi, Kanagawa, 230-004 Japan.
Contact: Hiromi Tobita
Phone: +81-45-570-2073
Email: tobita@jet.or.jp
(terrestrial cells and modules)

National Institute of Advanced Industrial Science and Technology (AIST),
Central 2, Umezono 1-1-1, Tsukuba, Ibaraki, 305-8568 Japan.
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(terrestrial and concentrator cells and modules)

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(terrestrial, space, and concentrator cells and modules)

Newport PV Lab,
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(terrestrial cells)

APPENDIX B
AREA DEFINITIONS

The area of the cell or module is a key parameter in determining efficiency. The areas used in the tables conform to 1 of the 3 following classifications illustrated in Figure 5:

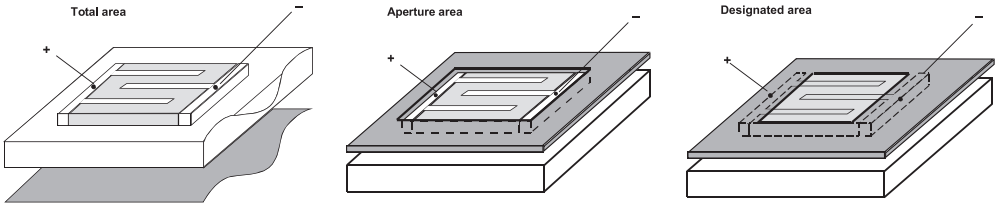

FIGURE 5 Area classifications: total area (shown grey), aperture area, and designated illumination area (the latter 2 areas are the areas not covered by the mask; masking is not required if the test centre is satisfied that there is no response from the areas shown masked)

1. Total area: The total projected area of the cell or module. This is the preferred area for reporting of results. For the case of a cell attached to glass, the total area would be the area of the glass sheet. For a module, it would include the area of frames.
2. Aperture area: The portion of the total cell or module area that includes all essential components, including active material, busbars, fingers, and interconnects. In principle, during testing, illumination is restricted to this portion such as by masking. Such restriction is not essential if the test centre is satisfied that there is no response from light incident outside the assigned aperture area.
3. Designated illumination area: A portion of the cell or module area from which some cell or module contacting components are excluded. In principle, during testing, illumination is restricted to this portion such as by masking. Such restriction is not essential if the test centre is satisfied that there is no response from light incident outside the assigned designated illumination area. For concentrator cells, cell busbars would lie outside of the area designed for illumination and this area classification would be the most appropriate. For a cell on insulating substrates, cell contacts may lie outside the designated illumination area. For modules, cell string interconnects may lie outside the masked area.