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SHORT COMMUNICATION

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Solar cell efficiency tables (Version 63)

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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 2023 are reviewed.

KEYWORDS

energy conversion efficiency, photovoltaic efficiency, solar cell efficiency

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 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, 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 elsewhere.[1,2] A distinction is made between three different eligible definitions of cell area: total area, aperture area and designated illumination area, as also defined elsewhere[2] (note that, if masking is used, masks must have a simple aperture geometry, such as square, rectangular or circular — masks with multiple openings are not eligible). '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, 200 cm^2 for a "submodule" and 800 cm^2 for a module).

In recent years, approaches for contacting large-area solar cells during measurement have become increasingly complex. Since there is no explicit standard for the design of solar cell contacting units, in an earlier issue,[3] we describe approaches for temporary electrical contacting of large-area solar cells both with and without busbars. To enable comparability between different contacting approaches and to clarify the corresponding measurement conditions, an unambiguous denotation was introduced and used in subsequent versions of these tables.

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 or 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)	26.8 ± 0.4[a]	274.4 (t)	0.7514	41.45[b]	86.1	ISFH (10/22)	LONGi, n-type HJT[4]
Si (DS wafer cell)	24.4 ± 0.3[a]	267.5 (t)	0.7132	41.47[c]	82.5	ISFH (8/20)	Jinko Solar, n-type
Si (thin transfer submodule)	21.2 ± 0.4	239.7 (ap)	0.687[e]	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[e]	29.7[d,f]	72.1	FhG-ISE (8/07)	CSG Solar (<2 µm on glass)[6]
III-V cells							
GaAs (thin film cell)	29.1 ± 0.6	0.998 (ap)	1.1272	29.78[g]	86.7	FhG-ISE (10/18)	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[h]	1.008 (ap)	0.939	31.15[i]	82.6	NREL (3/13)	NREL[9]
Thin film chalcogenide							
CIGS (cell) (Cd-free)	23.35 ± 0.5	1.043 (da)	0.734	39.58[j]	80.4	AIST (11/18)	Solar Frontier[10]
CIGSSe (submodule)	20.3 ± 0.4	526.7 (ap)	0.6834	39.55[d,k]	75.1	NREL (5/23)	Avancis, 100 cells[11]
CdTe (cell)	21.0 ± 0.4	1.0623 (ap)	0.8759	30.25[e]	79.4	Newport (8/14)	First Solar, on glass[12]
CZTSSe (cell)	12.1 ± 0.3	1.066 (da)	0.5379	35.29[k]	63.6	NPVM (4/23)	IoP/CAS[13]
CZTS (cell)	10.0 ± 0.2	1.113 (da)	0.7083	21.77[i]	65.1	NREL (3/17)	UNSW[14]
Amorphous/Microcrystalline							
Si (amorphous cell)	10.2 ± 0.3[l,h]	1.001 (da)	0.896	16.36[e]	69.8	AIST (7/14)	AIST[15]
Si (microcrystalline cell)	11.9 ± 0.3[h]	1.044 (da)	0.550	29.72[i]	75.0	AIST (2/17)	AIST[16]
Perovskite							
Perovskite (cell)	**25.2 ± 0.8**[m]	**1.0347 (da)**	**1.162**	**26.39**[n]	**82.0**	**Newport (9/23)**	**NorthwesternU**[17]
Perovskite (minimodule)	22.4 ± 0.5[m]	26.02 (da)	1.127[d]	25.61[d,b]	77.6	NPVM (7/22)	EPFLSion/NCEPU, 8 cells[18]
Dye sensitised							
Dye (cell)	11.9 ± 0.4[o]	1.005 (da)	0.744	22.47[p]	71.2	AIST (9/12)	Sharp[19,20]
Dye (minimodule)	10.7 ± 0.4[o]	26.55 (da)	0.754[d]	20.19[d,q]	69.9	AIST (2/15)	Sharp, 7 serial cells[19,20]
Dye (submodule)	8.8 ± 0.3[o]	398.8 (da)	0.697[d]	18.42[d,r]	68.7	AIST (9/12)	Sharp, 26 serial cells[19,20]
Organic							
Organic (cell)	15.2 ± 0.2[h,s]	1.015 (da)	0.8467	24.24[c]	74.3	FhG-ISE (10/20)	Fraunhofer ISE[21]
Organic (minimodule)	15.7 ± 0.3[s]	19.31(da)	0.8771[d]	24.37[k]	73.4	JET (1/23)	ZhejiangU, 7 cells[22]
Organic (submodule)	11.7 ± 0.2[s]	203.98 (da)	0.8177[d]	20.68[d,t]	69.3	FhG-ISE (10/19)	ZAE Bayern, 33 cells[23]

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

[a]Contacting: Front: 9BB, busbar resistance neglecting; Rear: fully metallised, full-area contact.
[b]Spectral response and current–voltage curve reported in Version 61 of these Tables.
[c]Spectral response and current–voltage curve reported in Version 57 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 53 of these Tables.
[h]Not measured at an external laboratory.
[i]Spectral response and current–voltage curve reported in Version 50 of these Tables.
[j]Spectral response and current–voltage curve reported in Version 54 of these Tables.
[k]Spectral response and current–voltage curve reported in Version 62 of these Tables.
[l]Stabilised by 1000 h exposure to 1 sun light at 50°C.
[m]Initial performance. References[24] and[25] review the stability of similar devices.
[n]Spectral response and current–voltage curve reported in the present version of these Tables.
[o]Initial efficiency. Reference[26] reviews the stability of similar devices.
[p]Spectral response and current–voltage curve reported in Version 41 of these Tables.

[q]Spectral response and current–voltage curve reported in Version 46 of these Tables.
[r]Spectral response and current–voltage curve reported in Version 43 of these Tables.
[s]Initial performance. References[27] and[28] review the stability of similar devices.
[t]Spectral response and current–voltage curve reported in Version 55 of these Tables.

TABLE 2 'Notable exceptions' for single-junction cells and submodules: 'Top dozen' confirmed results, not class records, measured under the global AM1.5 spectrum (1000 Wm^{-2}) at 25°C (IEC 60904-3: 2008 or 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)	UNSW, p-type PERC[29]
Si (crystalline)	25.8 ± 0.5[b]	4.008 (da)	0.7241	42.87[c]	83.1	FhG-ISE (7/17)	FhG-ISE, n-type TOPCon[30]
Si (crystalline)	26.0 ± 0.5[b]	4.015 (da)	0.7323	42.05[d]	84.3	FhG-ISE (11/19)	FhG-ISE, p-type TOPCon
Si (crystalline)	26.7 ± 0.5	79.0 (da)	0.738	42.65[a]	84.9	AIST (3/17)	Kaneka, n-type rear IBC[31]
Si (crystalline)	26.1 ± 0.3[b]	3.9857 (da)	0.7266	42.62[e]	84.3	ISFH (2/18)	ISFH, p-type rear IBC[32]
Si (large)	24.0 ± 0.3[f]	244.59 (t)	0.6940	41.58[g]	83.3	ISFH (7/19)	LONGi, p-type PERC[33]
Si (large)	25.3 ± 0.4[h]	268.0 (t)	0.7214	42.07[i]	83.4	ISFH (11/21)	Jinko, n-type TOPCon[34]
Si (large)	26.6 ± 0.4[j]	274.1 (t)	0.7513	41.30[s]	85.6	ISFH (10/22)	LONGi, p-type HJT[35]
Si (large)	26.6 ± 0.5	179.74 (da)	0.7403	42.5[k]	84.7	FhG-ISE (11/16)	Kaneka, n-type rear IBC[31]
Cells (III-V)							
GaInP	22.0 ± 0.3[b]	0.2502 (ap)	1.4695	16.63[L]	90.2	NREL (1/19)	NREL, rear HJ, strained AlInP[36]
Cells (chalcogenide)							
CIGS (thin-film)	23.6 ± 0.4	0.899 (da)	0.7671	38.30[m]	80.5	FhG-ISE (1/23)	Evolar/UppsalaU[37]
CdTe (thin-film)	**22.4 ± 0.3**	**0.4497 (da)**	**0.8996**	**31.40[n]**	**79.3**	**NREL (9/23)**	**First Solar[38]**
CZTSSe (thin-film)	14.9 ± 0.3	0.2694 (da)	0.5554	36.93[m]	72.5	NPVM (4/23)	IoP/CAS[13]
CZTS (thin-film)	11.4 ± 0.3	0.2039(da)	0.7458	21.79[m]	69.9	NPVM (5/23)	UNSW (Cd-free)[39]
Cells (other)							
Perovskite (thin-film)	**26.1 ± 0.5[o,p]**	**0.05127 (da)**	**1.201**	**25.73[n]**	**84.6**	**NPVM (5/23)**	**USTC[40]**
Perovskite (thin-film)	**26.1 ± 0.8[o]**	**0.04929 (da)**	**1.174**	**26.13[n]**	**85.2**	**Newport (7/23)**	**NorthwesternU/UToronto[17]**
Organic (thin-film)	19.2 ± 0.3[q]	0.0326 (da)	0.9135	26.61[m]	79.0	NREL (3/23)	SJTU[41]
Dye sensitised	13.0 ± 0.4[r]	0.1155 (da)	1.0396	15.55[m]	80.4	FhG-ISE (10/20)	EPFL[42]

Abbreviations: AIST, Japanese National Institute of Advanced Industrial Science and Technology; (ap), aperture area; CIGS, $CuIn_{1-y}Ga_ySe_2$; CZTSSe, $Cu_2ZnSnS_{4-y}Se_y$; CZTS, Cu_2ZnSnS_4; (da), designated illumination area; FhG-ISE, Fraunhofer-Institut für Solare Energiesysteme; ISFH, Institute for Solar Energy Research, Hamelin; NREL, National Renewable Energy Laboratory; (t), total area.
[a]Spectral response reported in Version 36 of these Tables.
[b]Not measured at an external laboratory.
[c]Spectral response and current–voltage curves reported in Version 51 of these Tables.
[d]Spectral response and current–voltage curves reported in Version 55 of these Tables.
[e]Spectral response and current–voltage curve reported in Version 52 of these Tables.
[f]Contacting: Front: 12BB, busbar resistance neglected; Rear: fully metallised, full area contacting.
[g]Spectral response and current–voltage curves reported in Version 57 of these Tables.
[h]Contacting: Front: 0BB, grid resistance neglecting; Rear: 9BB, full area contacting, highly reflective chuck.
[i]Spectral response and current–voltage curves reported in the Version 60 of these Tables.
[j]Contacting: Front: busbar resistance neglecting contacting; Rear: 9BB, grid resistance neglecting contacting, gold plated chuck.
[k]Spectral response and current–voltage curves reported in Version 50 of these Tables.
[l]Spectral response and current–voltage curve reported in Version 54 of these Tables.
[m]Spectral response and current–voltage curves reported in Version 62 of these Tables.
[n]Spectral response and current–voltage curves reported in the present version of these Tables.
[o]Stability not investigated. References[24] and[25] document stability of similar devices.
[p]Measured using 10-point IV sweep with constant voltage bias until current change rate <0.07%/min.
[q]Long-term stability not investigated. References[27] and[28] document stability of similar devices.
[r]Long-term stability not investigated. Reference[26] documents stability of similar devices.

TABLE 3 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 or ASTM G-173-03 global).

Classification	Efficiency (%)	Area (cm^2)	Voc (V)	Jsc (mA/cm^2)	Fill factor (%)	Test Centre (date)	Description
III-V Multijunctions							
5 junction cell (bonded) (2.17/1.68/1.40/1.06/.73 eV)	38.8 ± 1.2	1.021 (ap)	4.767	9.564	85.2	NREL (7/13)	Spectrolab, 2-terminal
InGaP/GaAs/InGaAs	37.9 ± 1.2	1.047 (ap)	3.065	14.27[a]	86.7	AIST (2/13)	Sharp, 2 term.[43]
GaInP/GaAs (monolithic)	32.8 ± 1.4	1.000 (ap)	2.568	14.56[b]	87.7	NREL (9/17)	LG Electronics, 2 term.
III-V/Si Multijunctions							
GaInP/GaInAsP//Si (bonded)	**36.1 ± 1.3**[c]	**3.987 (ap)**	**3.309**	**12.70**[d]	**86.0**	**FhG-ISE (5/23)**	**FhG-ISE/AMOLF, 2-term.**[44]
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.[45]
GaInP/GaAs/Si (monolithic)	25.9 ± 0.9[c]	3.987 (ap)	2.647	12.21[e]	80.2	FhG-ISE (6/20)	Fraunhofer ISE, 2-term.[46]
GaAsP/Si (monolithic)	23.4 ± 0.3	1.026 (ap)	1.732	17.34[f]	77.7	NREL (5/20)	OSU/UNSW/SolAero, 2-term[47]
GaAs/Si (mech. stack)	32.8 ± 0.5[c]	1.003 (da)	1.09/0.683	28.9/11.1[g]	85.0/79.2	NREL (12/16)	NREL/CSEM/EPFL, 4-term.[45]
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.[48]
Perov./Si Multijunctions							
Perovskite/Si	33.9 ± 0.3[h]	1.0044(da)	1.966	20.76[i]	83.0	NREL (9/23)	LONGi, 2-term.[49]
Perovskite/Si (large)	28.6 ± 1.4[h]	258.14(t)	1.909	19.11[i]	78.3	FhG-ISE (5/23)	Oxford PV, 2-term.[50]
Perov.(minimod.)/Si (cell)	28.4 ± 0.7[h]	63.98(da)	1.21[j]/.648	21.9[i,j]/14.3	78.7/81.4	AIST (1/23)	Kaneka, 4-term.[51]
Other Multijunctions							
Perovskite/CIGS	24.2 ± 0.7[h]	1.045 (da)	1.768	19.24[f]	72.9	FhG-ISE (1/20)	HZB, 2-terminal[52]
Perovskite/perovskite	28.2 ± 0.5[h]	1.038(da)	2.159	16.59[i]	78.9	JET (12/22)	NanjingU/Renshine, 2-term.[53]
Perovskite/perovskite (minimodule)	24.5 ± 0.6[h]	20.25(da)	2.157	14.86[k]	77.5	JET (6/22)	NanjingU/Renshine, 2-term.[54]
a-Si/nc-Si/nc-Si (thin-film)	14.0 ± 0.4[l,c]	1.045 (da)	1.922	9.94[m]	73.4	AIST (5/16)	AIST, 2-term.[55]
a-Si/nc-Si (thin-film cell)	12.7 ± 0.4[l,c]	1.000(da)	1.342	13.45[n]	70.2	AIST (10/14)	AIST, 2-term.[56]
'Notable Exceptions'							
GaInP/GaAs (mqw)	32.9 ± 0.5[c]	0.250 (ap)	2.500	15.36[o]	85.7	NREL (1/20)	NREL/UNSW, multiple QW
GaInP/GaAs/GaInAs	37.8 ± 1.4	0.998 (ap)	3.013	14.60[o]	85.8	NREL (1/18)	Microlink (ELO)[57]
GaInP/GaAs (mqw)/GaInAs	39.5 ± 0.5[c]	0.242 (ap)	2.997	15.44[p]	85.3	NREL (9/21)	NREL, multiple QW
6 junction (monolithic) (2.19/1.76/1.45/1.19/.97/.7 eV)	39.2 ± 3.2[c]	0.247 (ap)	5.549	8.457[q]	83.5	NREL (11/18)	NREL, inv. metamorphic[58]
GaInP/AlGaAs/CIGS	28.1 ± 1.2[c]	0.1386(da)	2.952	11.72[r]	81.1	AIST (1/21)	AIST/FhG-ISE, 2-term.[59]
Perovskite/perovskite	29.1 ± 0.5[h]	0.0489(da)	2.154	16.51[i]	81.7	JET (12/22)	NanjingU/Renshine, 2-term.[53]
Perovskite/organic	23.4 ± 0.8[h]	0.0552(da)	2.136	14.56[s]	75.6	JET (3/22)	NUS/SERIS, 2-term.

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

[a]Spectral response and current–voltage curve reported in Version 42 of these Tables.

[b]Spectral response and current–voltage curve reported in the Version 51 of these Tables.

[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 curve reported in Version 57 of these Tables.
[f]Spectral response and current–voltage curve reported in Version 56 of these Tables.
[g]Spectral response and current–voltage curve reported in Version 52 of these Tables.
[h]Initial efficiency. References[24] and[25] review the stability of similar perovskite-based devices.
[i]Spectral response and current–voltage curves reported in the present version of these Tables.
[j]Reported on a 'per cell' basis.
[k]Spectral response and current–voltage curve reported in Version 61 of these Tables.
[l]Stabilised by 1000 h exposure to 1 sun light at 50°C.
[m]Spectral response and current–voltage curve reported in Version 49 of these Tables.
[n]Spectral responses and current–voltage curve reported in Version 45 of these Tables.
[o]Spectral response and current–voltage curve reported in Version 53 of these Tables.
[p]Spectral response and current–voltage curves reported in Version 59 of these Tables.
[q]Spectral response and current–voltage curve reported in Version 54 of these Tables.
[r]Spectral response and current–voltage curve reported in Version 58 of these Tables.
[s]Spectral response and current–voltage curve reported in Version 60 of these Tables.

TABLE 4 Confirmed non-concentrating 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 or ASTM G-173-03 global).

Classification	Effic. (%)	Area (cm^2)	V_{oc} (V)	I_{sc} (A)	FF (%)	Test Centre (date)	Description
Si (crystalline)	24.7 ± 0.3	17,806 (da)	83.04	6.384[a]	82.9	NREL (4/23)	Maxeon (112 cells)
Si (multicrystalline)	20.4 ± 0.3	14,818 (ap)	39.90	9.833[b]	77.2	FhG-ISE (10/19)	Hanwha Q Cells (60 cells)[60]
GaAs (thin-film)	25.1 ± 0.8	866.45 (ap)	11.08	2.303[c]	85.3	FhG-ISE (11/17)	Alta Devices[61]
CIGS (Cd-free)	19.2 ± 0.5	841 (ap)	48.0	0.456[c]	73.7	AIST (1/17)	Solar Frontier (70 cells)[62]
CdTe (thin-film)	19.5 ± 1.4	23,582 (da)	227.9	2.622[d]	76.8	NREL (9/21)	First Solar[63]
a-Si/nc-Si (tandem)	12.3 ± 0.3[e]	14,322 (t)	280.1	0.902[f]	69.9	ESTI (9/14)	TEL Solar, Trubbach Labs[64]
Perovskite	18.6 ± 0.7[g]	809.9 (da)	44.7	0.479[h]	70.3	JET (5/23)	UtmoLight (39 cells)[65]
Organic	13.1 ± 0.3[i]	1475.0 (da)	48.10	0.6015[j]	67.0	NREL (5/23)	Waystech/Nanobit[66]
Multijunction							
InGaP/GaAs/InGaAs	32.65 ± 0.7	965 (da)	24.30	1.520[d]	85.3	AIST (2/22)	Sharp (40 cells; 8 series)[67]
'Notable Exceptions'							
CIGS (large)	18.6 ± 0.6	10,858 (ap)	58.00	4.545[b]	76.8	FhG-ISE (10/19)	Miasole[68]
InGaP/GaAs//Si	33.7 ± 0.7	775 (da)	20.3/2.83	1.25/1.93[a]	86.5/78.0	AIST (2/23)	Sharp/Toyota TI, 4-term.[69]
InGaP/GaAs//CIGS	31.2 ± 0.7	778 (ap)	20.3/16.9	1.24/.26[a]	85.7/59.8	AIST (2/23)	Sharp/Idemitsu, 4-term.[69]

Abbreviations: a-Si, amorphous silicon/hydrogen alloy; a-SiGe, amorphous silicon/germanium/hydrogen alloy; (ap), aperture area; CIGSS, CuInGaSSe; (da), designated illumination area; Effic., efficiency; FF, fill factor; nc-Si, nanocrystalline or microcrystalline silicon; (t), total area.
[a]Spectral response and current voltage curve reported Version 62 of these Tables.
[b]Spectral response and current–voltage curve reported in Version 55 of these Tables.
[c]Spectral response and current–voltage curve reported in Version 50 or 51 of these Tables.
[d]Spectral response and current–voltage curve reported in Version 60 of these Tables.
[e]Stabilised at the manufacturer to the 2% level following IEC procedure of repeated measurements.
[f]Spectral response and/or current–voltage curve reported in Version 46 of these tables.
[g]Initial performance. References[25] and[26] review the stability of similar devices.
[h]Spectral response and current–voltage curve reported in Version 57 of these Tables.
[i]Initial performance. References[28] and[29] review the stability of similar devices.
[j]Spectral response and current–voltage curve reported in Version 45 of these Tables.

Tabled results are reported for cells and modules made from different semiconductors and for sub-categories within each semiconductor grouping (e.g., crystalline, polycrystalline or directionally solidified and thin film). From Version 36 onwards, spectral response information is included (when possible) 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.

Highest confirmed 'one 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

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 (except where noted for the hybrid and luminescent modules).

Classification	Effic. (%)	Area (cm^2)	Intensity[a] (suns)	Test Centre (date)	Description
Single cells					
GaAs	30.8 ± 1.9[b,c]	0.0990 (da)	61	NREL (1/22)	NREL, 1 junction (1 J)
Si	27.6 ± 1.2[d]	1.00 (da)	92	FhG-ISE (11/04)	Amonix back-contact[70]
CIGS (thin-film)	23.3 ± 1.2[b,e]	0.09902 (ap)	15	NREL (3/14)	NREL[71]
Multijunction cells					
AlGaInP/AlGaAs/GaAs/GaInAs(3) (2.15/1.72/1.41/1.17/0.96/0.70 eV)	47.1 ± 2.6[b,f]	0.099 (da)	143	NREL (3/19)	NREL, 6 J inv. metamorphic[58]
GaInP/GaInAs; GaInAsP/GaInAs	47.6 ± 2.6[b,g]	0.0452 (da)	665	FhG-ISE (5/22)	FhG-ISE 4 J bonded[72]
GaInP/GaAs/GaInAs/GaInAs	45.7 ± 2.3[b,h]	0.09709 (da)	234	NREL (9/14)	NREL, 4 J monolithic[73]
InGaP/GaAs/InGaAs	44.4 ± 2.6[i]	0.1652 (da)	302	FhG-ISE (4/13)	Sharp, 3 J inverted metamorphic[74]
GaInAsP/GaInAs	35.5 ± 1.2[b,j]	0.10031 (da)	38	NREL (10/17)	NREL 2-junction (2 J)[75]
Minimodule					
GaInP/GaAs; GaInAsP/GaInAs	43.4 ± 2.4[b,k]	18.2 (ap)	340[l]	FhG-ISE (7/15)	Fraunhofer ISE 4 J (lens/cell)[76]
Submodule					
GaInP/GaInAs/Ge; Si	40.6 ± 2.0[k]	287 (ap)	365	NREL (4/16)	UNSW 4 J split spectrum[77]
Modules					
Si	20.5 ± 0.8[b]	1875 (ap)	79	Sandia (4/89)[l]	Sandia/UNSW/ENTECH (12 cells)[78]
Three Junction (3 J)	35.9 ± 1.8[m]	1,092 (ap)	N/A	NREL (8/13)	Amonix[79]
Four Junction (4 J)	38.9 ± 2.5[n]	812.3 (ap)	333	FhG-ISE (4/15)	Soitec[80]
Hybrid module[o]					
4-Junction (4 J)/bifacial c-Si	34.2 ± 1.9[b,o]	1,088 (ap)	CPV/PV	FhG-ISE (9/19)	FhG-ISE (48/8 cells; 4 T)[81]
'Notable Exceptions'					
Si (large area)	21.7 ± 0.7	20.0 (da)	11	Sandia (9/90)[l]	UNSW laser grooved[82]
Luminescent Minimodule[o]	7.1 ± 0.2	25 (ap)	2.5[p]	ESTI (9/08)	ECN Petten, GaAs cells[83]
4 J Minimodule	41.4 ± 2.6[b]	121.8 (ap)	230	FhG-ISE (9/18)	FhG-ISE, 10 cells[84]

Note: Following the normal convention, efficiencies calculated under this direct beam spectrum neglect the diffuse sunlight component that would accompany this direct spectrum. These direct beam efficiencies need to be multiplied by a factor estimated as 0.8746 to convert to thermodynamic efficiencies.[85]

Abbreviations: (ap), aperture area; CIGS, $CuInGaSe_2$; (da), designated illumination area; 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]Not measured at an external laboratory.

[c]Spectral response and current–voltage curve reported in Version 60 of these Tables.

[d]Measured under a low aerosol optical depth spectrum similar to ASTM G-173-03 direct.[86]

[e]Spectral response and current–voltage curve reported in Version 44 of these Tables.

[f]Spectral response and current–voltage curve reported in Version 54 of these Tables.

[g]Spectral response and current–voltage curve reported in Version 61 of these Tables.

[h]Spectral response and current–voltage curve reported in Version 46 of these Tables.

[i]Spectral response and current–voltage curve reported in Version 42 of these Tables.

[j]Spectral response and current–voltage curve reported in Version 51 of these Tables.

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

[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.

[o]Thermodynamic efficiency. Hybrid and luminescent modules measured under the ASTM G-173-03 or IEC 60904-3: 2008 global AM1.5 spectrum at a cell temperature of 25°C. 4-terminal module with external dual-axis tracking. Power rating of CPV follows IEC 62670-3 standard, front power rating of flat plate PV based on IEC 60904-3, -5, -7, -10 and 60891 with modified current translation approach; rear power rating of flat plate PV based on IEC TS 60904-1-2 and 60891.

[p]Geometric concentration.

the lead author). Table 1 summarises the best-reported measurements for 'one-sun' (non-concentrator) single-junction cells and submodules.

Table 2 contains what might be described as 'notable exceptions' for 'one-sun' single-junction cells and submodules in the above category. While not conforming to the requirements to be recognised as a class record, the devices in Table 2 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, the table is limited to nominally 12 entries with the present authors having voted for their preferences for inclusion. Readers who have suggestions of notable exceptions for inclusion into this or subsequent tables 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 3 was first introduced in Version 49 of these tables and summarises the growing number of cell and submodule results involving high efficiency, one-sun multiple-junction devices (previously reported in Table 1). Table 4 shows the best results for one-sun modules, both single- and multiple-junction, while Table 5 shows the best results for concentrator cells and concentrator modules. A small number of 'notable exceptions' are also included in Tables 3 to 5.

2 | NEW RESULTS

Six new results are reported in the present version of these tables. The first is reported in Table 1 ('one-sun cells and submodules'). An efficiency of 25.2% is reported for a 1-cm^2 lead halide perovskite cell fabricated by Northwestern University (Illinois, USA)[38] as measured by the Newport PV Lab, a major increase over the 24.35% result inthe previous version [1]. Also a correction is reported in the footnote of Table 1 reporting measurement details of the record 26.8% efficient, large-area silicon cell fabricated by LONGi Solar in 2022. These were incorrectly reported in both Versions 61 and 62 as '*Contacting: Front: 9BB, busbar resistance neglecting; Rear: 9BB, full area contacting, highly reflective chuck*'. As correctly described in the main text, this cell was a monofacial cell and the correct measurement details are '*Contacting: Front: 9BB, busbar resistance*

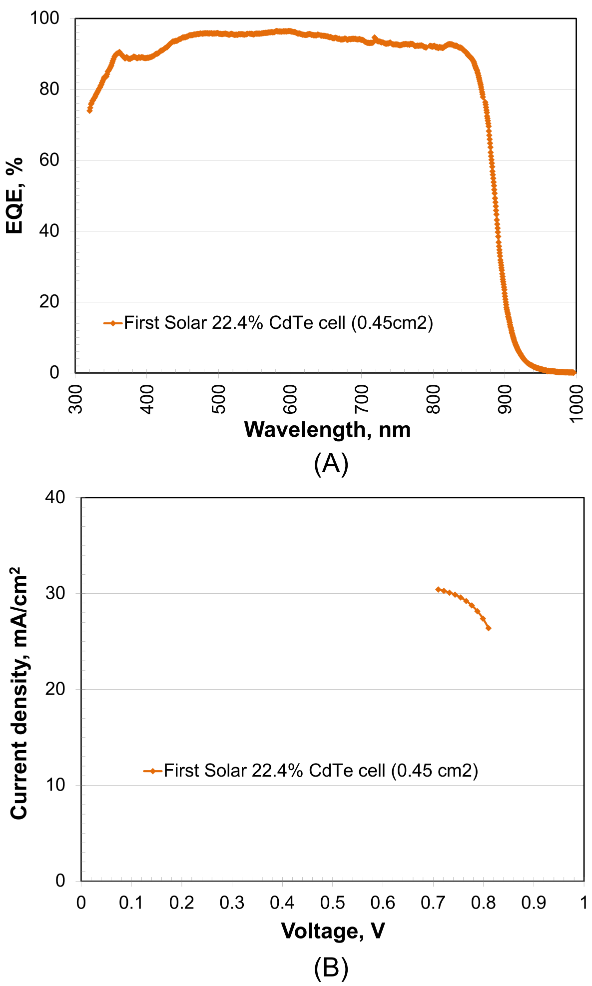

FIGURE 1 (A) External quantum efficiency (EQE) for the new CdTe thin-film cell result reported in this issue. (B) Corresponding current density–voltage (JV) curve.

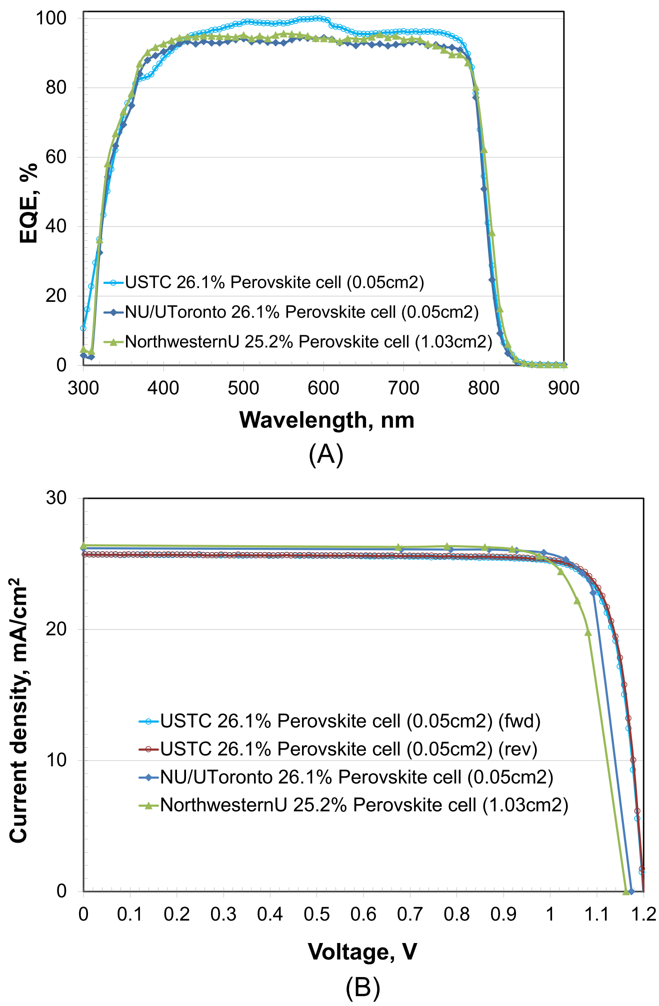

FIGURE 2 (A) External quantum efficiency (EQE) for the new perovskite thin-film cell results reported in this issue (one curve is normalised). (B) Corresponding current density–voltage (JV) curve.

neglecting; Rear: fully metallised, full-area contact'. Please see Version 60 for a full explanation of this terminology.[3]

Three new results are reported in Table 2 (one-sun 'notable exceptions'), all involving small area, thin-film solar cells. The first is an increase in efficiency to 22.4% for a small area (0.45 cm^2) CdTe-based cell fabricated by First Solar[38] and measured by the US National Renewable Energy Laboratory (NREL), improving on the 22.3% result reported in the previous version of these tables.[1] The second new result is a similar incremental improvement to 26.1% efficiency for a very small area 0.05 cm^2 Pb-halide perovskite solar cell fabricated by the University of Science and Technology of China (USTC)[40] and measured by the Chinese National Photovoltaic Industry Measurement and Testing Center (NPVM).

The third new result in Table 2 is the same incremental improvement to 26.1% efficiency again for a very small area 0.05-cm2 Pb-halide perovskite solar cell fabricated by Northwestern University in conjunction with the University of Toronto [17] and measured by the Newport PV Lab [1].

For all three results, cell area is too small for classification as an outright record, with solar cell efficiency targets in governmental research programs generally specified in terms of a cell area of 1 cm^2 or larger.[87–89]

The fifth new result in this version is reported in Table 3 describing results for one-sun, multijunction devices. An efficiency of 36.1% is reported for a two-terminal, triple-junction GaInP/GaInAsP//Si (wafer bonded) cell fabricated by the Fraunhofer Institute for Solar Energy Systems (FhG-ISE) and AMOLF (Amsterdam)[44] and measured

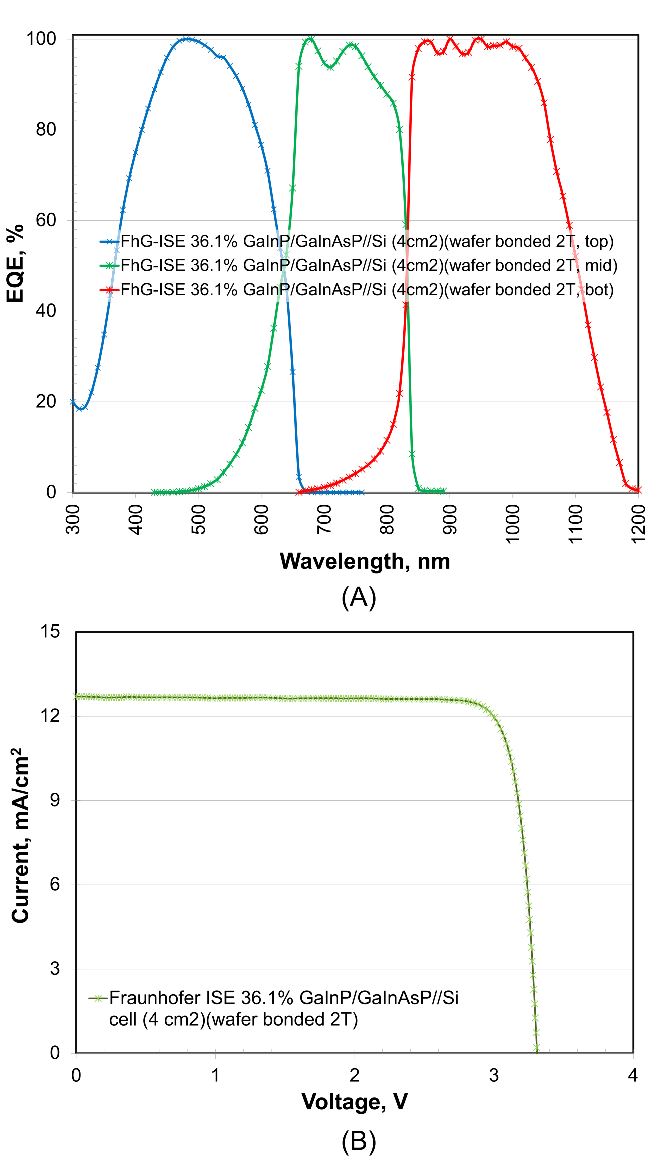

FIGURE 3 (A) External quantum efficiency (EQE) for the new 2-terminal triple-junction GaInP/GaInAsP//Si (wafer bonded) multijunction cell result reported in this issue (results are normalised). (B) Corresponding current density–voltage (JV) curve.

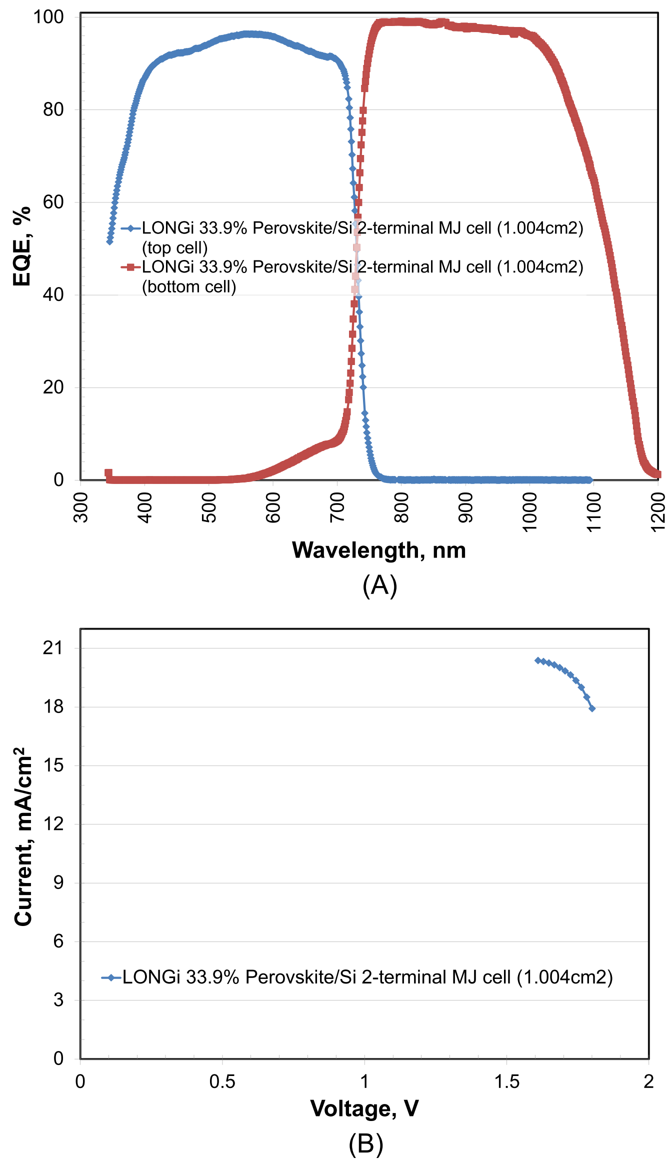

FIGURE 4 (A) External quantum efficiency (EQE) for the new 2-terminal double-junction Perovskite/Si multijunction cell result reported in this issue (results are normalised). (B) Corresponding current density-voltage (JV) curve.

by FhG-ISE. This has been reported as the highest one-sun efficiency ever reached for a solar cell based on silicon. The final new result is 33.9% efficiency for a 1-cm^2, 2-terminal, double-junction perovskite/Si cell fabricated by LONGi[49] and measured by NREL.

There are two corrections in Table 4 (one-sun modules) involving two results reported as 'notable exceptions' in the previous version of these tables.[1] The two high efficiency four-terminal modules reported as fabricated by Sharp and measured by AIST should have been reported as being fabricated by Sharp/Toyota-TI and Sharp/Idemitsu, respectively.

The EQE spectra for the new CdTe thin-film cell reported in the present issue of these tables are shown in Figure 1(A), with Figure 1(B) showing the current density–voltage (JV) curves for the same device. Figure 2(A) and (B) shows the corresponding EQE and JV curves for the new perovskite thin-film cell results. Figure 3(A) and (B) shows these for the new triple-junction GaInP/GaInAsP//Si (wafer-bonded) multijunction cell result while Figure 4(A) and (B) shows these for the new perovskite/Si 2-terminal, double junction device.

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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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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