


Solar cell efficiency tables (Version 61)

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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 2022 are reviewed. Graphs showing progress with each cell technology over the 30-year history of the tables are also included plus an updated list of designated test centres.

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.^{1,2} 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. A distinction is made

between three different eligible definitions of cell area: total area, aperture area and designated illumination area, as defined in Appendix B (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 cm² for a concentrator cell, 1 cm² for a one-sun cell, 200 cm² for a “submodule” and 800 cm² 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 Appendix A of the previous issue,¹ we describe approaches for temporary electrical contacting of large-area solar cells with and without busbars. To enable comparability between different contacting

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TABLE 1 Confirmed single-junction terrestrial cell and submodule efficiencies measured under the global AM1.5 spectrum (1000 W/m²) 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
<i>Silicon</i>							
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 ³
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 ^d	38.50 ^{d,e}	80.3	NREL (4/14)	Solexel (35 μm thick) ⁴
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) ⁵
<i>III-V Cells</i>							
GaAs (thin film cell)	29.1 ± 0.6	0.998 (ap)	1.1272	29.78 ^g	86.7	FhG-ISE (10/18)	Alta Devices ⁶
GaAs (multicrystalline)	18.4 ± 0.5	4.011 (t)	0.994	23.2	79.7	NREL (11/95)	RTI, Ge substrate ⁷
InP (crystalline cell)	24.2 ± 0.5 ^h	1.008 (ap)	0.939	31.15 ⁱ	82.6	NREL (3/13)	NREL ⁸
<i>Thin Film Chalcogenide</i>							
CIGS (cell) (Cd-free)	23.35 ± 0.5	1.043 (da)	0.734	39.58 ^j	80.4	AIST (11/18)	Solar Frontier ⁹
CIGSSe (submodule)	19.8 ± 0.5	665.4 (ap)	0.688	37.96 ^k	75.9	NREL (12/21)	Avancis, 110 cells 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
CZTSSe (cell)	11.3 ± 0.3	1.1761 (da)	0.5333	33.57 ^g	63.0	Newport (10/18)	DGIST, Korea ¹²
CZTS (cell)	10.0 ± 0.2	1.113 (da)	0.7083	21.77 ⁱ	65.1	NREL (3/17)	UNSW ¹³
<i>Amorphous/Microcrystalline</i>							
Si (amorphous cell)	10.2 ± 0.3 ^{l,h}	1.001 (da)	0.896	16.36 ^e	69.8	AIST (7/14)	AIST ¹⁴
Si (microcrystalline cell)	11.9 ± 0.3 ^h	1.044 (da)	0.550	29.72 ⁱ	75.0	AIST (2/17)	AIST ¹⁵
<i>Perovskite</i>							
Perovskite (cell)	23.7 ± 0.5 ^m	1.062 (da)	1.213	24.99 ^k	78.4	NPVM (5/22)	U.Sci.Tech., Hefei ¹⁶
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 ¹⁷
<i>Dye sensitised</i>							
Dye (cell)	11.9 ± 0.4 ⁿ	1.005 (da)	0.744	22.47 ^o	71.2	AIST (9/12)	Sharp ^{18,19}
Dye (minimodule)	10.7 ± 0.4 ⁿ	26.55 (da)	0.754 ^d	20.19 ^{d,p}	69.9	AIST (2/15)	Sharp, 7 serial cells ^{18,19}
Dye (submodule)	8.8 ± 0.3 ⁿ	398.8 (da)	0.697 ^d	18.42 ^{d,q}	68.7	AIST (9/12)	Sharp, 26 serial cells ^{18,19}
<i>Organic</i>							
Organic (cell)	15.2 ± 0.2 ^{h,r}	1.015 (da)	0.8467	24.24 ^c	74.3	FhG-ISE (10/20)	Fraunhofer ISE ²⁰
Organic (minimodule)	14.5 ± 0.3 ^r	19.31 (da)	0.8518 ^d	23.51 ^{d,k}	72.5	JET (12/21)	ZJU/Microquanta, 7 cells ²¹
Organic (submodule)	11.7 ± 0.2 ^f	203.98 (da)	0.8177 ^d	20.68 ^{d,s}	69.3	FhG-ISE (10/19)	ZAE Bayern, 33 cells ²²

Abbreviations: (ap), aperture area; AIST, Japanese National Institute of Advanced Industrial Science and Technology; a-Si, amorphous silicon/hydrogen alloy; CIGS, CuIn_{1-y}Ga_ySe₂; CZTS, Cu₂ZnSnS₄; CZTSSe, Cu₂ZnSnS_{4-y}Se_y; (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.

^aContacting: front: 9BB, busbar resistance neglecting; rear: 9BB, full area contacting, highly reflective chuck.

^bSpectral response and current–voltage curve reported in present version of these tables.

^cSpectral response and current–voltage curve reported in Version 57 of these tables.

^dReported on a “per cell” basis.

^eSpectral responses and current–voltage curve reported in Version 45 of these tables.

^fRecalibrated from original measurement.

^gSpectral response and current–voltage curve reported in Version 53 of these tables.

^hNot measured at an external laboratory.

ⁱSpectral response and current–voltage curve reported in Version 50 of these tables.

^jSpectral response and current–voltage curve reported in Version 54 of these tables.

^kSpectral response and current–voltage curve reported in Version 60 of these tables.

^lStabilized by 1000 h exposure to 1 sun light at 50°C.

^mInitial performance. Han et al.²³ and Yang and You²⁴ review the stability of similar devices.

ⁿInitial efficiency. Krašovec et al.²⁵ review the stability of similar devices.

^oSpectral response and current–voltage curve reported in Version 41 of these tables.

^pSpectral response and current–voltage curve reported in Version 46 of these tables.

^qSpectral response and current–voltage curve reported in Version 43 of these tables.

^rInitial performance. Tanembaum et al.,²⁶ Krebs,²⁷ and Jorgensen et al.²⁸ review the stability of similar devices.

^sSpectral 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 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
<i>Cells (silicon)</i>							
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	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 ^f	84.9	AIST (3/17)	Kaneka, n-type rear IBC ³²
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 ³¹
Si (large crystalline)	24.0 ± 0.3 ^g	244.59 (t)	0.6940	41.58 ^h	83.3	ISFH (7/19)	LONGi, p-type PERC ³³
Si (large crystalline)	25.3 ± 0.4 ⁱ	268.0 (t)	0.7214	42.07 ^j	83.4	ISFH (11/21)	Jinko, n-type TOPCon ³⁴
Si (large crystalline)	26.6 ± 0.4^k	274.1 (t)	0.7513	41.30^l	85.6	ISFH (10/22)	LONGi, p-type HJT³⁵
Si (large crystalline)	26.6 ± 0.5	179.74 (da)	0.7403	42.5 ^f	84.7	FhG-ISE (11/16)	Kaneka, n-type rear IBC ³²
<i>Cells (III-V)</i>							
GaInP	22.0 ± 0.3 ^b	0.2502 (ap)	1.4695	16.63 ^m	90.2	NREL (1/19)	NREL, rear HJ, strained AlInP ³⁶
<i>Cells (chalcogenide)</i>							
CdTe (thin-film)	22.1 ± 0.5	0.4798 (da)	0.8872	31.69 ⁿ	78.5	Newport (11/15)	First Solar on glass ³⁷
CZTSSe (thin-film)	13.0 ± 0.1	0.1072 (ap)	0.5294	33.58 ^o	72.9	NREL (6/21)	NJUPT (10% Ag) ³⁸
CZTS (thin-film)	11.0 ± 0.2	0.2339 (da)	0.7306	21.74 ^f	69.3	NREL (3/17)	UNSW on glass ³⁹
<i>Cells (other)</i>							
Perovskite (thin-film)	25.7 ± 0.8 ^{p,q}	0.09597 (ap)	1.1790	25.80 ^j	84.6	Newport (11/21)	UNIST Ulsan ⁴⁰
Organic (thin-film)	18.2 ± 0.2 ^r	0.0322 (da)	0.8965	25.72 ^h	78.9	NREL (10/20)	SJTU Shanghai/Beihang U.
Dye sensitised	12.25 ± 0.4 ^s	0.0963 (ap)	1.0203	15.17 ^d	79.1	Newport (8/19)	EPFL ⁴¹

Abbreviations: AIST, Japanese National Institute of Advanced Industrial Science and Technology; (ap), aperture area; CIGSSe, CuInGaSSe; CZTSSe, Cu₂ZnSnS_{4-y}Se_y; CZTS, Cu₂ZnSnS₄; (da), designated illumination area; DS, directionally solidified (including mono cast and multicrystalline); FhG-ISE, Fraunhofer-Institut für Solare Energiesysteme; ISFH, Institute for Solar Energy Research, Hamelin; NREL, National Renewable Energy Laboratory; (t), total area.

^aSpectral response reported in Version 36 of these tables.

^bNot measured at an external laboratory.

^cSpectral response and current–voltage curves reported in Version 51 of these tables.

^dSpectral response and current–voltage curves reported in Version 55 of these tables.

^eSpectral response and current–voltage curve reported in Version 52 of these tables.

^fSpectral response and current–voltage curves reported in Version 50 of these tables.

^gContacting: front: 12BB, busbar resistance neglected; rear: fully metallized, full area contacting.

^hSpectral response and current–voltage curves reported in Version 57 of these tables.

ⁱContacting: front: OBB, grid resistance neglecting; rear: 9BB, full area contacting, highly reflective chuck.

^jSpectral response and current–voltage curves reported in the Version 60 of these tables.

^kContacting: front: busbar resistance neglecting contacting; rear: 9BB, grid resistance neglecting contacting, gold plated chuck.

^lSpectral response and current–voltage curve reported in present version of these tables.

^mSpectral response and current–voltage curve reported in Version 54 of these tables.

ⁿSpectral response and/or current–voltage curves reported in Version 46 of these tables.

^oSpectral response and current–voltage curves reported in Version 59 of these tables.

^pStability not investigated. Han et al.²³ and Yang and You²⁴ document stability of similar devices.

^qMeasured using 10-point IV sweep with constant voltage bias until current change rate <0.07%/min.

^rLong-term stability not investigated. Tanembaum et al.,²⁶ Krebs,²⁷ and Jorgensen et al.²⁸ document stability of similar devices.

^sLong-term stability not investigated. Krašovec et al.²⁵ document stability of similar devices.

TABLE 3 Confirmed multiple-junction terrestrial cell and submodule efficiencies measured under the global AM1.5 spectrum (1000 W/m²) 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
<i>III-V Multijunctions</i>							
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. ⁴²
GaInP/GaAs (monolithic)	32.8 ± 1.4	1.000 (ap)	2.568	14.56 ^b	87.7	NREL (9/17)	LG Electronics, 2 term.
<i>Multijunctions with c-Si</i>							
GaInP/GaInAsP/Si (wafer bonded)	35.9 ± 1.3 ^c	3.987 (ap)	3.248	13.11 ^d	84.3	FhG-ISE (4/20)	Fraunhofer ISE, 2-term. ⁴³
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. ⁴⁴
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. ⁴⁵
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 ⁴⁶
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. ⁴⁴
Perovskite/Si	31.3 ± 0.3^h	1.1677 (da)	1.9131	20.47ⁱ	79.8	NREL (6/22)	EPFL/CSEM, 2-term.⁴⁷
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
<i>Other Multijunctions</i>							
Perovskite/CIGS	24.2 ± 0.7 ^h	1.045 (da)	1.768	19.24 ^f	72.9	FhG-ISE (1/20)	HZB, 2-terminal ⁴⁹
Perovskite/perovskite	26.4 ± 0.7 ^h	1.044 (da)	2.118	15.22 ^p	82.6	JET (3/22)	SichuanU/EMPA, 2-term. ⁵⁰
Perovskite/perovskite (minimodule)	24.5 ± 0.6 ^h	20.25 (da)	2.157	14.86 ⁱ	77.5	JET (6/22)	Nanjing/Renshine, 2-term. ⁵¹
a-Si/nc-Si/nc-Si (thin-film)	14.0 ± 0.4 ^{jc}	1.045 (da)	1.922	9.94 ^k	73.4	AIST (5/16)	AIST, 2-term. ⁵²
a-Si/nc-Si (thin-film cell)	12.7 ± 0.4 ^{jc}	1.000 (da)	1.342	13.45 ^l	70.2	AIST (10/14)	AIST, 2-term. ⁵³
<i>“Notable Exceptions”</i>							
GaInP/GaAs (mqw)	32.9 ± 0.5 ^c	0.250 (ap)	2.500	15.36 ^m	85.7	NREL (1/20)	NREL/UNSW, multiple QW
GaInP/GaAs/GaInAs	37.8 ± 1.4	0.998 (ap)	3.013	14.60 ^m	85.8	NREL (1/18)	Microlink (ELO) ⁵⁴
GaInP/GaAs (mqw)/GaInAs	39.5 ± 0.5 ^c	0.242 (ap)	2.997	15.44 ⁿ	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 ^o	83.5	NREL (11/18)	NREL, inv. metamorphic ⁵⁵
GaInP/AlGaAs/CIGS	28.1 ± 1.2 ^c	0.1386 (da)	2.952	11.72 ^d	81.1	AIST (1/21)	AIST/FhG-ISE, 2-term. ⁵⁶
Perovskite/Si (large)	26.8 ± 1.2 ^h	274.22 (t)	1.891	17.84 ^p	79.4	FhG-ISE (11/21)	Oxford PV, 2-term.
Perovskite/perovskite	28.0 ± 0.6 ^h	0.0495 (da)	2.125	16.42 ^p	80.3	JET (12/21)	Nanjing U, 2-term. ⁵¹
Perovskite/organic	23.4 ± 0.8 ^h	0.0552 (da)	2.136	14.56 ^p	75.6	JET (3/22)	NUS/SERIS, 2-term. ⁵⁷

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

^aSpectral response and current–voltage curve reported in Version 42 of these tables.

^bSpectral response and current–voltage curve reported in the Version 51 of these tables.

^cNot measured at an external laboratory.

^dSpectral response and current–voltage curve reported in Version 58 of these tables.

^eSpectral response and current–voltage curve reported in Version 57 of these tables.

^fSpectral response and current–voltage curve reported in Version 56 of these tables.

^gSpectral response and current–voltage curve reported in Version 52 of these tables.

^hInitial efficiency. Han et al.²³ and Yang and You²⁴ review the stability of similar perovskite-based devices.

ⁱSpectral response and current–voltage curves reported in the present version of these tables.

^jStabilized by 1000 h exposure to 1 sun light at 50°C.

^kSpectral response and current–voltage curve reported in Version 49 of these tables.

^lSpectral responses and current–voltage curve reported in Version 45 of these tables.

^mSpectral response and current–voltage curve reported in Version 53 of these tables.

ⁿSpectral response and current–voltage curves reported in Version 59 of these tables.

^oSpectral response and current–voltage curve reported in Version 54 of these tables.

^pSpectral 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/m²) 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)	24.4 ± 0.5	13,177 (da)	79.5	5.04 ^a	80.1	AIST (9/16)	Kaneka (108 cells) ³²
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) ⁵⁸
GaAs (thin-film)	25.1 ± 0.8	866.45 (ap)	11.08	2.303 ^c	85.3	FhG-ISE (11/17)	Alta Devices ⁵⁹
CIGS (Cd-free)	19.2 ± 0.5	841 (ap)	48.0	0.456 ^c	73.7	AIST (1/17)	Solar Frontier (70 cells) ⁶⁰
CdTe (thin-film)	19.5 ± 1.4	23,582 (da)	227.9	2.622 ^d	76.8	NREL (9/21)	First Solar ⁶¹
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 ⁶²
Perovskite	17.9 ± 0.5 ^g	804 (da)	58.7	0.323 ^h	76.1	AIST (1/20)	Panasonic (55 cells) ⁶³
Organic	8.7 ± 0.3 ⁱ	802 (da)	17.47	0.569 ^j	70.4	AIST (5/14)	Toshiba ⁶⁴
<u>Multijunction</u>							
InGaP/GaAs/InGaAs	32.65 ± 0.7	965 (da)	24.30	1.520 ^d	85.3	AIST (2/22)	Sharp (40 cells; 8 series) ⁶⁵
<u>“Notable Exception”</u>							
CIGS (large)	18.6 ± 0.6	10,858 (ap)	58.00	4.545 ^b	76.8	FhG-ISE (10/19)	Miasole ⁶⁶

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

^aSpectral response and current voltage curve reported in Version 49 of these tables.

^bSpectral response and current–voltage curve reported in Version 55 of these tables.

^cSpectral response and current–voltage curve reported in Version 50 or 51 of these tables.

^dSpectral response and current–voltage curve reported in Version 60 of these tables.

^eStabilised at the manufacturer to the 2% level following IEC procedure of repeated measurements.

^fSpectral response and/or current–voltage curve reported in Version 46 of these tables.

^gInitial performance. Yang and You²⁴ and Krašovec et al.²⁵ review the stability of similar devices.

^hSpectral response and current–voltage curve reported in Version 57 of these tables.

ⁱInitial performance. Green,²⁹ Krebs,²⁷ and Jorgensen et al.²⁸ review the stability of similar devices.

^jSpectral response and current–voltage curve reported in Version 45 of these tables.

approaches and to clarify the corresponding measurement conditions, an unambiguous denotation was introduced and used in the present version of these tables.

Table results are reported for cells and modules made from different semiconductors and for subcategories 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 published¹ are set in bold type. In most cases, a literature reference is provided that describes either the result reported or a similar result

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
<u>Single cells</u>					
GaAs	30.8 ± 1.9 ^{b,c}	0.0990 (da)	61	NREL (1/22)	NREL, 1 junction (1J)
Si	27.6 ± 1.2 ^d	1.00 (da)	92	FhG-ISE (11/04)	Amonix back-contact ⁶⁷
CIGS (thin-film)	23.3 ± 1.2 ^{b,e}	0.09902 (ap)	15	NREL (3/14)	NREL ⁶⁸
<u>Multijunction cells</u>					
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, 6J inv. metamorphic ⁵⁵
GaInP/GaInAs; GaInAsP/GaInAs	47.6 ± 2.6^{b,g}	0.0452 (da)	665	FhG-ISE (5/22)	FhG-ISE 4J bonded⁶⁹
GaInP/GaAs/GaInAs/GaInAs	45.7 ± 2.3 ^{b,h}	0.09709 (da)	234	NREL (9/14)	NREL, 4J monolithic ⁷⁰
InGaP/GaAs/InGaAs	44.4 ± 2.6 ⁱ	0.1652 (da)	302	FhG-ISE (4/13)	Sharp, 3J inverted metamorphic ⁷¹
GaInAsP/GaInAs	35.5 ± 1.2 ^{b,j}	0.10031 (da)	38	NREL (10/17)	NREL 2-junction (2J) ⁷²
<u>Minimodule</u>					
GaInP/GaAs; GaInAsP/GaInAs	43.4 ± 2.4 ^{b,k}	18.2 (ap)	340 ^l	FhG-ISE (7/15)	Fraunhofer ISE 4J (lens/cell) ⁷³
<u>Submodule</u>					
GaInP/GaInAs/Ge; Si	40.6 ± 2.0 ^k	287 (ap)	365	NREL (4/16)	UNSW 4J split spectrum ⁷⁴
<u>Modules</u>					
Si	20.5 ± 0.8 ^b	1875 (ap)	79	Sandia (4/89) ^l	Sandia/UNSW/ENTECH (12 cells) ⁷⁵
Three Junction (3J)	35.9 ± 1.8 ^m	1,092 (ap)	N/A	NREL (8/13)	Amonix ⁷⁶
Four Junction (4J)	38.9 ± 2.5 ⁿ	812.3 (ap)	333	FhG-ISE (4/15)	Soitec ⁷⁷
<u>Hybrid module^o</u>					
4-Junction (4J)/bifacial c-Si	34.2 ± 1.9 ^{b,o}	1,088 (ap)	CPV/PV	FhG-ISE (9/19)	FhG-ISE (48/8 cells; 4T) ⁷⁸
<u>“Notable exceptions”</u>					
Si (large area)	21.7 ± 0.7	20.0 (da)	11	Sandia (9/90) ^l	UNSW laser grooved ⁷⁹
Luminescent Minimodule ^o	7.1 ± 0.2	25 (ap)	2.5 ^p	ESTI (9/08)	ECN Petten, GaAs cells ⁸⁰
4J Minimodule	41.4 ± 2.6 ^b	121.8 (ap)	230	FhG-ISE (9/18)	FhG-ISE, 10 cells ⁸¹

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.⁸²

Abbreviations: (ap), aperture area; CIGS, CuInGaSe₂; (da), designated illumination area; Effic., efficiency; FhG-ISE, Fraunhofer-Institut für Solare Energiesysteme; NREL, National Renewable Energy Laboratory.

^aOne sun corresponds to direct irradiance of 1000 W m⁻².

^bNot measured at an external laboratory.

^cSpectral response and current-voltage curve reported in Version 60 of these tables.

^dMeasured under a low aerosol optical depth spectrum similar to ASTM G-173-03 direct.⁸³

^eSpectral response and current-voltage curve reported in Version 44 of these tables.

^fSpectral response and current-voltage curve reported in Version 54 of these tables.

^gSpectral response and current-voltage curve reported in the present version of these tables.

^hSpectral response and current-voltage curve reported in Version 46 of these tables.

ⁱSpectral response and current-voltage curve reported in Version 42 of these tables.

^jSpectral response and current-voltage curve reported in Version 51 of these tables.

^kDetermined at IEC 62670-1 CSTC reference conditions.

^lRecalibrated from original measurement.

^mReferred to 1000 W/m² direct irradiance and 25°C cell temperature using the prevailing solar spectrum and an in-house procedure for temperature translation.

ⁿMeasured under IEC 62670-1 reference conditions following the current IEC power rating draft 62670-3.

^oThermodynamic 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.

The hybrid module was a 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, 60904-5, 60904-7, and 60904-10 and 60891 with modified current translation approach; rear power rating of flat plate PV based on IEC TS 60904-1-2 and 60891.

^pGeometric concentration.

(readers identifying improved references are welcome to submit to 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 new result in Table 1 (“one-sun cells and submodules”) is 26.8% total area efficiency for a large area silicon cell using the silicon heterojunction (HJT) approach, fabricated on an M6 wafer (274 cm²) by LONGi Solar³ and measured by the Institute für Solarenergieforschung (ISFH). This was a monofacial cell measured on a gold-plated brass chuck with frontside busbar and rearside grid resistance

neglecting contacting.¹ The result improves upon the 26.3% HJT result also from LONGi on an M6 wafer reported in Version 59 of these tables and a further improvement to 26.5% reported in June 2022. In September, Sundrive Solar Pty Ltd reported an intermediate HJT result of 26.4% also confirmed by ISFH, using Cu-plated contacts. These efficiencies are all based on total cell area, and the cells are also much larger than the 26.7% former outright record-holding cell, with this cell result now moved to Table 2 as the highest-performing interdigitated back contact (IBC) cell.

The second new result in Table 1 is 22.4% efficiency for a 26-cm² perovskite minimodule¹⁷ (a package of interconnected cells of area <200 cm²) fabricated by École Polytechnique Fédérale de Lausanne, Sion campus (EPFL-Sion) in conjunction with the North China Electric Power University (NCEPU) and measured by the Chinese National Photovoltaic Industry Measurement and Testing Center (NPVM), improving on the previous 21.4% result.

There is one new result in Table 2 (one-sun “notable exceptions”). LONGi issued a press release³⁵ in September 2022 reporting that 26.1% efficiency has been measured by ISFH for a large-area (274 cm²) gallium-doped p-type silicon cell using LONGi's silicon heterojunction (HJT) approach. In October, this was further improved to 26.6%, narrowing the gap to the outright n-type cell record. This result was for a bifacial cell, measured on a reflective gold-plated brass chuck with frontside busbar and rearside grid resistance neglecting contacting.¹ This is the highest ever efficiency reported for a cell on a p-type wafer.

There are two new results reported in Table 3 relating to one-sun, multijunction devices, all involving perovskite solar cells in various combinations, demonstrating the strength of this technology notwithstanding concerns re long-term stability and toxicity. The first of these new results is 31.3% efficiency for a 1-cm² perovskite/silicon monolithic two-junction, two-terminal device fabricated by EPFL PVLAB/CSEM and measured by the US National Renewable Energy Laboratory (NREL). This is the first perovskite tandem cell to exceed the 30% milestone. The second is 24.5% efficiency measured for a

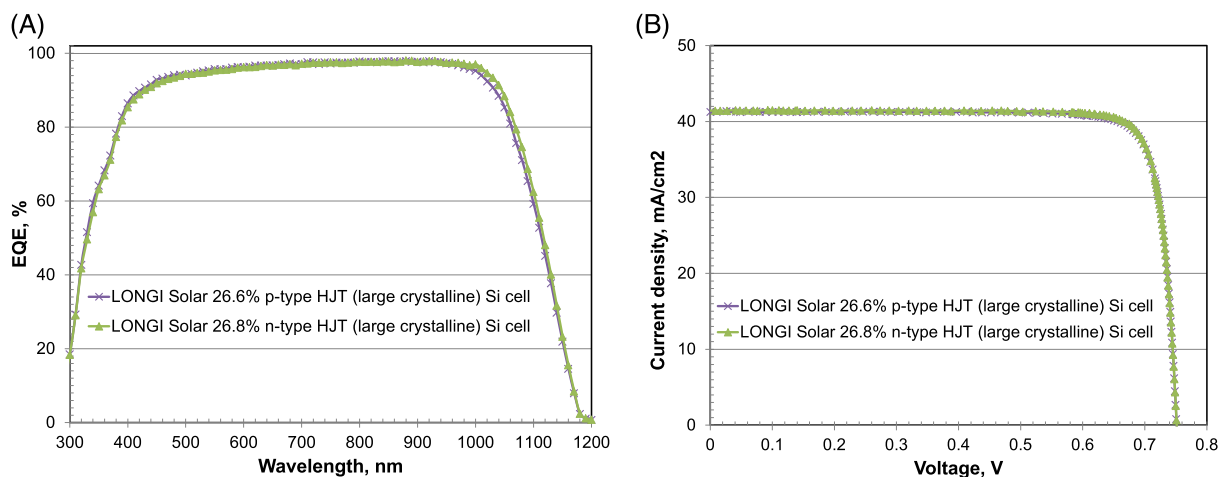


FIGURE 1 (A) External quantum efficiency (EQE) for the new Si cell results reported in this issue. (B) Corresponding current density–voltage (JV) curves

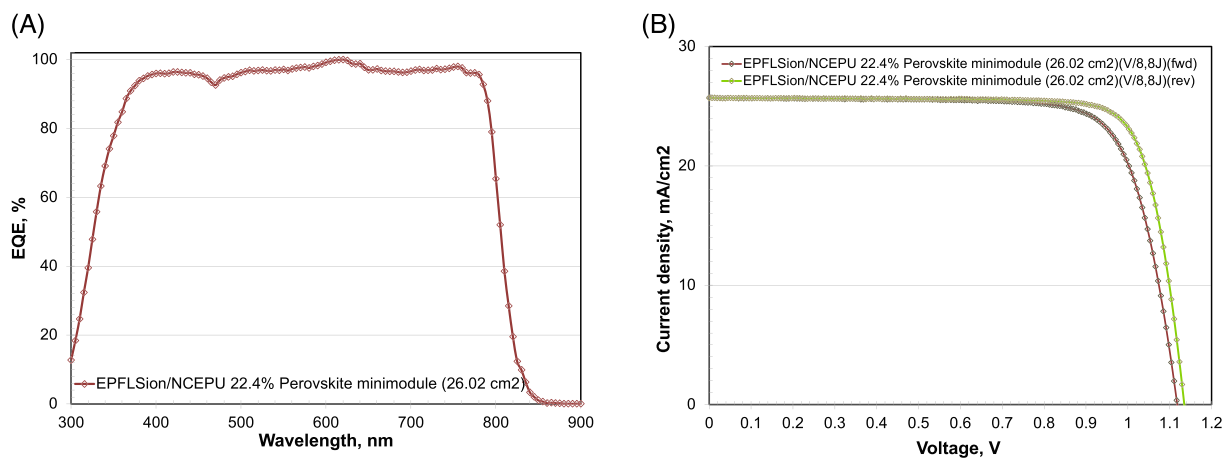


FIGURE 2 (A) External quantum efficiency (EQE) for the new thin-film cell and minimodule results reported in this issue (some results are normalised). (B) Corresponding current density-voltage (JV) curves

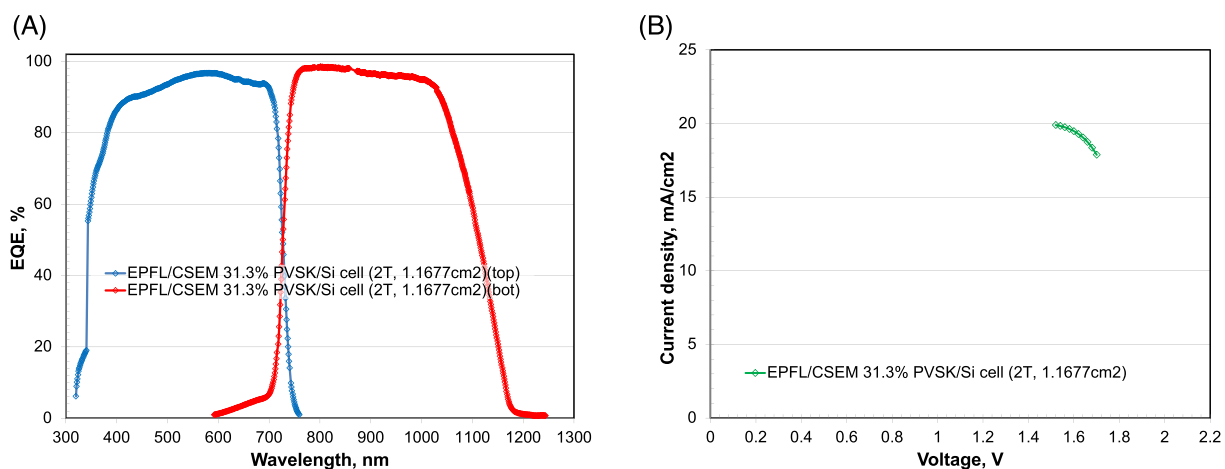


FIGURE 3 (A) External quantum efficiency (EQE) for the new multijunction cell results reported in this issue (all results are normalised). (B) Corresponding current density-voltage (JV) curves

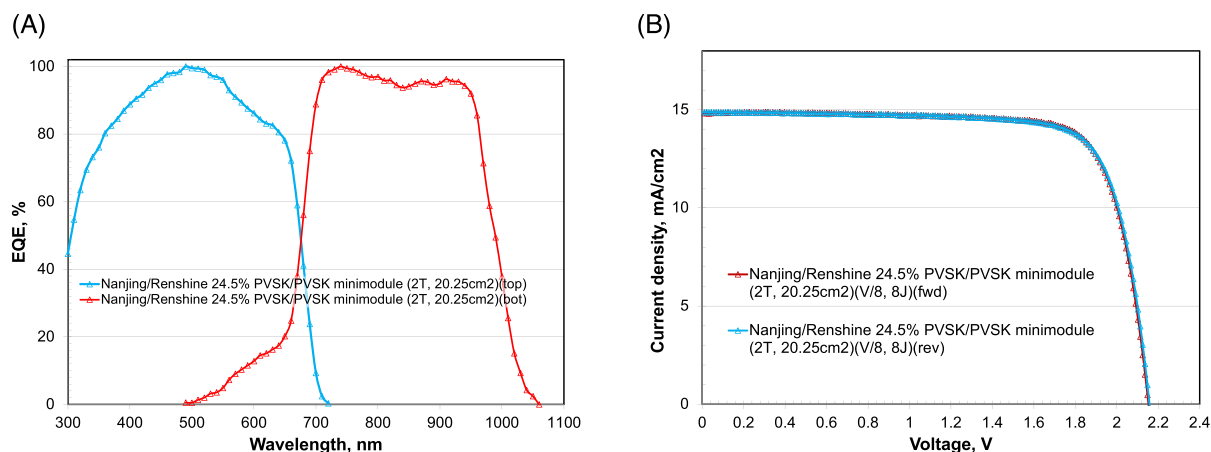


FIGURE 4 (A) External quantum efficiency (EQE) for the new module results reported in this issue (all results are normalised). (B) Corresponding current density-voltage (JV) curves

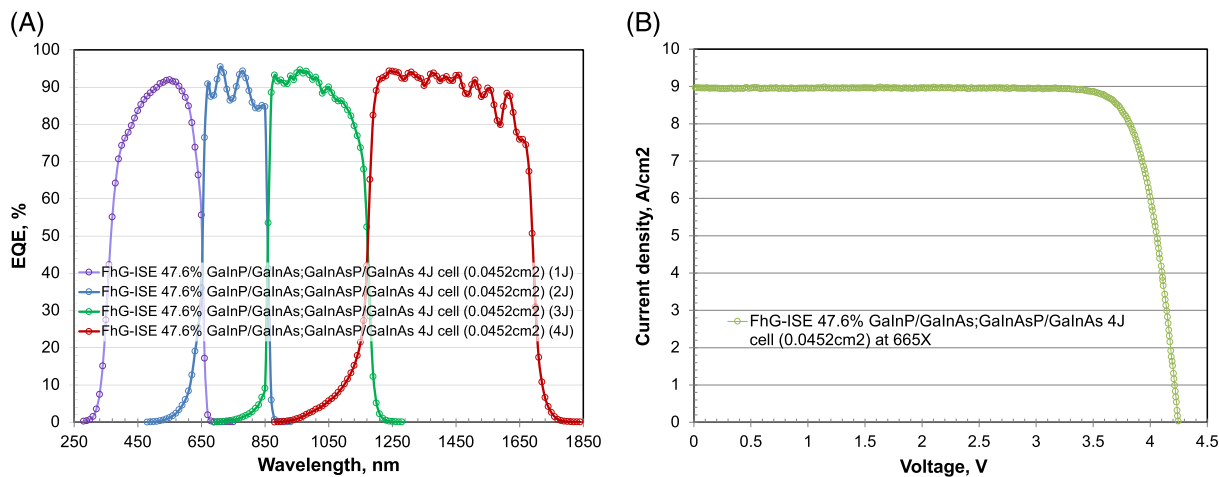


FIGURE 5 (A) External quantum efficiency (EQE) for the new concentrator cell result reported in this issue. (B) Corresponding current density–voltage (JV) curve

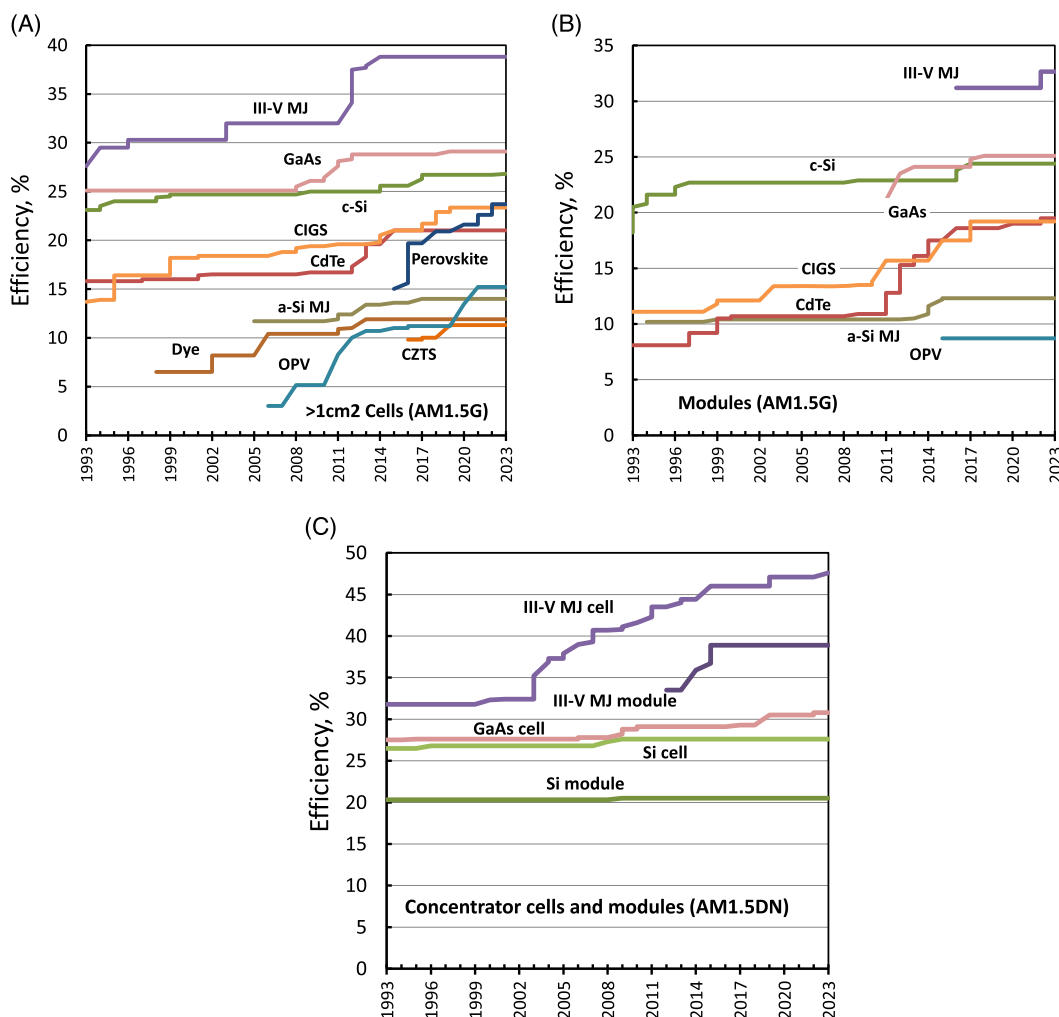


FIGURE 6 Thirty years of progress: (A) highest confirmed efficiencies for $\geq 1\text{-cm}^2$ area cells fabricated using the different technologies shown; (B) highest confirmed module results for modules sizes $\geq 800\text{ cm}^2$; (C) highest confirmed concentrator cell and module results

20-cm² perovskite/perovskite two-junction, two-terminal minimodule fabricated by Nanjing University and Renshine Solar (Suzhou) Co. Ltd and measured by the Japan Electrical Safety and Environment Technology Laboratories (JET), improving significantly on the team's earlier 21.7% result.

The final new result is in Table 5 (concentrator cells and modules) and documents an improvement to 47.6% efficiency for a four-junction, wafer-bonded concentrator cell based on Group III-V cell technology, with the cell fabricated and measured by the Fraunhofer Institute for Solar Energy Systems (FhG-ISE). This is the highest ever efficiency for a concentrator cell. It should be noted such concentrator cell efficiencies are not directly comparable with the efficiencies of non-concentrating cells, since the former are not true thermodynamic efficiencies (diffuse light that cannot be concentrated is not included into the efficiency definition).

The EQE spectra for the new silicon cells 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 same devices. Figure 2A,B shows the corresponding EQE and JV curves for the new thin-film cell minimodule results, Figure 3A,B shows these for the new multijunction cell results, and Figure 4A,B show these for the new module results while Figure 5A,B shows these for the new GaAs concentrator cell result.

3 | PROGRESS OVER THE LAST 30 YEARS

Figure 6 reports 30 years of progress in confirmed cell and module efficiencies since the first version of these tables was published in 1993. Figure 6A shows the progress with ‘one-sun’ cells of $\geq 1\text{-cm}^2$ area. Recent progress with organic, perovskite and CdTe cells has been most notable, with good progress also with CIGS. Figure 6B shows similar progress with photovoltaic modules with CdTe and CIGS being the recent standouts. Figure 6C 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 47.6% over the 30-year period (efficiency, in this case, is boosted relative to results in Figure 6A,B since based on only the direct normal component of the solar spectrum, with the diffuse component neglected in the efficiency calculation as previously mentioned).

4 | 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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APPENDIX A: AREA DEFINITIONS

The area of the cell or module is a key parameter in determining efficiency. The areas used in the tables conform to one of the three following classifications illustrated in Figure A1:

- i. **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.

- ii. **Aperture area:** The portion of the total cell or module area that includes all essential components, including active material, busbars, fingers and interconnects.

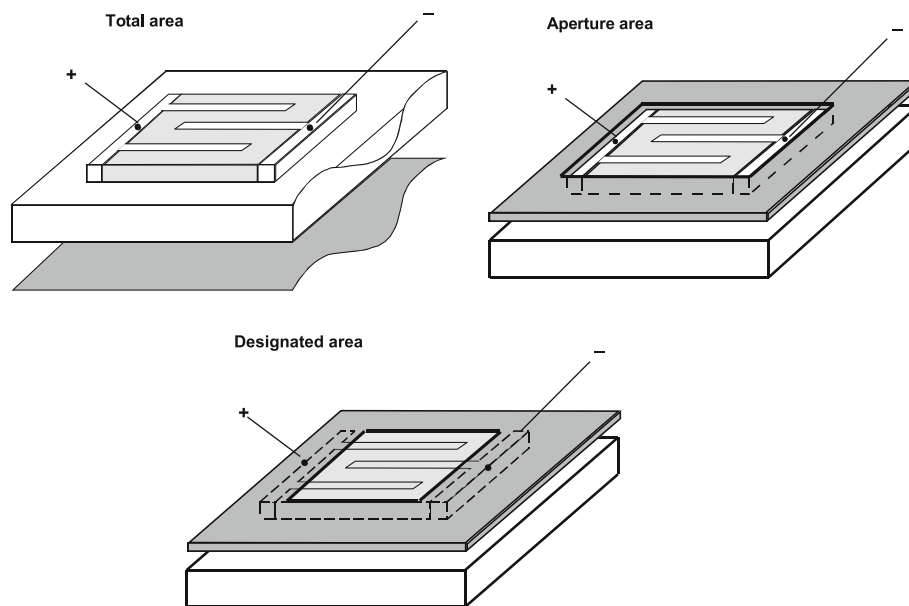


FIGURE A1 Area classifications: “Total area” (shown grey), “Aperture area” and “Designated illumination area” (the latter two areas are the areas not covered by the mask; masking is not required if the test centre is satisfied that there is no response from the areas shown masked; areas should have a simple non-convoluted geometry such as square, rectangular or circular)

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. Note that the assigned aperture area must have a simple geometry, such as square, rectangular or circular.

iii. 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. Note that the assigned designated illumination area must have a simple geometry, such as square, rectangular or circular.

APPENDIX B: LIST OF DESIGNATED TEST CENTRES

A list of designated test centres follows. The 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.

Commonwealth Scientific and Industrial Research Organization (CSIRO)

PV Performance Laboratory
 10 Murray Dwyer Circuit, Mayfield West, NSW 2304, Australia.
 Contact: Dr Chris Fell
 Phone: +61 (2) 4960 6000
 Email: chris.fell@csiro.au
 (Perovskite and thin-film solar cells)

European Solar Test Installation (ESTI)

European Commission – Joint Research Centre, Ispra (VA), Italy.
 Contact: Dr Ewan Dunlop
 Telephone: +39 332-789090
 Facsimile: +39 332-789-268
 E-mail: esti.services@jrc.ec.europa.eu
 (Cells and modules)

Fraunhofer-Institut für Solare Energiesysteme ISE - ISE Callab

Heidenhofstr. 2, D-79110 Freiburg, Germany.
 Contacts:
 Dr Jochen Hohl-Ebinger (terrestrial cells, tandem cells)
 Phone: +49 (0) 761 4588-5359
 Facsimile: +49 (0) 761 4588-9359
 E-mail: jochen.hohl-ebinger@ise.fraunhofer.de

Dr Gerald Siefer (space and concentrator cells and modules, tandem devices)
 Phone: +49 (0) 761 4588-5433
 E-mail: gerald.siefer@ise.fraunhofer.de

Frank Neuberger (terrestrial modules),
Phone: +49 (0) 7614588-5280
Facsimile: +49 (0) 761 4588-9280
E-mail: frank.neuberger@ise.fraunhofer.de

Institut für Solarenergieforschung GmbH (ISFH)

Calibration and Test Center (CaTeC), 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
E-mail: 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 including tandem devices)

National Institute of Advanced Industrial Science and Technology
(AIST)

Central 2, Umezono 1-1-1, Tsukuba, Ibaraki, 305-8568 Japan.
Contact: Dr Masahiro Yoshita
Telephone: +81 29-861-3607
E-mail: m-yoshita@aist.go.jp
(Terrestrial and concentrator cells and modules including tandem devices)

National Photovoltaic Industry Metrology and Testing Center
(NPVM)

9-3, Pingdong Road, Fuzhou City, Fujian Province, China.
Contact: Mr Li Jiansheng
Telephone: +86 0591 8782 5895 or +86 0591 8780 1715
Facsimile: +86 0591 8782 5895
Email: ljs@fjil.net
(Terrestrial silicon and thin-film solar cells)

National Renewable Energy Laboratory (NREL)

15013 Denver West Parkway, Golden, CO 80401, USA.
Contact: Nikos Kopidakis
Telephone: +1 303-384-6605
Facsimile: +1 303-384-6604
E-mail: niko.kopidakis@nrel.gov
(Terrestrial, space and concentrator cells and modules including tandem devices)