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Osbel Almora, Derya Baran, Guillermo C. Bazan, Christian Berger, Carlos I. Cabrera, Kylie R. Catchpole, Sule Erten-Ela, Fei Guo, Jens Hauch, Anita W. Y. Ho-Baillie, T. Jesper Jacobsson, Rene A. J. Janssen, Thomas Kirchartz, Nikos Kopidakis, Yongfang Li, Maria A. Loi, Richard R. Lunt, Xavier Mathew, Michael D. McGehee, Jie Min, David B. Mitzi, Mohammad K. Nazeeruddin, Jenny Nelson, Ana F. Nogueira, Ulrich W. Paetzold, Nam-Gyu Park, Barry P. Rand, Uwe Rau, Henry J. Snaith, Eva Unger, Lídice Vaillant-Roca, Hin-Lap Yip, and Christoph J. Brabec**

Following the 1st release of the *"Emerging photovoltaic (PV) reports"*, the best achievements in the performance of emerging photovoltaic devices in diverse emerging photovoltaic research subjects are summarized, as reported in peer-reviewed articles in academic journals since August 2020. Updated graphs, tables, and analyses are provided with several performance parameters, e.g., power conversion efficiency, open-circuit voltage, short-circuit current density, fill factor, light utilization efficiency, and stability test energy yield. These parameters are presented as a function of the photovoltaic bandgap energy and the average visible transmittance for each technology and application and are put into perspective using, e.g., the detailed balance efficiency limit. The 2nd instalment of the *"Emerging PV reports"* extends the scope toward tandem solar cells and presents the current state-of-the-art in tandem solar cell performance for various material combinations.

1. Introduction

Unlike established photovoltaic (PV) technologies (e.g., silicon and inorganic thin film solar cells) already in the market, emerging photovoltaic (e-PV) technologies are mostly in the research phase and include—but are not limited to—organic (OPV), dye sensitized (DSSCs), and perovskite solar cells (PSCs), made from polymers, molecules, or (colloidal) precursors, among many other material classes like the oxides, chalcogenides, or silicides. The focus of e-PVs is not restricted to supplying green electricity to the grid, but it also aims at providing alternatives to Si in applications beyond the utility-scale

O. Almora
Institute of Advanced Materials
Universitat Jaume I
Castelló 12006, Spain
E-mail: osbel.almora@fau.de

O. Almora, C. J. Brabec
Erlangen Graduate School of Advanced Optical Technologies (SAOT)
91052 Erlangen, Germany
E-mail: christoph.brabec@fau.de

O. Almora, C. J. Brabec
Institute of Materials for Electronics and Energy Technology (i-MEET)
Friedrich-Alexander-Universität Erlangen-Nürnberg
91058 Erlangen, Germany

D. Baran
King Abdullah University of Science and Technology (KAUST)
Division of Physical Sciences and Engineering (PSE)
KAUST Solar Center (KSC)
Thuwal 23955, Saudi Arabia

The ORCID identification number(s) for the author(s) of this article can be found under https://doi.org/10.1002/aenm.202102526.

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G. C. Bazan
Departments of Chemistry and Chemical Engineering
National University of Singapore
Singapore 117543, Singapore

C. Berger
TREVISTO AG
90489 Nuremberg, Germany

C. Berger, J. Hauch, C. J. Brabec
Forschungszentrum Jülich GmbH
Helmholtz-Institut Erlangen-Nürnberg for Renewable Energy (HI ERN)
91058 Erlangen, Germany

C. I. Cabrera
Unidad Académica de Ciencia y Tecnología de la Luz y la Materia
Universidad Autónoma de Zacatecas
Zacatecas 98160, Mexico

K. R. Catchpole
Research School of Electrical
Energy and Materials Engineering
The Australian National University
Canberra 2601, Australia

S. Erten-Ela
Ege University
Solar Energy Institute
Bornova, Izmir 35100, Turkey

F. Guo

market and to provide solutions for integration into buildings, greenhouses, airplanes, sails, automobiles, fabrics, or indoor applications that require flexible and semitransparent devices. Some of these applications tend to sacrifice efficiency to obtain additional functionalities (such as flexibility, low weight or transparency).

Institute of New Energy Technology
College of Information Science and Technology
Jinan University
Guangzhou 510632, China

A. W. Y. Ho-Baillie
School of Physics and The University of Sydney Nano Institute
The University of Sydney
Sydney, NSW 2006, Australia

T. J. Jacobsson, E. Unger
HySPRINT Innovation Lab (Young Investigator Group Hybrid Materials Formation and Scaling)
Helmholtz Zentrum Berlin
Kekuléstrasse 5, 12489 Berlin, Germany

T. J. Jacobsson
Institute of Photoelectronic Thin Film Devices and Technology
Nankai University
Tianjin 300350, China

R. A. J. Janssen
Molecular Materials and Nanosystems and Institute for Complex Molecular Systems
Eindhoven University of Technology
Eindhoven 5600 MB, The Netherlands

R. A. J. Janssen
Dutch Institute for Fundamental Energy Research
De Zaale 20, Eindhoven 5612 AJ, The Netherlands

T. Kirchartz, U. Rau
IEK5-Photovoltaics
Forschungszentrum Jülich
52425 Jülich, Germany

T. Kirchartz
Faculty of Engineering and CENIDE
University of Duisburg-Essen
47057 Duisburg, Germany

N. Kopidakis
PV Cell and Module Performance group
National Renewable Energy Laboratory (NREL)
Denver West Parkway, 15313, Golden, CO 80401, USA

Y. Li
School of Chemical Science
University of Chinese Academy of Sciences
Beijing 100049, China

Y. Li
Beijing National Laboratory for Molecular Sciences
CAS Key Laboratory of Organic Solids
Institute of Chemistry
Chinese Academy of Sciences
Beijing 100190, China

M. A. Loi
Photophysics and OptoElectronics Group
Zernike Institute for Advanced Materials
University of Groningen
Nijenborgh 4, Groningen NL-9747 AG, The Netherlands

R. R. Lunt
Department of Chemical Engineering and Materials Science
Department of Physics and Astronomy
Michigan State University
East Lansing, MI 48824, USA

X. Mathew
Instituto de Energías Renovables
Universidad Nacional Autónoma de México
Temixco, Morelos 62580, México

M. D. McGehee
Department of Chemical and Biological Engineering
and Materials Science and Engineering Program
University of Colorado
Boulder, CO 80309, USA

M. D. McGehee
National Renewable Energy Laboratory
15013 Denver West Parkway, Golden, CO 80401, USA

J. Min
The Institute for Advanced Studies
Wuhan University
Wuhan 430072, China

J. Min
Key Laboratory of Materials Processing and Mold (Zhengzhou University)
Ministry of Education
Zhengzhou 450002, China

D. B. Mitzi
Department of Mechanical Engineering and Material Science
and Department of Chemistry
Duke University
Durham, NC 27708, USA

M. K. Nazeeruddin
Group for Molecular Engineering and Functional Materials
Ecole Polytechnique Fédérale de Lausanne
Institut des Sciences et Ingénierie Chimiques
Sion CH-1951, Switzerland

J. Nelson
Department of Physics
Imperial College London
London SW7 2BZ, UK

A. F. Nogueira
Chemistry Institute
University of Campinas
PO Box 6154, Campinas, São Paulo 13083-9 70, Brazil

U. W. Paetzold
Institute of Microstructure Technology (IMT)
Karlsruhe Institute of Technology (KIT)
76344 Eggenstein-Leopoldshafen, Germany

U. W. Paetzold
Light Technology Institute (LTI)
Karlsruhe Institute of Technology (KIT)
76131 Karlsruhe, Germany

N.-G. Park
School of Chemical Engineering
Sungkyunkwan University
Suwon 16419, South Korea

B. P. Rand
Department of Electrical Engineering and Andlinger Center for Energy and the Environment
Princeton University
Princeton, NJ 08544, USA

H. J. Snaith
Clarendon Laboratory
Department of Physics
University of Oxford
Oxford OX1 3PU, UK

L. Vaillant-Roca
Photovoltaic Research Laboratory
Institute of Materials Science and Technology – Physics Faculty
University of Havana
Havana 10400, Cuba

H.-L. Yip
Department of Materials Science and Engineering
and Hong Kong Institute for Clean Energy
City University of Hong Kong
Tat Chee Avenue, Kowloon 999077, Hong Kong

C. J. Brabec
Zernike Institute for Advanced Materials University of Groningen
Groningen 9747, The Netherlands

Published in November, 2020, the first version of the emerging PV reports (e-PVr)[1] survey provided a reference for good practices and state-of-the-art reports as published in academic journals with data about the best performing devices in the research of e-PV devices. In this context, we report not only the performance of the best e-PV devices (e.g., see Green et al.[2]) but put the performance data into perspective by comparing the devices in certain categories defined by the class of absorber material or the application. Notably, the e-PVr lists and displays the performance parameters of the top efficiency cells for each technology and at each absorber material bandgap energy. Accordingly, the data are put into perspective with the corresponding theoretical limit in the detailed balance (DB)[3] model. Moreover, in addition to stating efficiency records for different technologies and bandgaps, we present the most operationally stable devices as well as the best performing devices in the sub-categories of flexible and transparent/semitransparent cells.

The criteria for inclusion in the e-PVr require that the data should be published in a peer-reviewed academic journal with a proper method section that allows experimental reproduction of the result as well as enough data to perform self-consistency checks. For the efficiency values, the current density–voltage (J–V) curve measured under standard conditions and the external quantum efficiency (EQE) spectra should be presented and should be consistent insofar that the short-circuit current density J_{sc} determined from both methods should not differ by more than 10%. The reporting of 5 min maximum power point (MPP) tracking is encouraged. For flexible and transparent/semitransparent devices evidence of the bending radius and the transmittance (T) spectra should be provided, respectively. In the case of operational stability test results, the initial and final efficiencies before and after 200 or 1000 h are expected to be specified in the published manuscript. Exceptionally, for properly described operational stability tests with a duration 500 h $\leq \Delta\tau <$ 1000 h, an extrapolation toward the performance at 1000 h can be considered for representation purposes. In addition, articles lacking some of the mandatory requirements to be included in the e-PVr could be reconsidered, provided an extended or additional supporting information document to be posted in the *emerging-pv.org* website. Further details on the accuracy, performance parameters, discarding and tie rules can be found in the previous e-PVr[1] and in Sections S1.5 and S1.6 of the Supporting Information.

The innovation factor $0 \leq InF < 1$ is first introduced here in Equation (8), defined as a ratio of the number of the new record performance cells published in research articles with respect to both, the total of record cells in a category and the total overall categories. The use of InF is meant to inform on the current status of the PV field and is most useful to compare our different categories of attention. Notably, the InF is a statistical figure of merit based on the set of inclusion criteria of the e-PVr initiative, which may evolve in future versions of our surveys.

The optimization factor OpF is also first introduced here in Equation (9), accounting for both the performance increment and the corresponding theoretical detailed-balance[3–5] optimization limit. For instance, between two optimized cells which increased 1% efficiency with respect to their respective references, the closer to the efficiency limit the higher the OpF. Unlike most typical relative optimization percentages, the OpF avoids common artifacts, such as overestimation due to low reference values. It also allows comparison between any performance enhancement with respect to the same selection criteria for the reference value. In the following, we define the absorption onset of the solar cells as the main criterion for considering an optimization. Note that, a new optimized cell is included in our tables when either there was no previous performance record at the corresponding E_g value or the new record reports higher values than those at $E_g \pm 10$ meV. Accordingly, some new record cells will not be considered by OpF due to their novelty in terms of absorption onset. Therefore, for a new record performance cell at E_g we consider it an optimization of the reference cell with the highest of the lower previous performance records in the range of the thermal energy $E_g \pm k_B T$. Furthermore, the definition (9) makes $0 \leq OpF \leq 1$ and values slightly >1 would indicate full optimization with a E_g change in $\pm k_B T$.

Table 1 summarizes the equations, definitions, and useful references already tackled in the previous e-PVr and now updated in the current version, whereas Table S1 in the Supporting Information summarizes the minimal details to include in a research article to be considered in an e-PVr.

Similarly to the previous e-PVr,[1] each section includes the best performing cells as reported in the literature and grouped in different technologies or material families. The corresponding abbreviations are summarized in **Table 2**. Note that as a novelty, monolithic/2-terminal tandem cells are also included in the next sections. Here being the top-cell that with the higher absorber material bandgap energy ($E_{g,top}$) receives the total incident photon flux, while the bottom-cell with the lower absorber material bandgap energy ($E_{g,bottom}$) receives the filtered incident photon flux, that is transmitted by the top-cell.

In this article, the updated graphs and tables of the best performing research solar cells are presented with the latest reports since August, 2020. In the plot representations (Sections 2–5), older and newer values are displayed with lighter and opaquer dot colors, respectively. Similarly, new entries are a bold case in the tables (Appendix).

2. Highest Efficiency Research Solar Cells

The top efficiency single junction research cells are summarized in **Figure 1** as a function of the PV bandgap, along with the detailed-balance theoretical efficiency limit[3] for a single junction assuming radiative emission from the front and rear side of the solar cell.[10] The new entries in the database are highlighted in opaquer colors. In total, 59 out of 273 single junction top efficiency cells are new in the chart, implying that we have 22% new record performance reports within less than 1 year. This rate of progress is impressive and underlines the rapid development of emerging PV technologies.

Among new PSCs entries, we want to highlight the increased interest in narrow bandgap (1.28–1.36 eV) devices with a new absolute efficiency record of Sn-based PSCs of 21.7% (certified 20.7%).[11] This optimization (OpF = 6.8%) was due to the introduction of strongly reductive surface-anchoring zwitterionic molecules which inhibit Sn^{2+} oxidation and passivate defects at the grain surfaces in mixed lead–tin perovskite films. Moreover,

Table 1. Equations and definitions considered in this work.

No.	Equation	Definitions and comments	Ref.
(1)	$PCE = \frac{P_{out}}{P_{in}} = \frac{V_{oc} \cdot J_{sc} \cdot FF}{P_{in}}$	*PCE*, power conversion efficiency; P_{out}, output power density, P_{in}, incoming power density; V_{oc}, open-circuit voltage; J_{sc}, short-circuit current density; *FF*, fill factor	[1]
(2)	$EQE = \frac{A_m}{1+\exp[\kappa(\lambda - hc/E_g)/\lambda_s]}$	Procedure to determine E_g from the $EQE(\lambda)$ spectrum: *EQE*, external quantum efficiency; λ, wavelength; A_m, maximum *EQE* value just above the bandgap absorption threshold; *h*, Planck's constant; *c*, speed of light; E_g, photovoltaic bandgap energy; λ_s, sigmoid wavelength width parameter (*EQE* onset quality wavelength), $\kappa = \ln[7+4\sqrt{3}] \approx 2.63$	[6]
(3)	$\frac{PCE^{real}}{PCE^{ideal}} = \frac{J_{sc}^{real}}{J_{sc}^{ideal}} \frac{V_{oc}^{real}}{V_{oc}^{ideal}} \frac{FF^{real}}{FF^{ideal}}$	The "real" superscript refers to the experimental values; the "ideal" superscript refers to the ideal limit of each performance parameter as in the detailed-balance models[3–5]	[7]
(4)	$AVT = \frac{\int T(\lambda) P(\lambda) \Gamma_{AM1.5G}(\lambda) d\lambda}{\int P(\lambda) \Gamma_{AM1.5G}(\lambda) d\lambda}$	*AVT*, average visible transmittance; *T*, transmittance; *P*, photopic response of the human eye; $\Gamma_{AM1.5G}$ is the standard 1 sun illumination intensity AM1.5G spectrum, typically in units of W m^{-2} nm^{-1}	[8]
(5)	$LUE = AVT \cdot \text{PCE}$	*LUE*, light utilization efficiency	[9]
(6)	$E_{\Delta\tau} = \int_0^{\Delta\tau} P_{out} dt = \int_0^{\Delta\tau} P_{in}\ PCE\ dt$	$\Delta\tau$, operational stability test time; $E_{\Delta\tau}$, operational stability test energy yield (STEY) for a test of duration $\Delta\tau$; *t*, time; STEY is taken for 200 and 1000 h of stability tests as E_{200h} and E_{1000h}, respectively	[1]
(7)	$DR_{\Delta\tau} = \frac{PCE(\tau) - PCE(0)}{\Delta\tau}$	$DR_{\Delta\tau}$, effective overall degradation rate for a operational stability test of duration $\Delta\tau$; DR_{200h} and DR_{1000h} are taken as the overall degradation rates for 200 and 1000 h of stability tests, respectively	[1]
(8)	$InF = \frac{NcC^2}{TcC \times TcA}$	*InF*, innovation factor; NcC, new cells in a category; TcC, total of cells in a category, TcA, total of cells among all the categories; the categories can be top *PCE*, flexibility, transparency and stability	
(9)	$OpF = \frac{X_{opt}^{real} - X_{ref}^{real}}{X_{ref}^{ideal} - X_{ref}^{real}}$	*OpF*, optimization factor; X_{opt}^{real}, optimized experimental value of parameter *X*; X_{ref}^{real}, reference experimental value of parameter *X* which is optimized; X_{ref}^{ideal}, theoretical limit in the detailed-balance models[3–5] at the E_g and *T* of X_{ref}^{real}; the parameter *X* can be *PCE*, *LUE*, E_{1000h}	

overall PSCs, two studies top efficiencies with 25.3% (certified 25.2%)[12] and 24.5% (certified 25.2%)[13] since February and April 2021, respectively. In the first one[12] (*OpF* = 1.8%), the electron transport layer (ETL) was optimized by tuning the chemical bath deposition of tin dioxide and the passivation strategy between the bulk and the interface was decoupled while minimizing the bandgap penalty in mixed cation and anion PSCs. The other study[13] was on α-$CH(NH_2)_2PbI_3$-based PSCs (*OpF* = 9.3%) and introduced an anion engineering concept that uses the pseudo-halide anion formate ($HCOO^-$) to augment the crystallinity and to suppress anion-vacancy defects that are present at grain boundaries and at the surface of the films.

For OPVs, most of the results cluster around 1.35 eV, which relates to the most common use of Y6 nonfullerene acceptors and their derivatives as low bandgap acceptor components. Importantly, a new overall OPV efficiency record of 18.3% has been published.[14] This new achievement (*OpF* = 3.9%) was possible because of the addition of neutral Diquat in ternary bulk-heterojunction cells based on PM6:Y6:$PC_{71}BM$. The Diquat acts as an n-type dopant and modifies the morphology of the active layer. The resulting n-doped absorber layers allow the cells to exhibit higher optical absorption coefficients, balanced ambipolar transport, longer carrier lifetimes and suppressed bimolecular recombination.

New record kesterite devices, for their respective E_g, continued to improve V_{oc} along with comparable photocurrent and fill factor enhancements, although rather low V_{oc} on the order of 500 mV and *FF* values below 70% remain as the main issues. Among other technologies, the newest reports on DSSCs and Sb_2Se_3-based solar cells also demonstrated ongoing bandgap variations.

The major novelty of this second e-PVr version is the inclusion of monolithic/2-terminal tandem research cells.[16–18] These devices are composed of two series connected subcells (junctions) whose bandgaps are chosen such that the incoming spectrum is split in (ideally) equal parts. The top junction, with absorber material bandgap energy $E_{g,top}$, receives the total incident light flux and absorbs photons with energy $E > E_{g,top}$, whereas the bottom junction, with absorber material bandgap energy $E_{g,bottom}$, can absorb photons with energy $E_{g,bottom} < E < E_{g,top}$ that are transmitted by the top sub-cell. As a result, both junctions will operate at the same current and the generated photovoltages will add up. Thereby, for a well-designed tandem cell, the efficiency will be able to surpass those of each individual junction. Note that, for each $E_{g,bottom}$ there is an optimal $E_{g,top}$ value that will deliver the highest possible efficiency (lines in top panel of **Figure 2**) and any other $E_{g,top}$ value would result in a reduced performance (contour plots in bottom panel of Figure 2).

Monolithic/2-terminal tandem cells are considered first among the multijunction PVs due to their recent development in efficiency and the fact of being the next step in terms of theoretical and technological complexity after the single junction cells. The rules for including a tandem cell in this and future versions of the e-PVr are those of a single junction device, plus the requirement of providing the *EQE* spectra for evaluation of the $E_{g,top}$ value. It is here implied that the absorption onset of the *EQE* of the full tandem cell will be approximately identical to the *EQE* of the bottom sub-cell.

Table 2. Abbreviations for PV technologies or material families considered in this work.

Abbreviation	Meaning and comments
a-Si:H	Amorphous silicon single junction solar cell; for representation purposes, a-SiGe:H-based single junction cells are exceptionally considered within this abbreviation.
CdTe	Cadmium telluride single junction solar cell
CIGS	$CuIn_xGa_{1-x}Se_2$-based single junction solar cell
CIGS/DSSC	Monolithic/2-terminal tandem solar cell: $CuIn_xGa_{1-x}Se_2$-based bottom junction and dye sensitized top junction
CIGS/perovskite	Monolithic/2-terminal tandem solar cell: $CuIn_xGa_{1-x}Se_2$-based bottom junction and perovskite-based top junction
CZTS	$Cu_2ZnSn(S,Se)_4$-based single junction solar cell
DSSC	Dye sensitized single junction solar cell
DSSC/perovskite	Monolithic/2-terminal tandem solar cell: dye sensitized bottom junction and perovskite-based top junction
GaAs	Gallium arsenide single junction solar cell
GaAs/GaInP	Monolithic/2-terminal tandem solar cell: GaAs-based bottom junction and GaInP-based top junction
GaAs/perovskite	Monolithic/2-terminal tandem solar cell: GaAs-based bottom junction and perovskite-based top junction
nc-Si/a-Si	Monolithic/2-terminal tandem solar cell: nanocrystalline or microcrystalline Si bottom junction and amorphous Si top junction
OPV	Organic photovoltaic material-based single junction solar cell
OPV/a-Si	Monolithic/2-terminal tandem solar cell: organic-based bottom junction and amorphous silicon-based top junction
OPV/perovskite	Monolithic/2-terminal tandem solar cell: the bottom and top junctions are organic- and perovskite-based, respectively or vice versa.
PSC	Perovskite single junction solar cell
SbS	$Sb_2(S,Se)_3$-based single junction solar cell
Si	Monocrystalline or polycrystalline silicon single junction solar cell
Si/DSSC	Monolithic/2-terminal tandem solar cell: Si-based bottom junction and dye sensitized top junction
Si/GaAsP	Monolithic/2-terminal tandem solar cell: Si-based bottom junction and $GaAs_{1-x}P_x$-based top junction
Si/perovskite	Monolithic/2-terminal tandem solar cell: Si-based bottom junction and perovskite-based top junction

The absolute values for efficiency, photocurrent and photovoltages of monolithic tandem solar cells are presented in the top panel of Figure 2 and are put into perspective by comparison to the optimized bandgap DB efficiency limit including radiative coupling.[4,5] The top performance is exhibited by GaAs/GaInP devices, with efficiencies above 30% and an impressive $V_{oc} > 2.5$ V. Other all inorganic technologies such as the Si/GaAsP and the tandem between nano/microcrystalline and amorphous silicon (nc-Si/a-Si) show efficiencies above 20% and 10%, respectively. Among the tandem solar cells presented here, 21 out of 58 emerging cell entries (36%) were published after August 2020. Innovation in single junction materials appears to transfer seamlessly and with rather short delay time for tandem cell incorporation.

The top efficiency emerging tandem solar cells are shown to be those utilizing perovskites as top junction over a silicon bottom cell. These devices are able to deliver J_{sc} and V_{oc} values in the ranges 18–20 mA cm^{-2} and 1.7–1.9 V, respectively, for efficiencies of as high as 25–29%, which represents up to 65% of the top-junction-bandgap-optimized theoretical power conversion efficiency limit (DBtop). The highest published efficiency of a Si/perovskite tandem solar cells has been certified as 29.15% from the MPP tracking and 28.8% from the *J–V* curve.[19] Achieving this top performance (*OpF* = 13%) was primarily attributed to the use of a novel self-assembled methyl-substituted carbazole monolayer as the hole transport layer (HTL) in the perovskite sub-cell. An even higher efficiency of 29.5% for a Si/perovskite device has been reported by Oxford Photovoltaics,[2] but no details on the device structure are known.

Subsequently, with >20% efficiency, all-perovskite tandem cells and those using $CuIn_xGa_{1-x}Se_2$ (CIGS) or GaAs as a bottom junction with perovskite on top offer the next best performance. Among the all-perovskite tandems, the top published efficiency of 25.5% was the result of the above mentioned top optimized Sn-based single junction PSC,[11] with an *OpF* of 5.9%. An even higher efficiency of 26.4% for a perovskite-perovskite tandem is listed in the efficiency tables of Green et al.,[2] but currently there is no further information on the specifics of the cell stack. Also, just below the 24.2% reported by Green et al.,[2] the next top efficiency CIGS/perovskite tandem cell achieved a 23.26% efficiency by introducing new hole-selective contacts self-assembled monolayers (SAMs) for p–i–n PSCs based on carbazole cores with phosphonic acid anchoring groups.[20]

Regarding the V_{oc}, note that only all-perovskite and GaAs/perovskite tandem devices report values >2.0 V among e-PV materials-based tandem cells, resulting in ≈75% of the DBtop. Ranging 14–21% efficiency, best OPV/perovskite and all-organic tandem cells surpass the Si/DSSC best efficiency due to their V_{oc} values above 1.5 V. At the bottom of the efficiency chart, Si/DSSC, all-dye-sensitized, and nc-Si/a-Si devices result in efficiencies not too far from 10%, mainly due to limitations in V_{oc} with values ≈1.5 V.

The optimization level of the top absorber bandgap can be estimated from the bottom panel of Figure 2. The top performing tandem cells, such as GaAs/GaInP, Si/perovskite, all-perovskite, and CIGS/perovskite, are reasonably close to the optimal configuration. Curiously, some of the lowest efficiency devices, such as nc-Si/a-Si and CIGS/DSSC, are the closest to the optimized top bandgap energy configuration. In general, it can be seen that low V_{oc} values are the main issue for the optimization of these devices.

A closer view to the influence of each performance parameter over the efficiency can be found by calculating the logarithmic fractions that parameterize the losses of photovoltage, photocurrent, and fill factor. This concept is presented in **Figure 3** for the absolute highest efficiency in each PV technology. The closer the bars are to the 100% level the more efficient the cell is, and the longer a section in each bar is the higher the corresponding efficiency losses are.

Among the single junction solar cells (Figure 3 left), the updated values are italic highlighted for the $Cu_2ZnSn(S,Se)_4$-based single junction solar cell (CZTS),[15] OPV,[14] and PSC[21] records. Importantly, the new champion PSC is dominantly affected by *FF* losses rather than V_{oc} losses, which seems to be a typical feature among high efficiency PSCs. For instance, the

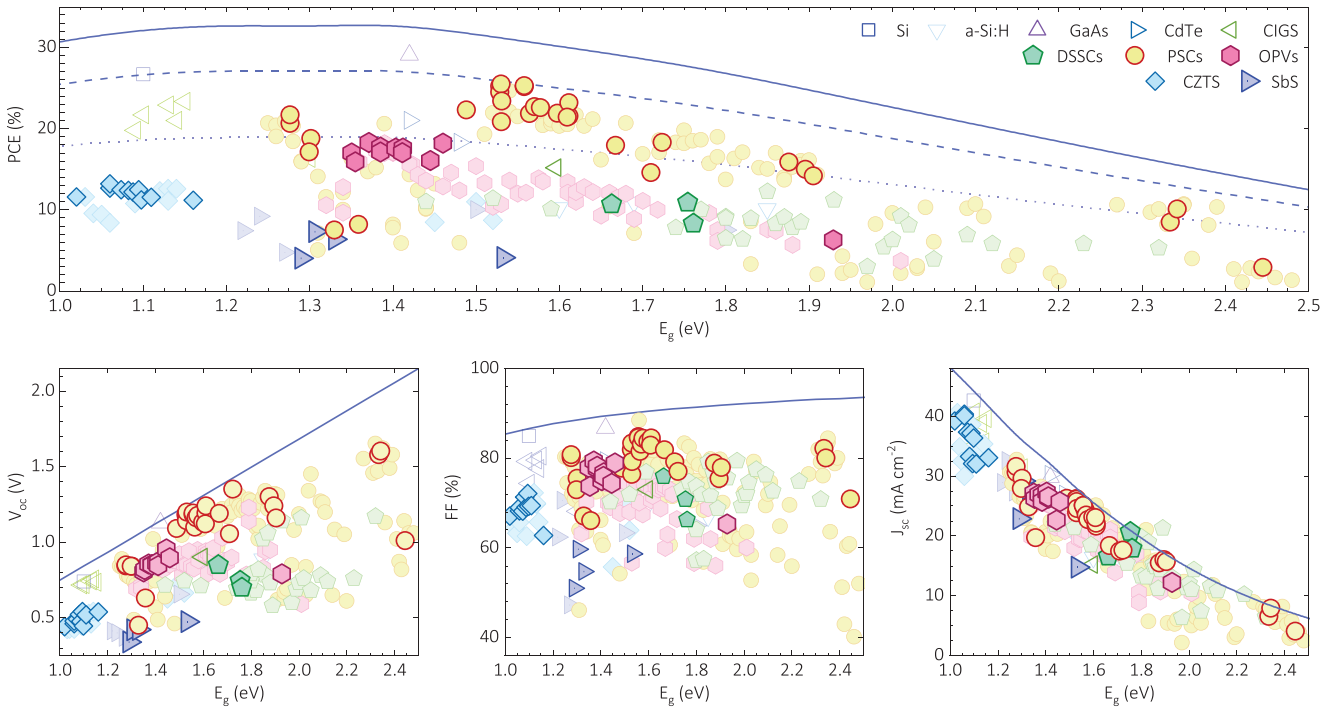

Figure 1. Highest efficiency single junction solar cells. Performance parameters as a function of effective absorber bandgap for different photovoltaic technologies: power conversion efficiency (top) open-circuit voltage (bottom left), fill factor (bottom center), and short-circuit current density (bottom right). Experimental data are summarized in Section A.1, with the lighter and opaquer dots corresponding to the older and updated cells, respectively. The solid, dashed, and dotted lines indicate 100%, 83%, and 58% of the theoretical detailed-balance efficiency limit,[10] respectively.

inset of Figure 3 shows how seven out of ten of the latest PSCs with the highest efficiency (>22%) present *FF* losses larger than the V_{oc} losses. In general, high *FF* losses while low V_{oc} losses (and ideality factor close to 1) have been associated with resistive issues: high series resistance and low shunt resistance.[7] Specifically on PSCs, the insulating nature of some passivation layers needed to boost the V_{oc} increases the series resistance of the cell[22,23] while the high defect densities at the grain boundaries of the perovskite layer lower the shunt resistance.[24] Accordingly, the product $FF \times V_{oc}$ can be suggested as a more useful parameter to compare future performance records in high efficiency PSCs.

In the case of the new champion OPV,[14] interestingly both the photovoltage and photocurrent losses contribute a similar fraction of the total loss. Traditionally, OPVs were long considered to have an intrinsic disadvantage in achieving high V_{oc} values due to band offsets at the donor–acceptor interface that were necessary to compensate for the considerable exciton binding energies of organic semiconductors. However, recent work[25] on nonfullerene acceptors has shown that fairly low nonradiative voltage losses are possible even at small band offsets, thereby reducing voltage losses substantially relative to the situation before the development of high efficiency nonfullerene acceptor based OPVs. Illustratively, Figure 3 reveals that the V_{oc} losses of the best OPV relative to the DB limit are comparable to those of the best CdTe and CIGS solar cells. However, J_{sc} losses are significantly larger for the OPV technology family. These results highlight that it may be timely for the PV community to reshift some part of the research focus to J_{sc} losses.

Among the champion tandem devices, the GaAs/GaInP cells are mostly affected by photocurrent losses, whereas photovoltage losses dominate the efficiency decrease in any other technology. Actually, in some cases the presence of shunts produce extreme photovoltage drops along with J_{sc} increments toward the highest of the photogenerated currents among the two sub-cells.[26–28] For example, this situation occurs for the champion cells of Si/DSSC and DSSC/perovskite (not included in Figure 3), where the J_{sc} exceeds the optimal in the DB efficiency limit, preventing their correct representation in terms of the logarithmic fractions of Equation (3).

The V_{oc} optimization of tandem solar cells must address the challenges from each individual single junction sub-cell, besides those common to the multijunction structure, such as the shunting of sub-cells.[26–28] For instance, low-E_g-perovskite-based devices may present low V_{oc} due to high electronic disorder[29] and large band offsets at the perovskite/ETL interface,[30] whereas wide-E_g-perovskite-based cells can suffer from photoinduced phase segregation[31] and energetic misalignment at the perovskite/HTL interface.[32] For OPV devices, the V_{oc} losses have been associated with the offsets at the donor–acceptor heterojunction and the fast charge recombination in the organic semiconductors.[33,34] For the dye-based cells, the dye regeneration is most probably the largest single source for V_{oc} loss in the device, where more than 200 meV of overpotential can be required to oxidize the electrolyte.[35] For kesterite cells, the crystalline disorder[36] and the high deep defect densities[37] trigger the nonradiative recombination with the consequent detriment of V_{oc}.

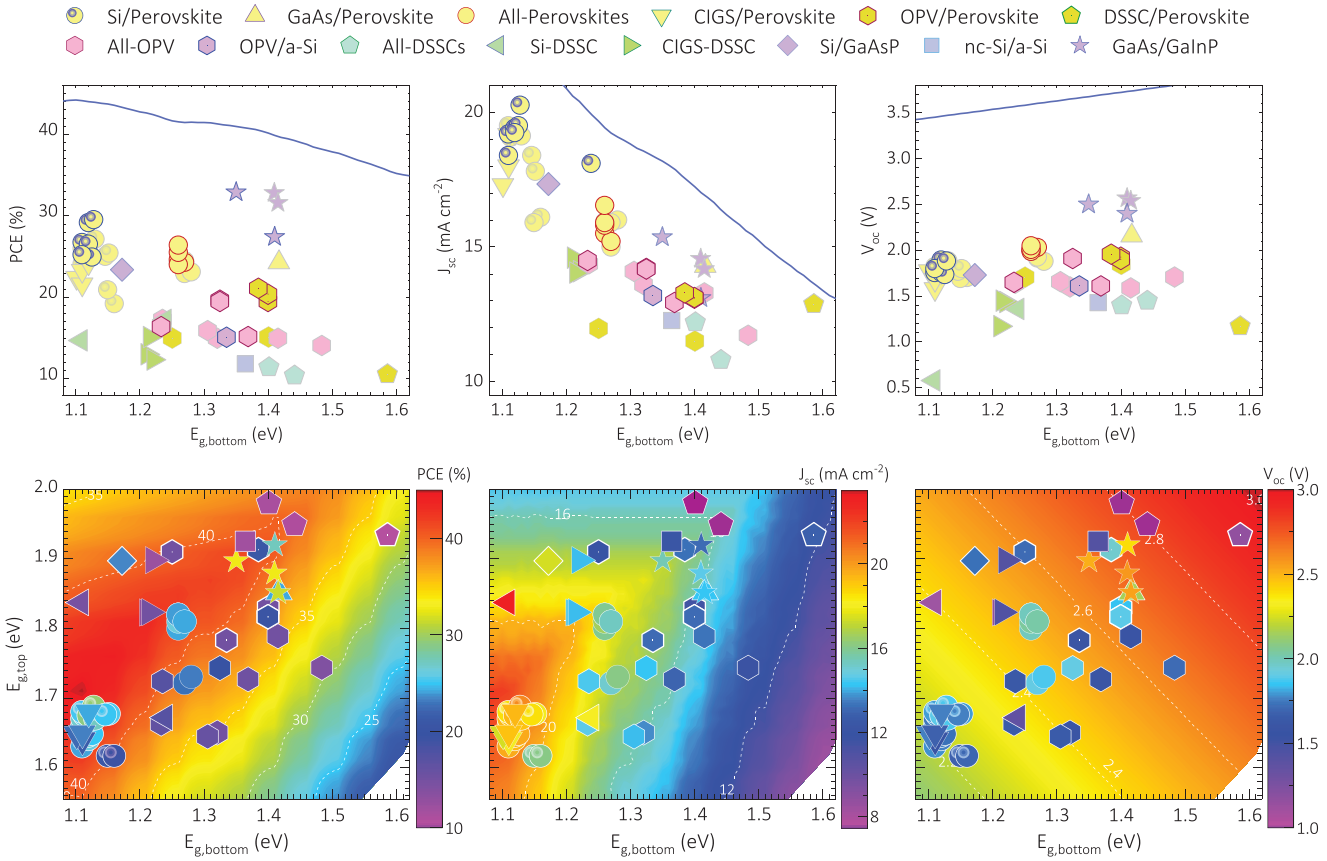

Figure 2. Highest efficiency monolithic/2 terminal tandem solar research cells: Performance parameters as a function of bottom junction absorber bandgap energy for various photovoltaic technologies: power conversion efficiency (left), short-circuit current density (center), and open-circuit voltage (right). The top panel shows the absolute values of each performance parameter in the ordinate axes, including both the experimental data (dots, see Section A.1) and the upper performance limit corresponding to each optimized top junction bandgap energy (solid line).[4,5] The bottom panel comprises different parameters for the top and the bottom junction bandgap energies as the ordinate and abscise axes, respectively. The gray edged dots in the top panel indicate the reports published before August 2020. Unlike the top panel, in the bottom panel the color scales indicate the performance parameter value for both the experimental data (dots) and the theoretical performance limit[4] (contour plots).

3. Flexible PVs: Best Research Solar Cells

The subject of flexible PVs provides the most prominent progress over the last year, with 26 novel entries out of a total of 74 (**Figure 4**), making it up to 35% new entrants. Not only does each emerging PV technology present new champion flexible cells, but the emergence of new approaches is encouraging. For flexible PSCs and OPVs, the latest progress appears in the

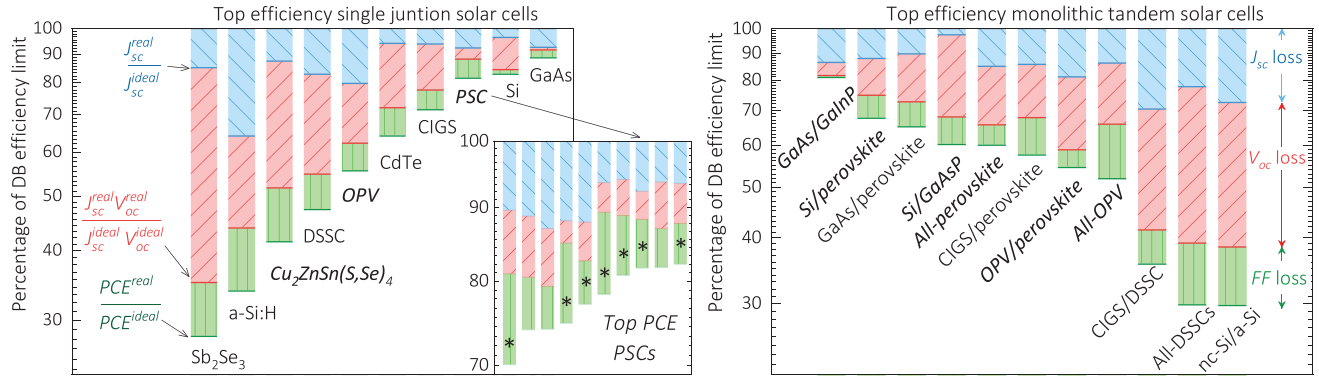

Figure 3. Percentage of detailed balance efficiency limits as defined by Equation (3) for the most efficient single junction[3,10] (left) and monolithic/2-terminal tandem[4] (right) research solar cells of each PV technology. The inset shows the same logarithmic percentages for the latest top-10 efficiency single junction perovskite cells and the asterisk indicates where the fill factor losses are higher than the open-circuit losses. Experimental data are summarized in Section A.1. No tie rules (see Section S1.6, Supporting Information) were considered for this data selection, only the highest efficiency from each technology comparing *PCE*, V_{oc}, *FF*, and J_{sc}, in that order.

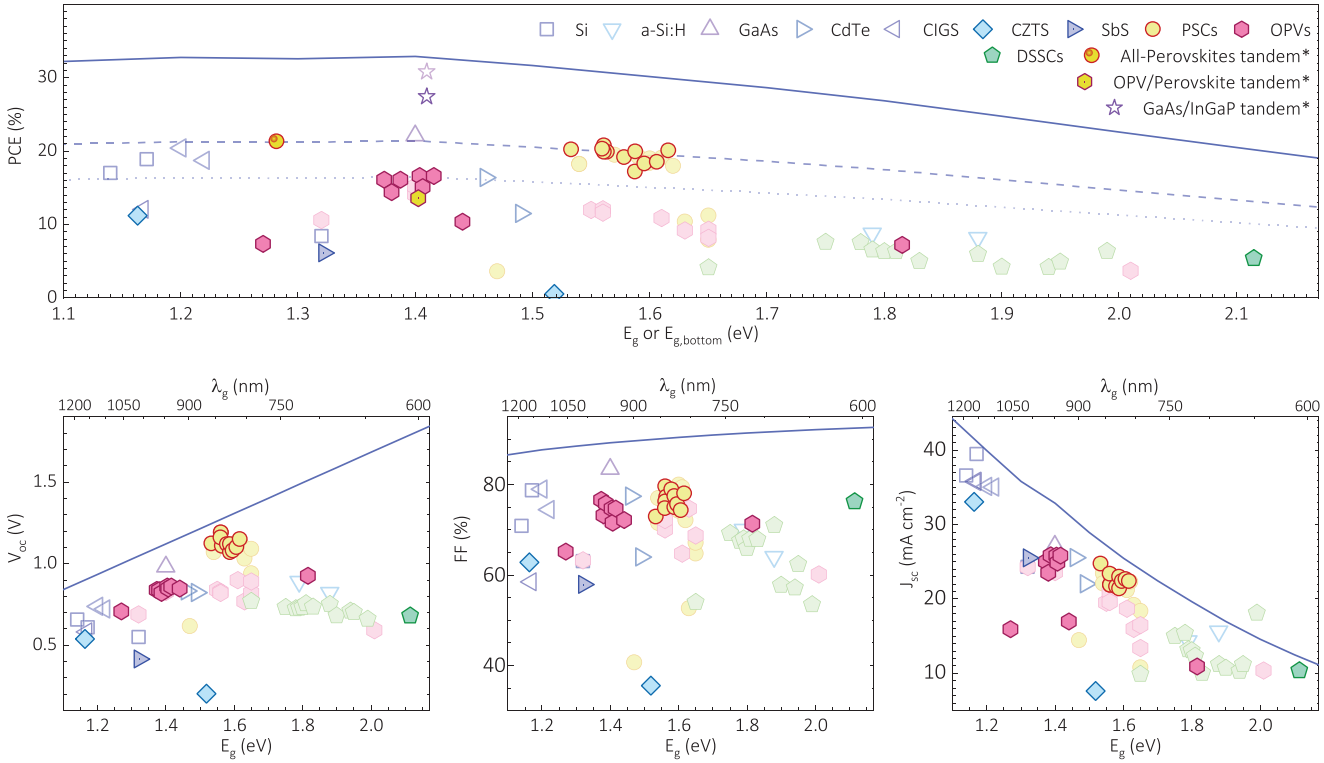

Figure 4. Flexible PVs: Best performance parameters as a function of absorber (or bottom junction absorber in case of tandem devices) bandgap energy for various photovoltaic technologies: power conversion efficiency (top) open circuit voltage (bottom left), fill factor (bottom center), and short-circuit current density (bottom right). Experimental data are summarized in Section A.2 and the solid, dashed, and dotted lines indicate 100%, 65%, and 50% of the theoretical detailed balance efficiency limit,[10] respectively. The tandem cells performance is only included in the efficiency graph.

direction of optimization of already reported material systems, whereas DSSC shows several material approaches. The top efficiency flexible PSC shows a *PCE* of 20.75% (certified 19.9%)[38] and an *OpF* of 11.3% thanks to the introduction of a low temperature processed porous planar Zn_2SnO_4/SnO_2 ETL with a mesoporous structure. Notably, in this work,[38] the authors also managed to fabricate a 360 cm^2 minimodule with 13% efficiency for a remarkable output power per area of 36 μW cm^{-4}. Moreover, the new champion flexible OPV, with an efficiency of 16.61%[39] and an *OpF* of 8%, owes this achievement to the use of a transparent conducting PEDOT:PSS anode doped with trifluoromethanesulfonic acid (CF_3SO_3H), which minimized the energy level mismatch and enhanced charge carrier extraction. Interestingly, $Cu_2ZnSn(S,Se)_4$- and Sb_2Se_3-based flexible solar cells were recently reported with performances in the range of their absolute champion cells (see Figure 1).

Flexible tandem solar cells are another novel category in this report that we present in Figure 4. The efficiencies of flexible GaAs/InGaP and all-perovskite tandem solar cells surpass those of their single junction counterparts, i.e., flexible GaAs and PSCs, respectively.[40,41] On the other hand, the flexible tandem cell with a perovskite absorber on top of an organic based subcell[42] did not yet go beyond the performance of single junction organic solar cells. Interestingly, the latest report of flexible GaAs/InGaP tandem[40] is also presented as a record for highest power-to-weight ratio (specific power) of >5 kW kg^{-1}. The specific power of solar cells must be reasonably high to be used in mobile equipment or wearable devices, which are primary targets for flexible PV applications.

4. Transparent and Semitransparent PVs: Best Research Solar Cells

Transparent and semitransparent PVs have also experienced significant progress recently, resulting in 35 new emerging cell reports out of a total 117 (24%; see **Figure 5**). Most impressively, a new top *LUE* = 5.46% champion transparent solar cell has been reported for an OPV[43] with an efficiency of 9.1% over an AVT of 60% and an *OpF* of 57%. This was the result of an optimization of a sequential deposition process of transport and active layers in PTB7-Th:IEICO-4F-based cells with slot-die coating,[43] which consolidates OPV as the most promising technology in the research field of high *AVT* cells. Compared to the next *LUE* champion, a 2.35 eV bandgap PSC,[44] the organic solar cell had a bandgap of about 1.3 eV, clearly indicating the superiority of selective absorbers for transparent devices.

The DSSCs are also showing new relevant results among the transparent devices, with particular focus on greenhouse integration. The new *LUE* = 2.2% DSSC record (*PCE* = 6.1%, *AVT* = 36%) corresponds to a wavelength-selective device with a low-cost triphenylamine-based dye and a highly transparent iodine-free electrolyte, also achieving a crop growth factor of ≈35%.[45]

New inorganic semitransparent achievements have also been reported, among which CIGS cells are the ones with the best performance of *LUE* = 1.3%. Emerging inorganic semitransparent devices have been demonstrated with $Cu_2ZnSn(S,Se)_4$ and Sb_2S_3-based solar cells with still low performance (*LUE* < 1%).

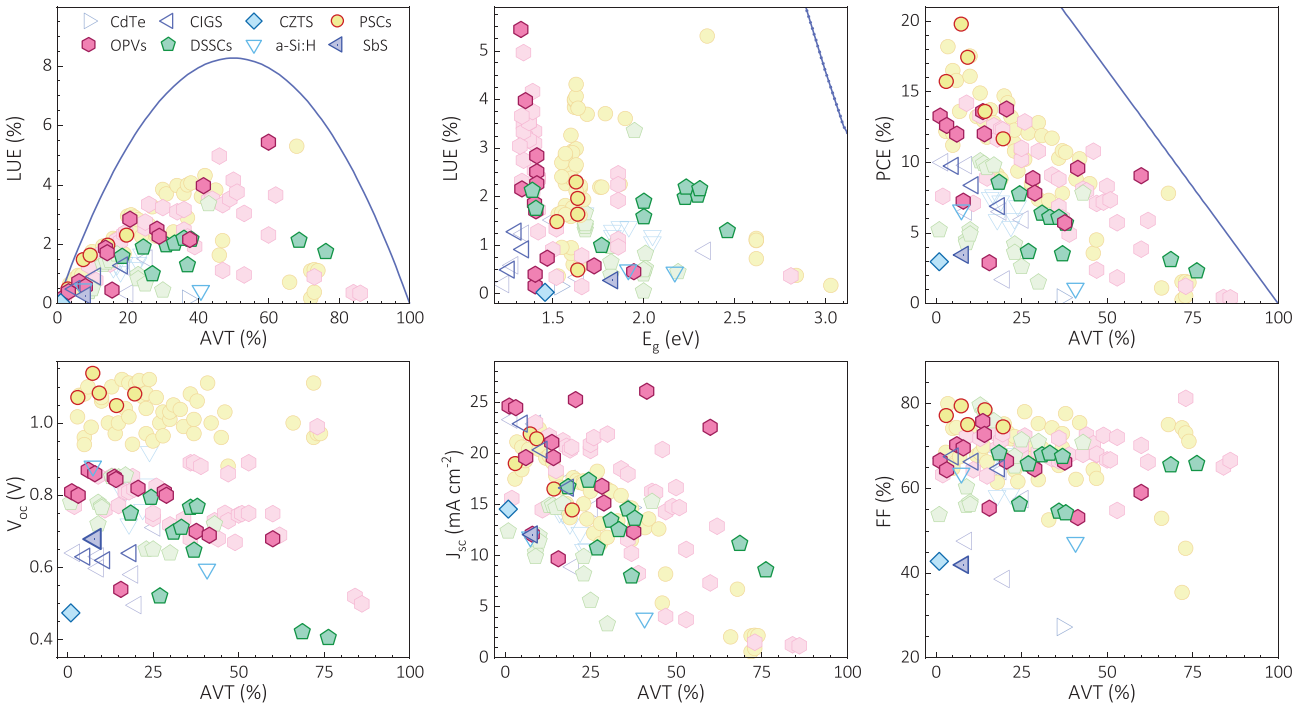

Figure 5. Best performing transparent and semitransparent PVs: light utilization efficiency versus average visible transmittance (top left) and photovoltaic bandgap energy (top center), and power conversion efficiency (top right), open circuit voltage (bottom left), short-circuit current density (bottom center), and fill factor (bottom right) as a function of average visible transmittance. Experimental data are summarized in Section A.3. The blue solid lines indicate the corresponding theoretical detailed balance efficiency limit for nonwavelength selective PVs.

5. Operational Stability in Emerging Research Solar Cells

The study of the operational stability among the e-PV technologies is still showing a rather low innovation rate, which we correlate with the complexity of correctly measuring the stability of solar cells in a representative way. In total, we had ten new reports out of 37, yielding an update rate of 27%. Unfortunately, the normalized plots for qualitatively illustrating trends without the data on the initial efficiency values and a lack of the precise description of the measurement conditions is still the most common practice to report lifetime data. Hopefully, following versions of the e-PVr will contribute to the development of the stability studies, not only in the number of data but also approaching new technologies, such as the compound semiconducting-based cells.

Certainly, the emergence of stability studies on tandem solar cells is noticed in **Figure 6**. A GaAs/perovskite tandem has been shown as the top performing device in terms of energy yield. Similarly, all-perovskites and CIGS/perovskite tandem devices are significantly more successful than most of the other single junction cells with respect to operational STEY. However, in terms of the degradation rate, the tandem devices are actually showing enhanced degradation compared to single junction cells. This means that, even though tandems can deliver more power during an operation span of 200 or 1000 h, their faster degradation kinetics would probably still disqualify them from real world applications. Given the worldwide efforts to develop Si/perovskite tandem cells as a follow-up technology for high-performance modules, degradation and stability of tandem cells clearly require enhanced attention.

The question on whether perovskite-based tandem solar cells are more unstable than single junction PSCs or not is an open problem that needs systematic attention. Even though the small size of our data is arguably not representative, a proper assessment would require an operational stability study of the multijunction devices in comparison with the single junction analogues to the sub-cells of the tandems. Hence, one could clarify whether these tandem cells were actually limited by summation of the instability issues of each individual sub-cell or whether they suffered from additional problems related to the device design.

6. Conclusions

In summary, we report a substantial update in the present version of the emerging photovoltaic reports with 150 new cell entries out of 588 (26% update quote). The most significant achievements in each category have been highlighted and new figures of merits for the parameterization of device performance and research trends have been introduced. On the latter, we specifically encourage the PV research community to use dimensional and performance-limit-normalized parameters (e.g., $DR\Delta_\tau$, $E\Delta_\tau$, OpF) rather than, or in addition to, relative percentages in the degradation and optimization studies.

Statistically, research on flexible photovoltaics and tandem solar cells appear as the most active subjects during the last year, if only taking their subfield as reference. With respect to the whole research sections reviewed above, the largest degree of innovation was observed in the categories of top efficiency single junction cells and flexible photovoltaics devices, with

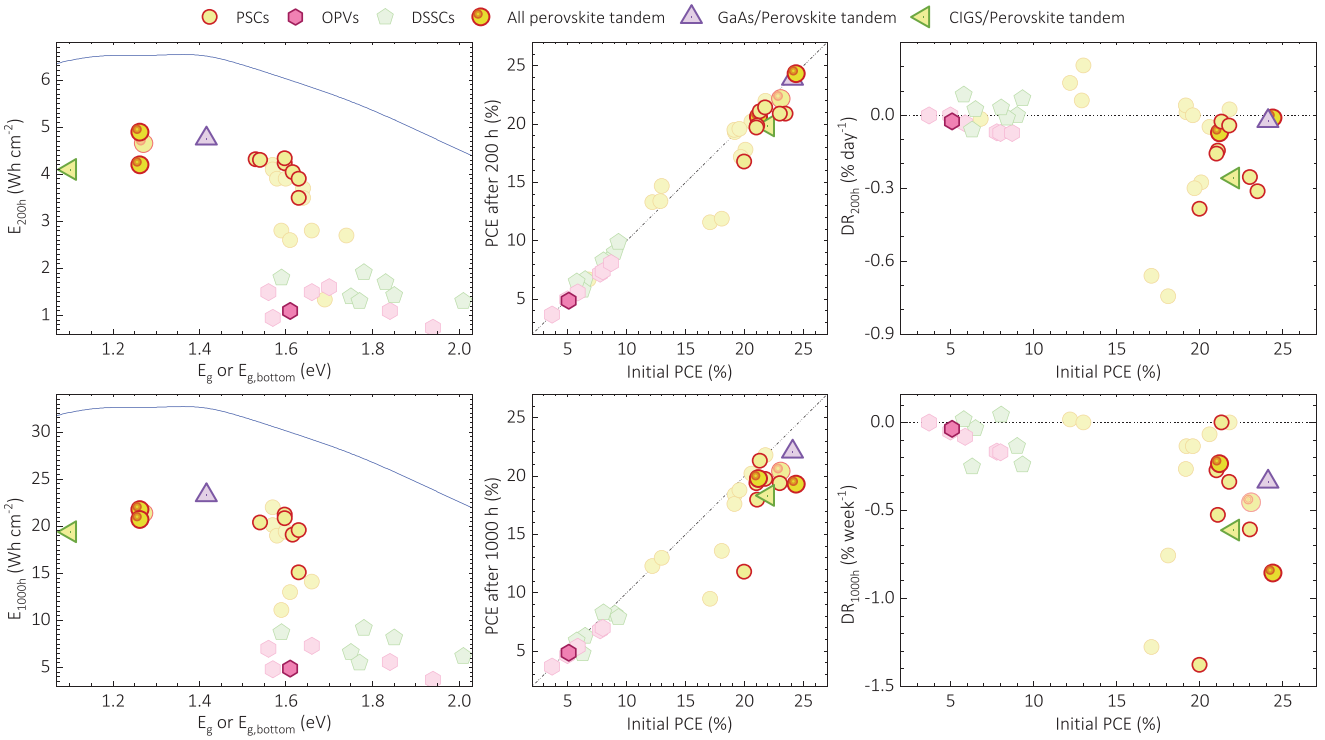

Figure 6. Most operationally stable emerging PVs for each technology during 200 h (top) and 1000 h (bottom) of testing: stability test energy yield (Equation (6)) as a function of bandgap energy (left), final power conversion efficiency as a function of the initial value (center), and overall degradation rate (Equation (7)) as a function of initial power conversion efficiency (right). The experimental data are summarized in Section A.4 and the solid blue lines in the STEY panel (left) are the corresponding DB theoretical limits. The diagonal dotted-dotted-dashed lines in the middle panel indicate where the final efficiencies equal the initial values. The positive values above the horizontal dotted lines in the degradation rate panel (right) indicate that *PCE* increases with respect to the initial values.

InF of 2.17% and 1.55%, respectively. In terms of optimization, among top efficiency single junction solar cells the top-average-*OpF* technologies are PSCs (11.3%), OPVs (9.6%), and CZTS (7.6%).

Among top efficiency cells, we highlight two main trends: the systematic optimization of kesterite solar cells and the predominance of *FF* losses among the latest record performance PSCs. The latter issue may suggest the product $FF \times V_{oc}$ as a more suitable parameter to focus on in future studies. The monolithic tandem solar cells not only report the highest efficiencies among the emerging PV technologies but also show versatility with the progress in flexible devices. Nevertheless, the stability of perovskite tandem cells is a subject that needs further attention. Within the field of transparent photovoltaics, we highlight the major achievement of *LUE* from nonfullerene OPVs.

Having started an effort to develop the e-PVr toward multijunction technologies, we will not stop the journey at simply considering tandems. In the next versions, we will implement metrics for benchmarking multijunction cells in a more generic way. We further plan to present first considerations of how to introduce exciting materials concept into this database, which are not at the stage of fully functional devices yet. Especially upconversion and downconversion concepts promise future performance enhancement and thus should be presented in the most comparable metrics from the beginning.

7. Tables

The tables below list the reports on best achievements in most of the established and emerging PV technologies as a function of the device bandgap E_g. Unless noted, the E_g values were estimated by fitting the absorption threshold region of the corresponding *EQE* spectra to Equation (2).[6]

In the case of *PCE* reports of PSCs showing hysteresis behavior in the *J–V* characteristic, while sweeping voltage in different directions and/or scan rates, the lower *PCE* value has been considered in each case (see Section S1.1, Supporting Information). Also, for perovskite-based devices, the cation compositions of methylammonium ($CH_3NH_3^+$) and formamidinium ($HC(NH_2)_2^+$) are abbreviated as MA and FA, respectively.

The *FF* values have been automatically corrected to match the reported values of *PCE*, J_{sc}, and V_{oc} under standard 100 mW cm^{-2} illumination of AM1.5G spectrum. For some reports, this has introduced up to ±0.5% discrepancies between the values in our tables and those reported in the original publications due to differences in the rounding digits and/or typos in the original publications. Cells with mismatches >0.5% may have been discarded (see Section S1.5, Supporting Information).

For the transparent/semitransparent cells, note that the *AVT* values may differ from those reported in the original manuscripts when a definition different than that of Equation (4) was used in the original published article.

7.1. Highest Efficiency Research Solar Cells Tables (Tables 3–10)

Table 3. Highest efficiency single junction perovskite research solar cells performance parameters as a function of device absorber bandgap energy (from *EQE* spectrum).

E_g [eV]	*PCE* [%]	V_{oc} [mV]	J_{sc} [mA cm^{-2}]	*FF* [%]	Absorber perovskite	Ref.
1.25	20.7	843	30.6	80.2	$(FASnI_3)_{0.6}(MAPbI_3)_{0.4}$	[46]
1.26	20.4	834	30.5	80.2	$GuaSCN:(FASnI_3)_{0.6}(MAPbI_3)_{0.4}$	[47]
1.26	19.0	888	28.8	74.5	$(FASnI_3)_{0.6}(MAPbI_3)_{0.34}(MAPbBr_3)_{0.06}$	[48]
1.27	20.9	827	31.4	80.5	$MA_{0.3}FA_{0.7}Pb_{0.5}Sn_{0.5}I_3$	[49]
1.28	**20.6**	**842**	**30.6**	**80.1**	**FSA:$MA_{0.3}FA_{0.7}Pb_{0.5}Sn_{0.5}I_3$**	[11][a]
1.28	**21.7**	**850**	**31.6**	**80.8**	**FSA:$MA_{0.3}FA_{0.7}Pb_{0.5}Sn_{0.5}I_3$**	[11]
1.28	20.3	850	30.2	79.1	$FA_{0.5}MA_{0.45}Cs_{0.05}Pb_{0.5}Sn_{0.5}I_3$	[50]
1.28	18.4	780	32.8	72.0	$Cs_{0.025}FA_{0.475}MA_{0.5}Sn_{0.5}Pb_{0.5}I_3$	[51]
1.29	16.0	771	29.3	70.8	$FASn_{0.5}Pb_{0.5}I_3$	[52]
1.29	15.9	770	26.5	78.0	$(FASnI_3)_{0.6}(MAPbI_3)_{0.3}(MAPbBr_3)_{0.1}$	[53]
1.30	**18.8**	**820**	**29.6**	**77.3**	**$(FASnI_3)_{0.6}(MAPbI_3)_{0.4}$**	[54]
1.30	**17.1**	**840**	**27.9**	**73.0**	**$FA_{0.8}MA_{0.15}Cs_{0.05}Pb_{0.5}Sn_{0.5}I_3$**	[29]
1.31	5.0	420	23.8	50.3	$CsSnI_3$	[55][b]
1.31	7.1	486	22.9	64.0	$MASnI_3$	[56][b]
1.31	14.1	740	26.7	71.4	$FA_{0.75}Cs_{0.25}Sn_{0.5}Pb_{0.5}I_3$	[57]
1.32	11.6	720	23.4	68.9	$MAPb_{0.4}Sn_{0.6}I_{2.8}Br_{0.2}$	[58]
133	**7.5**	**450**	**24.9**	**67.0**	**$CsSnI_3$:MBAA**	[59]
1.34	10.0	767	20.5	63.6	$MAPb_{0.4}Sn_{0.6}I_3$	[60]
1.34	12.1	780	20.7	75.1	$MAPb_{0.4}Sn_{0.6}I_{2.6}Br_{0.4}$	[58]
1.35	16.3	780	26.5	79.0	$FAPb_{0.7}Sn_{0.3}I_3$	[61]
1.36	**8.2**	**630**	**19.7**	**66.1**	**$CsSnI_3$**	[62]
1.37	14.7	737	27.1	73.6	$FA_{0.3}MA_{0.7}Pb_{0.7}Sn_{0.3}I_3$	[63]
1.38	17.3	810	28.2	75.4	$FAPb_{0.75}Sn_{0.25}I_3$	[64]
1.38	15.2	800	26.2	72.5	$MAPb_{0.75}Sn_{0.25}I_3$	[65]
1.39	20.6	1020	26.6	76.0	$FA_{0.7}MA_{0.3}Pb_{0.7}Sn_{0.3}I_3$	[66]
1.40	8.2	745	17.8	61.8	$MAPb_{0.6}Sn_{0.4}I_3$	[60]
1.40	7.8	570	20.7	66.2	$MASnI_3$	[67]
1.41	5.9	487	20.0	60.6	$FA_{1-x}Rb_xSnI_3$	[68]
1.42	14.4	820	22.4	78.0	$MAPb_{0.75}Sn_{0.25}I_3$	[69]
1.42	13.2	840	20.3	78.0	$(FA_{0.9}EA_{0.1})_{0.98}EDA_{0.01}SnI_3$	[70]
1.43	12.4	949	17.4	74.9	$PEA_{0.15}FA_{0.85}SnI_3:NH_4SCN$	[71][a]
1.44	10.4	640	21.6	75.2	$Cs_{0.2}FA_{0.8}SnI_3$	[72]
1.44	10.1	642	22.2	70.8	$Cs_{0.2}FA_{0.8}SnI_3$	[72][a]
1.44	10.2	638	22.0	72.5	$FASnI_3$:FOEI	[73][a]
1.48	6.0	460	23.9	53.9	$CsSnI_3$	[74]
1.49	**22.3**	**1090**	**26.3**	**78.0**	**$FA_{0.6}MA_{0.4}PbI_3$ (sc)**	[75]
1.51	19.3	1047	23.8	77.5	$FA_{0.6}MA_{0.4}PbI_3$	[76]
1.52	22.0	1120	24.9	78.6	$FA_{0.85}MA_{0.15}PbI_3$	[77]
1.53	**25.2**	**1174**	**26.2**	**81.8**	**α-$FAPbI_3$**	[13][a]
1.53	**24.5**	**1185**	**26.1**	**79.1**	**α-$FAPbI_3$**	[13]
1.53	**23.4**	**1200**	**24.6**	**79.3**	**$FA_{0.78}MA_{0.22}Pb(IBrCl)_3$**	[78]
1.53	**25.5**	**1189**	**25.7**	**83.2**	–[c]	[21][a]
1.53	**20.8**	**1143**	**23.9**	**77.0**	**$MAPbI_3$ (sc)**	[79][b]
1.54	24.6	1181	26.2	79.6	$FAPbI_3$	[80][a]
1.54	22.1	1105	25.0	80.3	$(FAPbI_3)_{0.9}(MAPbBr_3)_{0.1}$	[81][a]

Table 3. Continued.

E_g [eV]	*PCE* [%]	V_{oc} [mV]	J_{sc} [mA cm^{-2}]	*FF* [%]	Absorber perovskite	Ref.
1.55	21.5	1160	23.4	79.2	$Cs_{0.05}FA_{0.70}MA_{0.25}PbI_3$-DAP	[82]
1.56	25.2	1180	24.1	84.8	–[c]	[83][a]
1.56	**25.2**	**1181**	**25.1**	**84.8**	**$FAMAPb(IBrCl)_3$**	[12][a]
1.56	**25.3**	**1193**	**25.1**	**84.6**	**$FAMAPb(IBrCl)_3$**	[12]
1.56	**21.9**	**1100**	**24.4**	**81.4**	**$Rb_{0.05}Cs_{0.05}FA_{0.8}MA_{0.1}PbI_{2.85}Br_{0.15}$**	[84]
1.57	23.0	1170	24.1	81.6	$Cs_{0.05}(FA_{0.92}MA_{0.08})_{0.95}Pb(I_{0.92}Br_{0.08})_3$	[85]
1.57	22.3	1143	23.8	82.0	$Cs_{0.05}(FA_{0.92}MA_{0.08})_{0.95}Pb(I_{0.92}Br_{0.08})_3$	[85][a]
1.57	**22.7**	**1162**	**23.5**	**83.2**	**$Cs_{0.18}FA_{0.82}PbI_3$**	[86]
1.58	22.6	1186	24.2	78.6	$(FAPbI_3)_{0.92}(MAPbBr_3)_{0.08}$	[87][a]
1.58	**22.6**	**1178**	**22.7**	**84.4**	–[c]	[2][a]
1.58	**20.4**	**1125**	**23.3**	**77.8**	**$Cs_{0.05}(FAPbI_3)_{0.85}(MAPbBr_3)_{0.15}$**	[88]
1.58	21.9	1120	24.2	80.6	$FA_{0.15}MA_{0.85}PbI_3$	[89]
1.59	21.1	1086	24.0	81.0	$MAPb_{0.9}Sn_{0.05}Cu_{0.05}I_{2.9}Br_{0.1}$	[90]
1.59	21.0	1140	23.7	77.7	$FA_{0.85}MA_{0.15}Pb(I_{0.85}Br_{0.15})_3$	[91][a]
1.60	**21.9**	**1131**	**23.1**	**83.7**	**$CsMAFAPbI_3$:PPP**	[24]
1.60	20.3	1130	23.2	77.4	$MAPbI_{3-x}Cl_x$	[92][a]
1.61	**21.4**	**1120**	**23.1**	**82.9**	**$MAPbI_3$**	[93][b]
1.61	**21.5**	**1192**	**21.6**	**83.6**	**$Cs_{0.05}FA_{0.88}MA_{0.07}PbI_{2.56}Br_{0.44}$**	[22][a]
1.61	**23.2**	**1240**	**22.1**	**84.5**	**$Cs_{0.05}FA_{0.88}MA_{0.07}PbI_{2.56}Br_{0.44}$**	[22]
1.61	22.6	1200	24.0	78.5	$Cs_{0.07}Rb_{0.03}FA_{0.765}MA_{0.135}PbI_{2.55}Br_{0.45}$	[94]
1.62	21.7	1180	22.5	81.7	$MAPbI_3$-DAP	[82]
1.63	20.3	1130	23.4	76.8	$Cs_{0.05}FA_{0.76}MA_{0.19}PbBr_{0.6}I_{2.4}$	[95]
1.64	20.4	1140	23.6	75.8	$Cs_{0.05}(MA_{0.17}FA_{0.83})_{0.95}Pb(I_{0.83}Br_{0.17})_3$	[96]
1.65	16.2	1109	19.6	74.2	$MAPbI_{1-x}Br_x$	[97][a]
1.66	10.4	904	16.3	70.4	$MAPb(I_{0.87}Br_{0.13})_3$	[98]
1.67	**17.9**	**1190**	**18.4**	**81.9**	**$(PEA)_2(MA)_3Pb_4I_{13}$:$NH_4I_{0.2}Cl_{0.8}$**	[99]
1.68	20.7	1220	21.3	79.7	$Cs_{0.05}MA_{0.15}FA_{0.8}Pb(I_{0.75}Br_{0.25})_3$	[100]
1.69	7.1	936	10.4	63.0	$MAPb(I_{0.74}Br_{0.26})_3$	[101]
1.70	16.9	1170	20.2	71.5	$Cs_{0.2}FA_{0.8}Pb(I_{0.75}Br_{0.25})_3$	[100]
1.71	**14.6**	**1056**	**17.5**	**79.0**	**$CsPbI_3$**	[102]
1.72	18.6	1244	19.2	77.9	$FA_{0.17}Cs_{0.83}PbI_{2.2}Br_{0.8}$	[103]
1.72	**18.3**	**1350**	**17.6**	**77.0**	**$MAPbI_{2.4}Br_{0.6}$**	[104]
1.72	17.1	1200	19.4	73.5	$FA_{0.83}Cs_{0.17}Pb(I_{0.6}Br_{0.4})_3$	[105]
1.74	18.3	1269	18.9	76.3	$Rb_{0.05}Cs_{0.095}MA_{0.1425}FA_{0.7125}PbI_2Br$	[106]
1.75	19.8	1310	19.4	78.0	$FA_{0.83}Cs_{0.17}Pb(I_{0.6}Br_{0.4})_3$	[107]
1.76	18.5	1210	20.0	76.4	$(FA_{0.83}MA_{0.17})_{0.95}Cs_{0.05}Pb(I_{0.6}Br_{0.4})_3$	[108]
1.77	18.6	1234	18.3	82.5	$CsPbI_{3-x}Br_x$	[109]
1.78	15.7	1210	18.4	70.5	$Cs_{0.17}FA_{0.83}Pb(I_{0.6}Br_{0.4})_3$	[100]
1.79	19.0	1250	19.0	80.0	$Cs_{0.12}MA_{0.05}FA_{0.83}Pb(I_{0.6}Br_{0.4})_3$	[100]
1.79	16.5	1284	17.2	74.8	$Cs_{0.17}FA_{0.83}PbI_{1.8}Br_{1.2}$	[103]
1.80	13.7	1272	14.4	75.0	$MAPbBrI_2$	[110]
1.81	16.3	1220	17.0	78.6	$FA_{0.6}Cs_{0.4}Pb(I_{0.65}Br_{0.35})_3$	[50]
1.82	17.1	1100	21.0	74.0	$FAPbI_{1.5}Br_{1.5}$/$CsPbI_{1.5}Br_{1.5}$	[111]
1.83	3.3	1020	5.7	56.9	Cs_2TiBr_6	[112][b]
1.83	8.6	1110	11.3	68.4	$MA_{0.85}Cs_{0.15}Pb(I_{0.65}Br_{0.35})_3$	[113]
1.84	15.2	1260	15.6	77.3	$Cs_{0.2}FA_{0.8}Pb(I_{0.6}Br_{0.4})_3$-DAP	[82]
1.85	15.0	1296	15.6	74.2	$Cs_{0.17}FA_{0.83}PbI_{1.5}Br_{1.5}$	[103]
1.86	17.0	1340	15.9	79.8	$CsPb(I_{0.75}Br_{0.25})_3$-0.5FAOAc	[114]
1.87	14.0	1280	14.0	78.1	$CsPb_{0.8}Ba_{0.2}I_2Br$	[115]

Table 3. Continued.

E_g [eV]	*PCE* [%]	V_{oc} [mV]	J_{sc} [mA cm^{-2}]	*FF* [%]	Absorber perovskite	Ref.
1.87	13.7	1220	14.6	76.8	$CsPb_{0.95}Eu_{0.05}I_2Br$	[116]
1.88	**15.9**	**1300**	**15.5**	**79.1**	**$CsPbI_2Br$**	[117]
1.88	15.3	1250	15.4	79.0	$CsPbI_2Br$	[118]
1.89	16.0	1310	15.8	77.5	$CsPbI_2Br$	[32]
1.89	15.6	1300	15.3	78.3	$CsPbI_{2-x}Br(Ac)_x$	[119]
1.90	**15.0**	**1240**	**16.0**	**75.6**	**$InCl_3$:$CsPbI_2Br$**	[120][a]
1.90	16.1	1320	15.3	79.7	$CsPbI_2Br$	[121]
1.91	14.4	1312	15.6	70.1	$FA_{0.17}Cs_{0.83}PbI_{1.2}Br_{1.8}$	[103]
1.91	**14.2**	**1160**	**15.7**	**77.9**	**$CsPbI_2Br$**	[122]
1.91	2.0	620	5.4	60.8	$MA_3Sb_2I_9$+HI	[123][b]
1.94	4.3	630	10.7	63.8	Ag_3BiI_6	[124]
1.94	2.2	670	5.2	62.7	$AgBiI_4$	[125]
1.95	2.6	690	6.0	62.4	$AgBiI_5$	[125]
1.97	1.1	850	2.2	59.6	$Cs_3Bi_2I_9$	[126]
1.98	8.3	1080	12.3	62.0	$CsPbIBr_2$	[127]
2.00	9.6	1185	11.2	72.3	$Cs_{0.15}FA_{0.85}Pb(I_{0.3}Br_{0.7})_3$	[128]
2.03	2.8	836	6.4	52.7	$MAPb(I_{0.41}Br_{0.59})_3$	[129]
2.04	10.3	1340	9.7	79.2	$MAPb(I_{0.3}Br_{0.7})_xCl_{3-x}(Br)$	[130]
2.05	6.1	1450	5.4	77.1	$MAPbIBr_2$	[131]
2.09	10.2	1270	11.5	69.4	$CsPbIBr_2$	[132]
2.10	10.7	1261	11.8	72.0	$CsPbIBr_2$	[133]
2.11	9.2	1200	10.2	74.6	GAI-DEE-$CsPbIBr_2$	[134]
2.14	3.1	650	8.1	58.4	$MASbSI_2$	[135]
2.15	4.4	1084	6.3	64.8	$(FA_{0.85}MA_{0.15}Pb(I_{0.85}Br_{0.15})_3)$ $R = 0.7$	[136]
2.19	2.0	1051	3.0	69.5	$(FA_{0.85}MA_{0.15}Pb(I_{0.85}Br_{0.15})_3)$ $R = 0.56$	[136]
2.20	1.2	610	3.6	55.9	$Cs_3Sb_2I_9$	[137]
2.27	10.6	1552	8.9	76.5	$FAPbBr_3$	[138]
2.31	9.7	1458	8.1	81.9	$CsPbBr_3$	[139]
2.32	10.1	1653	7.7	79.1	$MAPbBr_3$	[110]
2.33	**8.5**	**1580**	**6.6**	**82.0**	**$CsPbBr_3$**	[140]
2.33	8.2	1470	7.3	76.1	$CsPbBr_3$	[141]
2.34	**10.1**	**1602**	**7.9**	**80.0**	**$CsPbBr_3$**	[142]
2.34	9.7	1584	7.4	82.8	$CsPbBr_3$	[143]
2.35	10.7	1622	7.9	83.5	$CsPbBr_3$	[144]
2.35	10.6	1610	7.8	84.4	$CsSnBr_3$	[145]
2.36	4.0	1130	5.5	63.6	$CsPbBr_{2.9}I_{0.1}$	[146]
2.37	2.2	690	5.0	63.5	$MA_3Sb_2Cl_xI_{9-x}$	[147]
2.38	8.1	1490	6.9	78.8	$CsPbBr_3$	[148]
2.39	10.3	1580	8.2	80.0	$Cs_{0.91}Rb_{0.09}PbBr_3$	[149]
2.41	2.7	1020	5.2	51.2	$Cs_2AgBiBr_6$	[150]
2.42	1.1	870	2.9	43.0	$BdAPbI_4$	[151]
2.43	2.8	820	5.7	60.3	$CsPb_2Br_5$	[152]
2.44	2.4	1140	3.4	60.9	$FAPbBr_{2.1}Cl_{0.9}$	[44]
2.45	**2.9**	**1010**	**4.1**	**70.9**	**$Cs_2AgBiBr_6$**	[153]
2.46	1.7	1060	3.9	40.2	$Cs_2AgBiBr_6$	[154]
2.48	1.4	1060	2.5	52.0	$FAPbBr_2Cl$	[44]

[a]Certified efficiency; [b]Exception included as a material highlight; [c]Exception included as a *PCE* highlight without the absorber information; sc, single crystal.

Table 4. Highest efficiency single junction organic research solar cells performance parameters as a function of device absorber bandgap energy (from *EQE* spectrum).

E_g [eV]	*PCE* [%]	V_{oc} [mV]	J_{sc} [mA cm^{-2}]	*FF* [%]	Absorber blend	Ref.
1.32	10.6	690	24.3	63.2	PTB7-Th:IEICO-4F	[155]
1.34	12.8	712	27.3	65.9	PTB7-Th:IEICO-4F	[156]
1.34	9.7	695	19.8	70.2	PBDTT-DPP:IEICO-4F	[157]
1.35	**17.0**	**804**	**27.2**	**76.4**	**PM6:mBzS-4F**	[158]
1.35	**15.9**	**820**	**26.3**	**73.4**	**PM6:Y6**	[159]
1.35	14.3	802	26.8	66.5	PBDB-T-2Cl:BTP-4F:$PC_{61}BM$	[160]
1.36	15.9	846	25.4	74.1	PM6:Y11	[161][a)]
1.37	**18.3**	**856**	**26.9**	**79.4**	**PM6:BTP-eC9:$PC_{71}BM$**	[14]
1.38	**17.7**	**852**	**26.8**	**77.7**	**PM6:PTQ10:PC71BM:N3**	[162]
1.38	17.3	841	26.2	78.5	PBDB-TF:BTP-eC9	[163][a)]
1.39	18.2	859	27.7	76.6	D18:Y6	[164][a)]
1.39	17.0	858	77.6	25.5	PBDB-TF:BTP-4Cl-12	[165][a)]
1.39	**17.1**	**850**	**25.8**	**78.1**	**BTIC-2Cl-γCF_3: PC_{71}ThBM: PBDB-TF**	[166]
1.40	**17.6**	**860**	**27.3**	**75.0**	**PM6-Tz20: Y6**	[167]
1.40	17.1	834	26.4	77.6	PM6:Y6	[168][a)]
1.40	16.5	867	25.4	75.0	PBDB-TF:BTP-4Cl	[169][a)]
1.41	**17.6**	**871**	**26.4**	**76.8**	**D18-Cl:PM6:Y6**	[170]
1.41	**17.1**	**845**	**26.6**	**76.0**	**PM6:Y6:DFBT-TT6**	[171]
1.41	17.4	862	25.8	77.9	–[b)]	[83][a)]
1.42	15.6	834	24.9	75.1	PBDB-TF:BTP-4F	[169]
1.42	15.6	838	25.0	74.4	–[b)]	[172][a)]
1.43	14.3	820	24.9	70.0	PM6:IDST-4F	[173]
144	**16.1**	**955**	**22.7**	**74.3**	**PM6:PY-IT:BN-T**	[174]
1.44	13.6	920	21.4	69.1	PBDB-TF:BTIC-F-m	[175]
1.46	**18.2**	**897**	**25.7**	**78.9**	–[b)]	[21][a)]
1.46	12.9	852	21.5	70.6	PM6:N-C11	[176]
1.47	14.6	882	23.1	71.7	PBDB-T-2Cl:BP-4F:MF1	[177]
1.48	12.4	880	20.8	67.7	PBDB-T:IDT-EDOT:$PC_{71}BM$	[178]
1.50	15.4	920	22.6	74.1	PM6:DTTC-4Cl	[179]
1.51	13.3	780	22.9	75.0	PM6:SeTIC4Cl-DIO	[180]
1.52	10.4	850	18.0	68.0	PBDB-T:IDT-EDOT:$PC_{71}BM$	[178]
1.53	10.7	850	22.2	56.7	PM6:SeTIC4Cl	[180]
1.54	13.6	940	19.5	73.8	BTR:NITI:$PC_{71}BM$	[181]
1.55	12.0	840	19.5	73.3	PM6:IT-4F	[182]
1.56	12.1	826	20.9	70.1	PBDB-T-2F:IT-4F	[183]
1.58	13.9	950	21.7	67.4	PM6:DTTC-4F	[179]
1.58	13.5	880	20.6	74.53	PBDB-T-SF:IT-4F	[184]
1.61	13.4	940	20.2	70.5	PM6:DTC-4F	[179]
1.61	12.1	916	18.1	73.0	PBDB-T-2Cl:MF1	[177]
1.62	11.0	793	19.4	71.5	–[b)]	[185][a)]
1.62	12.2	930	17.5	75.0	PTQ10:IDTPC	[186]
1.63	12.8	910	19.1	73.6	PTQ10:IDIC-2F	[187]
1.64	12.9	960	17.4	71.3	PTQ10:IDIC	[187]
1.65	9.3	820	16.5	68.7	J51:ITIC	[188]
1.66	12.1	815	20.3	73.2	–[b)]	[189][a)]
1.67	10.2	810	21.0	59.9	P4TIF:$PC_{61}BM$	[180]
1.67	11.5	791	19.7	73.7	–[b)]	[190][a)]
1.68	12.0	1030	18.5	63.0	PBDTTT-EFT:EHIDTBR	[191]

Table 4. Continued.

E_g [eV]	*PCE* [%]	V_{oc} [mV]	J_{sc} [mA cm^{-2}]	*FF* [%]	Absorber blend	Ref.
1.69	8.9	878	13.9	72.9	PBT1-C:NFA	[192]
1.70	11.1	867	17.8	71.9	–[b]	[193][a]
1.72	10.0	899	16.8	66.4	–[b]	[194][a]
1.78	9.6	786	17.0	72.0	PPDT2FBT:$PC_{70}BM$	[195]
1.79	7.5	1140	10.6	62.1	BDT-ffBX-DT:PDI4	[196]
1.79	6.2	1230	8.9	56.6	BDT-ffBX-DT:SFPDI	[196]
1.85	9.0	900	13.8	72.9	BTR:$PC_{71}BM$	[181]
1.85	7.6	830	13.3	69.1	PBDB-T:$PC_{71}BM$	[178]
1.86	7.4	940	12.7	61.9	PBDB-T:NDP-Se-DIO	[197]
1.88	5.7	950	10.7	55.9	PBDB-T-2Cl:$PC_{61}BM$	[160]
1.93	**6.3**	**790**	**12.2**	**65.3**	**P3HT:TCBD14**	[198]
2.01	3.7	592	10.4	59.2	P3HT:PCBM	[199]

[a]Certified efficiency; [b]Exception included as a *PCE* highlight without the absorber information.

Table 5. Highest efficiency single junction dye sensitized research solar cells performance parameters as a function of device absorber bandgap energy (from *EQE* spectrum).

E_g [eV]	*PCE* [%]	V_{oc} [mV]	J_{sc} [mA cm^{-2}]	*FF* [%]	Sensitizing dye	Ref.
1.44	11.0	714	21.9	70.3	–[a]	[194][b]
1.52	11.4	743	21.3	71.9	–[a]	[194][b]
1.59	10.1	710	18.5	76.9	TF-tBu_C_3F_7	[200]
1.66	**10.7**	**849**	**16.6**	**75.9**	**bJS2**	[201]
1.74	7.8	694	15.4	72.7	YD2	[202]
1.75	**10.9**	**745**	**20.7**	**70.8**	**YKP-88/YKP-137 (6/4)**	[203]
1.76	**8.3**	**700**	**17.9**	**66.3**	**TNA**	[204]
1.77	10	740	18.1	74.7	N719	[205]
1.80	9.1	744	19.0	64.0	N719	[206]
1.80	9.0	790	19.8	57.2	N719	[207]
1.80	6.5	663	13.3	74.5	SK7	[202]
1.82	6.4	680	13.1	71.8	AN-11	[208]
1.83	8.9	820	19.0	57.5	N719	[209]
1.85	12.3	1020	15.2	79.1	–[a]	[83]b)
1.86	8.3	782	14.8	71.7	N719	[210]
1.87	9.1	1060	11.2	76.7	L351	[211]
1.88	7.8	730	14.3	74.7	TY4	[205]
1.89	8.5	580	21.3	68.8	N719+W2	[212]
1.93	11.2	1140	13.0	75.6	L350	[211]
1.97	3.0	600	6.3	79.4	AN-14	[208]
1.99	5.4	689	11.3	69.5	SK6	[210]
2.00	6.3	732	12.0	71.7	CW10+SK6	[210]
2.01	9.2	1160	11.0	72.1	L349	[211]
2.02	8.1	760	14.3	75.0	TY6	[205]
2.05	3.9	680	7.4	77.5	AN-12	[208]
2.09	6.9	780	11.6	76.3	TY3	[205]
2.12	5.8	739	10.8	72.7	CW10	[210]
2.23	5.8	760	10.2	74.8	MS3	[205]
2.32	5.3	1170	6.4	70.8	L348	[211]

[a]Exception included as a *PCE* highlight without the absorber information; [b]Certified efficiency.

Table 6. Highest efficiency single junction research solar cells performance parameters as a function of device absorber bandgap energy (from *EQE* spectrum) among several inorganic emerging technologies.

E_g [eV]	*PCE* [%]	V_{oc} [mV]	J_{sc} [mA cm^{-2}]	*FF* [%]	Absorber material/ technology	Ref.
0.98	11.2	430	39.2	66.8	$Cu_2ZnSn(Se,S)_4$	[213]
1.02	**11.6**	**441**	**39.2**	**67.4**	**$Cu_2ZnSnSe_4$**	[214]
1.03	11.6	423	40.6	67.3	$Cu_2ZnSnSe_4$	[215][a]
1.04	9.6	425	34.9	64.5	$Cu_2ZnSnSe_4$	[216]
1.05	9.4	457	32.5	63.3	$Cu_2ZnSnSe_4$	[217]
1.06	9.5	460	31.1	66.4	$Cu_2ZnSnSe_4$	[217]
1.06	**13.2**	**477**	**40.1**	**69.0**	**$Cu_2ZnSn(S,Se)_4$**	[15][b]
1.06	**11.5**	**461**	**36.7**	**68.2**	**$Cu_2ZnSn(S,Se)_4$**	[15][a]
1.07	**12.5**	**491**	**37.4**	**68.2**	**$Cu_2ZnSnSe_4$**	[218][a]
1.08	**12.4**	**522**	**33.3**	**71.3**	**$Cu_2ZnSn(S,Se)_4$**	[219]
1.09	**12.2**	**475**	**37.2**	**68.8**	**$Cu_2ZnSn(S,Se)_4$**	[219]
1.09	**12.5**	**540**	**32.1**	**72.1**	**$(Ag,Cu)_2ZnSn(S,Se)_4$**	[37]
1.10	**11.2**	**445**	**36.4**	**69.3**	**$Cu_2ZnSn(S,Se)_4$**	[220]
1.11	**11.6**	**520**	**32.0**	**69.4**	**$Cu_2ZnSn(S,Se)_4$**	[219][a]
1.12	12.3	527	32.3	72.3	$Cu_2Zn(Sn_{0.78}Ge_{0.22})Se_4$	[221]
1.13	12.6	513	35.2	69.8	$Cu_2ZnSn(S,Se)_4$	[222][a]
1.13	11.1	460	34.5	69.8	$Cu_2ZnSn(S,Se)_4$	[223][a]
1.14	12.6	541	35.4	65.9	$Cu_2ZnSn(S,Se)_4$	[224][a]
1.16	**11.2**	**539**	**33.1**	**62.8**	**$Cu_2ZnSn(S,Se)_4$**	[225]
1.22	7.5	413	28.9	62.4	Sb_2Se_3	[226]
1.24	9.2	400	32.6	70.6	Sb_2Se_3	[227]
1.27	4.8	370	27.3	47.3	Sb_2Se_3	[227]
1.29	**4.0**	**340**	**22.9**	**51.0**	**Sb_2Se_3**	[228]
1.31	**7.3**	**420**	**29.2**	**59.7**	**Sb_2Se_3**	[229]
1.33	**6.4**	**421**	**27.8**	**54.7**	**Sb_2Se_3**	[214]
1.45	8.5	625	24.4	55.7	$Cu_2ZnGeSe_4$	[230]
1.50	11.0	731	21.7	69.3	Cu_2ZnSnS_4	[231][a]
1.50	10.0	655	24.1	63.3	$Sb_2(S,Se)_3$	[232][a]
1.52	8.73	664	20.6	63.9	$(Cu_{0.99}Ag_{0.01})_{1.85}(Zn_{0.8}Cd_{0.2})_{1.1}SnS_4$	[233]
1.53	**4.1**	**473**	**14.8**	**58.7**	**SbSeI:Sb_2Se_3**	[234]
1.80	7.5	711	16.1	65.0	Sb_2S_3	[235]

[a]Certified efficiency; [b]*PCE* and J_{sc} for active area.

Table 7. Highest efficiency single junction research solar cells performance parameters as a function of device absorber bandgap energy (from *EQE* spectrum) among established technologies.

E_g [eV]	*PCE* [%]	V_{oc} [mV]	J_{sc} [mA cm^{-2}]	*FF* [%]	Absorber material/ technology	Ref.
1.09	19.8	716	34.9	79.2	CIGS	[236][a]
1.10	21.7	718	40.7	74.3	CIGS	[189][a]
1.11	26.7	738	42.7	84.9	Si (crystalline)	[189][a]
1.13	22.9	744	38.8	79.5	CIGS	[237][a]
1.14	21.0	757	35.7	77.6	CIGS	[238][a]
1.15	23.4	734	39.6	80.4	CIGS	[172][a]
1.30	16.3	762	31.4	68.1	CIGS	[239]
1.42	29.1	1127	29.8	86.7	GaAs	[240][a]
1.42	21.0	876	30.3	79.4	CdTe	[185][a]
1.48	18.3	857	27.0	77.0	CdTe	[193][a]
1.60	**15.2**	**902**	**23.1**	**73**	**CIGS**	[241]
1.60	10.2	896	16.4	69.8	Si (amorphous)	[185][a]
1.69	10.6	896	16.1	75.6	Si (amorphous)	[242]
1.85	10.1	886	16.8	67.0	Si (amorphous)	[243][a]

[a]Certified efficiency

Table 8. Highest efficiency tandem perovskite-based monolithic research solar cells performance parameters as a function of the device bandgap energies (from *EQE* spectra) of the bottom and top absorber materials.

$E_{g,bottom}$ [eV]	$E_{g,top}$ [eV]	*PCE* [%]	V_{oc} [mV]	J_{sc} [mA cm^{-2}]	*FF* [%]	Bottom absorber material	Top absorber material	Ref.
						Si/perovskite		
1.11	1.63	24.1	1786	19.5	69.1	Si	$Cs_xFA_{1-x}Pb(I,Br)_3$	[244]
1.11	1.66	26.0	1820	19.2	75.4	Si	$Cs_{0.1}MA_{0.9}PbI_{2.7}Br_{0.3}$	[245]
1.11	**1.67**	**26.7**	**1756**	**19.2**	**79.2**	**Si**	**PEA($I_{0.25}SCN_{0.75}$)**	[246]
1.11	1.68	25.7	1781	19.1	75.4	Si	$Cs_{0.05}MA_{0.15}FA_{0.8}PbI_{2.25}Br_{0.75}$	[247][a]
1.11	**1.68**	**25.2**	**1800**	**18.4**	**75.6**	**Si**	–[b]	[248][a]
1.12	1.64	26.0	1760	19.2	76.5	Si	$FA_{0.83}MA_{0.17}PbI_3$	[249]
1.12	**1.65**	**26.5**	**1760**	**19.4**	**77.0**	**Si**	**$Cs_{0.05}MA_{0.16}FA_{0.79}PbI_{2.49}Br_{0.51}$**	[250]
1.12	**1.68**	**28.8**	**1895**	**19.2**	**78.9**	**Si**	**$Cs_{0.05}FA_{0.73}MA_{0.22}PbI_{2.31}Br_{0.69}$**	[19][c]
1.13	**1.65**	**24.9**	**1735**	**19.5**	**73.5**	**Si**	**$CsFAPb(IBr)_3$**	[251]
1.13	1.67	27.1	1886	19.1	75.3	Si	$CsFAMAPb(IBrCl)_3$	[252]
1.13	**1.69**	**29.5**	**1884**	**20.3**	**77.3**	**Si**	–[b]	[2]
1.15	1.62	20.9	1690	15.9	77.6	Si	MAPI	[253]
1.15	1.68	25.4	1800	17.8	79.4	Si	$Cs_{0.15}FA_{0.71}MA_{0.14}PbI_{2.4}Br_{0.6}$	[254]
1.15	1.68	25.0	1770	18.4	77.0	Si	$FA_{0.75}Cs_{0.25}PbI_{2.4}Br_{0.6}$	[255]
1.16	1.62	19.2	1701	16.1	70.1	Si	MAPI	[253]
						GaAs/perovskite		
1.42	1.85	24.3	2160	14.3	78.8	GaAs	$FA_{0.80}MA_{0.04}Cs_{0.16}Pb(I_{0.50}Br_{0.50})_3$	[256]
						CIGS/perovskite		
1.10	1.65	22.4	1774	17.3	73.1	CIGS	$Cs_{0.09}FA_{0.77}MA_{0.14}Pb(I_{0.86}Br_{0.14})_3$	[257][b]
1.11	1.64	21.6	1580	18.0	76.0	CIGS	$Cs_{0.05}(MA_{0.17}FA_{0.83})Pb_{1.1}(I_{0.83}Br_{0.17})_3$	[258]
1.11	1.65	23.3	1680	19.2	71.9	CIGS	$Cs_{0.05}(MA_{0.17}FA_{0.83})_{0.95}Pb(I_{0.83}Br_{0.17})_3$	[20]
1.12	1.68	24.2	1768	19.2	72.9	CIGS	–[b]	[259][a]
						Perovskite/perovskite		
1.26	**1.81**	**26.4**	**2048**	**16.5**	**77.9**	–[b]	–[b]	[2][a]
1.26	**1.82**	**24.0**	**1986**	**15.8**	**76.6**	**$FSA:MA_{0.3}FA_{0.7}Pb_{0.5}Sn_{0.5}I_3$**	**$FA_{0.8}Cs_{0.2}Pb(I_{0.6}Br_{0.4})_3$**	[11][a]
1.26	**1.82**	**25.5**	**2009**	**15.9**	**79.8**	**$FSA:MA_{0.3}FA_{0.7}Pb_{0.5}Sn_{0.5}I_3$**	**$FA_{0.8}Cs_{0.2}Pb(I_{0.6}Br_{0.4})_3$**	[11]
1.27	1.72	22.9	1915	15.0	79.8	$(FASnI_3)_{0.6}(MAPbI_3)_{0.4}$	$Cs_{0.05}FA_{0.8}MA_{0.15}PbI_{2.55}Br_{0.45}$	[47]
1.27	**1.81**	**24.3**	**2030**	**15.2**	**78.8**	**$Cs_{0.05}MA_{0.45}FA_{0.5}Pb_{0.5}Sn_{0.5}I_3$**	**$Cs_{0.4}FA_{0.6}PbI_{1.95}Br_{1.05}$**	[260]
1.27	1.81	24.5	1927	15.9	80.0	$FA_{0.7}MA_{0.3}Pb_{0.5}Sn_{0.5}I_3$	$FA_{0.8}Cs_{0.2}Pb(I_{0.6}Br_{0.4})_3$	[49][a]
1.28	1.73	23.1	1880	16.0	77.0	$FA_{0.75}Cs_{0.25}Sn_{0.5}Pb_{0.5}I_3$	$FA_{0.6}Cs_{0.3}DMA_{0.1}PbI_{2.4}Br_{0.6}$	[41]
						OPV/perovskite		
1.25	1.91	15.0	1710	12.0	73.4	PTB7-Th:COi8DFIC:$PC_{71}BM$	$CsPbI_2Br$	[261]
1.38	**1.91**	**21.1**	**1960**	**13.3**	**80.9**	**PM6:Y6-BO**	**$CsPbI_2Br$**	[262]
1.40	1.83	15.1	1850	11.5	71.0	PBDB-T:SN6IC-4F	$Cs_{0.1}(FA_{0.6}MA_{0.4})_{0.9}Pb(I_{0.6}Br_{0.4})_3$	[42]
1.40	**1.82**	**19.5**	**1925**	**13.1**	**77.2**	**PBDBT-2F:Y6:$PC_{71}BM$**	**$FA_{0.8}MA_{0.02}Cs_{0.18}PbI_{1.8}Br_{1.2}$**	[263][a]
1.40	**1.82**	**20.4**	**1902**	**13.1**	**81.5**	**PBDBT-2F:Y6:$PC_{71}BM$**	**$FA_{0.8}MA_{0.02}Cs_{0.18}PbI_{1.8}Br_{1.2}$**	[263]
						DSSC/perovskite		
1.59	1.93	10.5	1170	12.9	70.0	$(FAPbI_3)_{0.85}(MAPbBr_3)_{0.15}$	N719	[264]

[a]Certified efficiency; [b]Exception included as a *PCE* highlight without the absorber material information; [c]Certified efficiency from *J–V* curve with certified MPP tracking reporting *PCE* = 29.15%.[19]

Table 9. Highest efficiency tandem organic- and dye sensitized-based monolithic research solar cells performance parameters as a function of the device bandgap energies (from *EQE* spectra) of the bottom and top absorber materials.

$E_{g,bottom}$ [eV]	$E_{g,top}$ [eV]	*PCE* [%]	V_{oc} [mV]	J_{sc} [mA cm^{-2}]	*FF* [%]	Bottom absorber	Top absorber	Ref.
						OPV/OPV		
1.23	**1.66**	**16.4**	**1650**	**14.5**	**68.5**	**PTB7-Th:BTPV-4F:PC$_{71}$BM**	**PM6:m-DTC-2F**	[265]
1.24	1.72	17.3	1640	14.4	73.3	PTB7-Th:O6T-4F:PC$_{71}$BM	PBDB-T:F-M	[266]
1.31	1.64	15.9	1660	14.1	68.0	PM6:SFT8-4F	PCE-10:BT-CIC:BEIT-4F	[267]
1.32	1.65	15.0	1600	13.6	69.0	PTB7-Th:PCDTBT:IEICO-4F	PBDB-T-2F:TfIF-4FIC	[268]
1.32	**1.74**	**19.6**	**1910**	**14.2**	**72.4**	**PBDB-TF:ITCC**	**PBDB-TF:BTP-eC11**	[269]
1.32	**1.74**	**19.5**	**1912**	**14.2**	**72.0**	**PBDB-TF:ITCC**	**PBDB-TF:BTP-eC11**	[269]
1.37	**1.73**	**15.2**	**1610**	**12.9**	**73.0**	**PM6:Y6**	**PV2000:PCBM**	[270]
1.42	1.79	15.0	1590	13.3	71.0	PCE-10:BTCIC	DTDCPB:C$_{70}$	[271]
1.48	1.74	14.1	1710	11.7	70.0	PTB7-Th: NOBDT	PBDB-T: F-M	[272]
						OPV/a-Si		
1.33	**1.78**	**15.1**	**1610**	**13.2**	**71.0**	**PTB7-Th:IEICO-4F**	**a-Si**	[273]
						Si/DSSC		
1.11	1.84	14.7	580	40.9	62.0	Si	N719	[274]
1.24	1.67	17.2	1360	18.1	69.3	Si	SGT-021	[275]
						CIGS/DSSC		
1.21	1.82	13.0	1170	14.6	77.0	CIGS	N719	[276]
1.22	1.90	12.4	1435	14.1	61.0	CIGS	N719	[277]
1.22	1.82	15.1	1450	14.1	74.0	CIGS	N719	[278]
						DSSC/DSSC		
1.40	1.98	11.4	1400	12.2	66.7	DX1	N719	[279]
1.44	1.95	10.4	1450	10.8	67	N719	Black dye	[280]
1.78	2.37	7.1	1420	7.2	69	N719	D131	[281]

Table 10. Highest efficiency monolithic two junctions research solar cells performance parameters as a function of the device bandgap energies (from *EQE* spectra) of the bottom and top absorber materials among other established technologies.

$E_{g,bottom}$ [eV]	$E_{g,top}$ [eV]	*PCE* [%]	V_{oc} [mV]	J_{sc} [mA cm^{-2}]	*FF* [%]	Bottom absorber	Top absorber	Ref.
						GaAs/GaInP		
1.35	**1.90**	**32.9**	**2500**	**15.4**	**85.7**	**GaAs**	**GaInP**	[259]
1.41	1.88	32.8	2568	14.66	87.7	GaAs	GaInP	[282]
1.41	**1.92**	**27.4**	**2400**	**13.1**	**88.0**	**GaAs**	**GaInP**	[40]
1.42	1.85	31.6	2538	14.2	87.7	GaAs	GaInP	[283]
						Si/GaAsP		
1.17	**1.90**	**23.4**	**1732**	**17.34**	**77.7**	**Si**	**GaAsP**	[259]
						nc-Si/a-Si		
1.36	1.93	11.8	1428	12.27	67.5	nc-Si	a-Si	[284]

7.2. Best Performing Flexible Research Solar Cells Tables (Tables 11–16)

Table 11. Highest efficiency flexible perovskite single junction research solar cells performance parameters as a function of device absorber bandgap energy (from *EQE* spectrum).

E_g [eV]	*PCE* [%]	V_{oc} [mV]	J_{sc} [mA cm^{-2}]	*FF* [%]	Absorber perovskite	Ref.
1.47[a)]	3.6	616	14.5	40.6	$(5\text{-AVA})_\gamma(MA)_{1-\gamma}PbI_3$	[285]
1.53	**20.2**	**1123**	**24.7**	**72.9**	**$FA_{0.87}MA_{0.13}PbI_{3-x}Cl_x$**	[286]
1.54	18.3	1090	23.4	71.5	$FA_{0.95}Cs_{0.05}PbI_3$	[287]
1.54	18.2	1070	22.1	76.9	$FAPbI_{3-x}Br_x$	[288]
1.56	**20.8**	**1190**	**21.9**	**79.6**	**$(FAPbI_3)_{0.95}(MAPbBr_3)_{0.05}$**	[38]
1.56	**20.3**	**1160**	**23.4**	**74.8**	**$(FAPbI_3)_{0.95}(MAPbBr_3)_{0.05}$**	[289]
1.56	**19.9**	**1109**	**23.2**	**77.3**	**$Cs_{0.05}Rb_{0.05}(FA_{0.83}MA_{0.17})_{0.90}Pb(I_{0.95}Br_{0.05})_3$**	[290][b)]
1.56	**19.9**	**1192**	**21.9**	**76.3**	**$(FAPbI_3)_{0.95}(MAPbBr_3)_{0.05}$**	[38][b)]
1.57	19.5	1110	23.1	76.0	$FA_{0.945}MA_{0.025}Cs_{0.03}Pb(I_{0.975}Br_{0.025})_3$	[291]
1.58	**19.2**	**1120**	**21.7**	**78.9**	**$Cs_{0.08}MA_{0.05}FA_{0.87}PbI_{2.88}Br_{0.12}$**	[292]
1.59	**19.9**	**1120**	**23.0**	**77.5**	**$FAMAPb(IBr)_3$**	[293]
1.59	19.3	1090	22.7	78.1	$MAPbI_3$–NH4Cl	[294]
1.59	**17.2**	**1070**	**21.42**	**75.0**	**$(FA_{0.92}MA_{0.08})_{0.9}Cs_{0.1}Pb(I_{0.92}Br_{0.08})_3$**	[295]
1.60	19.0	1090	21.8	80.0	$MAPbI_3$	[296]
1.60	18.4	1103	22.5	74.2	$MAPbI_3$–dimethylsulfide	[297]
1.60	**18.3**	**1080**	**22.4**	**75.6**	**$Cs_{0.05}FA_{0.79}MA_{0.16}PbI_{2.49}Br_{0.51}$**	[298]
1.61	17.3	1062	21.7	74.9	$Cs_{0.05}FA_{0.81}MA_{0.14}PbI_{2.55}Br_{0.45}$	[299][b)]
1.61	**18.5**	**1100**	**22.7**	**74.3**	**$MAPbI_3$**	[300]
1.61	19.1	1135	21.2	79.2	$Rb_{0.01}K_{0.04}\,(Cs_{0.05}(FA_{0.83}MA_{0.17})_{0.95})_{0.95}Pb(I_{0.83}Br_{0.17})_3$	[301]
1.62	**20.1**	**1150**	**22.4**	**78.0**	**$Cs_{0.04}(FA_{0.84}MA_{0.16})_{0.96}Pb(I_{0.84}Br_{0.16})_3$**	[302]
1.62	18.0	1120	22.3	72.1	$Cs_{0.06}FA_{0.79}MA_{0.15}PbI_{2.55}Br_{0.45}$	[303]
1.63	10.4	1030	19.2	52.8	$(FAPbI_3)_{0.85}(MAPbBr_3)_{0.15}$	[304]
1.65	11.2	940	18.4	64.9	$MAPbI_3$	[305]
1.65	7.9	1090	10.8	70.7	$(\alpha\text{-}FAPbI_3)_{0.5}(MAPbI_2Br)_{0.5}$	[306]

[a)] E_g taken from absorption spectrum; [b)]Certified efficiency.

Table 12. Highest efficiency flexible organic single junction research solar cells performance parameters as a function of device absorber bandgap energy (from *EQE* spectrum).

E_g [eV]	*PCE* [%]	V_{oc} [mV]	J_{sc} [mA cm^{-2}]	*FF* [%]	Absorber blend	Ref.
1.27	**7.4**	**708**	**15.9**	**65.2**	**PTB7-Th:COi 8DFIC:$PC_{71}BM$**	[307]
1.32	10.6	690	24.3	63.2	PTB7-Th:IEICO-4F	[155]
1.37	**16.1**	**840**	**25.0**	**76.7**	**PM6:N3:$PC_{71}BM$**	[308]
1.38	**14.4**	**837**	**23.5**	**73.2**	**PM6:Y6**	[309]
1.39	**16.1**	**820**	**25.9**	**75.8**	**PBDB-T-2F:BTP-eC9:$PC_{71}BM$**	[310]
1.40	**16.1**	**860**	**25.9**	**74.7**	**PM6:Y6**	[39]
1.40	15.2	832	25.1	73.0	PBDB-T-2F:Y6	[311]
1.40	14.1	828	23.6	72.0	PM6:Y6:$PC_{71}BM$	[312]
1.41	**15.1**	**847**	**24.9**	**71.6**	**PM6:Y6:C6**	[313]
1.42	**16.6**	**860**	**25.9**	**74.7**	**PM6:Y6**	[39]
1.44	**10.4**	**848**	**17.0**	**72.2**	**PM6:Y6**	[307]
1.55	12.0	840	19.5	73.3	PM6:IT-4F	[182]
1.56	11.6	820	19.6	72.2	PBDB-T-2F:IT-4F	[314]
1.56	12.1	826	20.9	70.1	PBDB-T-2F:IT-4F	[183]
1.61	10.9	900	18.7	64.8	PBDB-T:ITIC	[183]
1.63	9.2	770	16.0	74.7	PTB7-Th:$PC_{71}BM$	[315]
1.65	9.3	820	16.5	68.7	J51:ITIC	[188]
1.65	8.2	890	13.4	68.6	PBDB-T:ITIC	[316]
1.82	**7.2**	**925**	**10.9**	**71.3**	**JP02**	[317]
2.01	3.7	592	10.4	59.2	P3HT:PCBM	[199]

Table 13. Highest efficiency flexible dye sensitized single junction research solar cells performance parameters as a function of device absorber bandgap energy (from *EQE* spectrum).

E_g [eV]	*PCE* [%]	V_{oc} [mV]	J_{sc} [mA cm^{-2}]	*FF* [%]	Sensitizing dye	Ref.	
1.65	4.1	770	9.9	53.9	N719	[318]	1
1.74	4.6	750	10.5	58.0	N719	[319]	2
1.75	7.6	732	15.0	69.2	N719	[320][a)]	3
1.78	7.5	725	15.4	67.5	N719	[321]	4
1.79	6.5	729	13.2	68.0	N719	[322]	5
1.80	6.3	732	13.1	66.0	N719	[323]	6
1.81	6.3	754	12.3	67.9	$(JH\text{-}1)_{0.6}(SQ2)_{0.4}$	[324]	7
183	5.0	735	10.0	67.8	N719	[325]	8
1.88	6.0	750	11.2	71.0	N719	[326]	9
1.90	4.2	680	10.7	57.7	N719	[327]	10
1.94	4.2	710	10.3	57.2	N719	[328]	11
1.95	4.9	702	11.2	62.3	N719	[329]	12
1.99	6.4	660	18.1	53.4	N719	[319]	13
2.12	**5.4**	**680**	**10.4**	**76.3**	**N719**	[330]	**14**

[a)]Certified efficiency.

Table 14. Highest efficiency flexible monolithic tandem research solar cells performance parameters as a function of device absorber bandgap energy (from *EQE* spectrum).

$E_{g,bottom}$ [eV]	$E_{g,top}$ [eV]	*PCE* [%]	V_{oc} [mV]	J_{sc} [mA cm^{-2}]	*FF* [%]	Bottom absorber material	Top absorber material	Ref.
1.28	1.73	21.3	1820	15.6	75.0	$FA_{0.75}Cs_{0.25}Sn_{0.5}Pb_{0.5}I_3$	$FA_{0.6}Cs_{0.3}DMA_{0.1}PbI_{2.4}Br_{0.6}$	[41]
1.40	1.82	13.6	1800	11.1	68.3	PBDB-T:SN6IC-4F	$Cs_{0.1}(FA_{0.6}MA_{0.4})_{0.9}Pb(I_{0.6}Br_{0.4})_3$	[42]
1.41	1.86	30.4	2547	14.3	84.7	GaAs	InGaP	[331]
1.41	**1.92**	**27.4**	**2400**	**13.1**	**88.0**	**GaAs**	**InGaP**	[40]

Table 15. Highest efficiency flexible single junction research solar cells performance parameters as a function of device absorber bandgap energy (from *EQE* spectrum) among emerging inorganic technologies.

E_g [eV]	*PCE* [%]	V_{oc} [mV]	J_{sc} [mA cm^{-2}]	*FF* [%]	Absorber material	Ref.
1.16	**11.2**	**539**	**33.1**	**62.8**	**$Cu_2ZnSn(S,Se)_4$**	[225]
1.32	**6.1**	**415**	**25.5**	**57.9**	**Sb_2Se_3**	[229]
1.52	**0.6**	**204**	**7.6**	**35.5**	**Cu_2ZnSnS_4**	[332]

Table 16. Highest efficiency flexible single junction research solar cells performance parameters as a function of device absorber bandgap energy (from *EQE* spectrum) among established inorganic technologies.

E_g [eV]	*PCE* [%]	V_{oc} [mV]	J_{sc} [mA cm^{-2}]	*FF* [%]	Absorber material/technology	Ref.
1.14	17.0	656	36.6	70.8	c-Si	[333]
1.17	18.9	608	39.5	63.0	c-Si	[334]
1.17	**12.0**	**580**	**35.8**	**58.4**	**CIGS**	[335]
1.20	20.4	736	35.1	78.9	CIGS	[336]
1.22	18.7	720	35.0	74.4	CIGS	[337]
1.32	8.4	550	24.3	63.0	c-Si	[338]
1.42	22.1	980	27.1	83.4	GaAs	[339]
1.46	16.4	831	25.5	77.4	CdTe	[340]
1.49	11.5	821	22.0	63.9	CdTe	[341]
1.79	8.8	888	14.3	70	a-Si:H	[342]
1.88	8.2	820	15.6	64.0	a-Si:H	[343]

7.3. Best Performing Transparent and Semitransparent Research Solar Cells Tables (Tables 17–21)

Table 17. Best transparent and semitransparent perovskite research solar cell performance parameters as a function of the average visible transmittance and the device absorber bandgap energy (from *EQE* spectrum).

AVT [%]	E_g [eV]	*PCE* [%]	V_{oc} [mV]	J_{sc} [mA cm^{-2}]	*FF* [%]	Absorber	Ref.
3	**1.64**	**15.7**	**1070**	**19.0**	**77.2**	**$Cs_{0.175}FA_{0.75}MA_{0.075}Pb\ (I_{0.875}Br_{0.125})_3$**	[344]
3	1.53	12.2	1017	17.5	68.5	$MAPbI_3$	[345]
4	1.63	18.2	1076	21.1	80.0	$CsFAMAPb(IBr)_3$	[346]
5	1.60	16.5	1080	20.6	74.2	$MAPbI_3$	[347]
5	1.61	12.0	960	19.2	65.3	$MAPbI_{3-x}Cl_x$	[348]
5	1.65	11.2	940	18.4	64.9	$MAPbI_3$	[305]
6	1.60	15.8	1100	19.3	74.4	$MAPbI_3$	[349]
7	1.55	13.6	988	20.4	67.5	$MAPbI_3$	[350]
8	**1.52**	**19.8**	**1137**	**21.9**	**79.5**	**$Cs_{0.05}FA_{0.95}PbI_3$**	[351]
9	**1.64**	**17.4**	**1083**	**21.5**	**75.1**	**$Cs_{0.175}FA_{0.825}Pb(I_{0.875}Br_{0.125})_3$**	[344]
10	1.59	17.5	1070	22.4	73.1	$MAPbI_3$	[352]
10	1.65	16.1	1060	20.4	74.5	$Cs_{0.05}(FA_{0.85}MA_{0.15})_{0.95}Pb(I_{0.85}Br_{0.15})_3$	[353]
12	1.60	13.2	1000	19.5	67.8	$MAPbI_3$	[352]
13	1.67	14.9	1100	19.8	68.4	$MAPbI_{2.5}Br_{0.5}$	[352]
14	**1.64**	**13.6**	**1048**	**16.5**	**78.6**	**$Cs_{0.175}FA_{0.825}Pb(I_{0.875}Br_{0.125})_3$**	[344]
14	1.57	13.0	970	19.1	69.9	$MAPbI_{3-x}Cl_x$	[354]
15	1.61	11.9	1000	17.8	66.3	$MAPbI_3$	[352]
16	1.76	13.7	1120	16.7	73.4	$MAPbI_2Br$	[352]
17	1.65	12.8	1040	16.6	74.1	$Cs_{0.05}(FA_{0.85}MA_{0.15})_{0.95}Pb(I_{0.85}Br_{0.15})_3$	[353]
18	1.77	12.2	1110	15.1	72.7	$MAPbI_2Br$	[352]
18	1.53	9.1	1017	14.6	61.5	$MAPbI_3$	[345]
19	1.55	8.8	941	13.7	68.3	$MAPbI_3$	[350]
20	**1.63**	**11.7**	**1080**	**14.5**	**74.6**	**$MAPbI_3$+ BiPy − I**	[355]
20	1.63	14.7	1108	17.6	75.2	$K_xCs_{0.05}(FA_{0.85}MA_{0.15})_{0.95}Pb(I_{0.85}Br_{0.15})_3$	[356]
21	1.63	14.2	1117	17.4	73.2	$K_xCs_{0.05}(FA_{0.85}MA_{0.15})_{0.95}Pb(I_{0.85}Br_{0.15})_3$	[356]
22	1.61	13.2	1073	17.2	71.7	$K_xCs_{0.05}(FA_{0.85}MA_{0.15})_{0.95}Pb(I_{0.85}Br_{0.15})_3$	[356]
23	1.61	12.3	1082	17.1	66.6	$K_xCs_{0.05}(FA_{0.85}MA_{0.15})_{0.95}Pb(I_{0.85}Br_{0.15})_3$	[356]
23	1.62	11.3	1040	15.1	72.3	$MAPbI_3$	[357]
23	1.57	10.8	970	17.3	64.4	$MAPbI_{3-x}Cl_x$	[354]
24	1.87	9.4	1120	13.6	61.6	$MAPbI_{1.5}Br_{1.5}$	[352]
25	1.55	10.8	950	16.3	69.7	$MAPbI_3$	[358]
26	1.63	10.2	1070	12.2	78.1	$MAPbI_3$	[359]
27	1.60	12.1	1000	18.3	66.2	$MAPbI_3$	[352]
28	1.60	8.5	964	13.1	66.8	$MAPbI_{3-x}Cl_x$	[360]
28	1.57	8.1	1030	11.2	70.2	$MAPbI_{3-x}Cl_x$	[354]
30	1.62	12.8	1030	16.5	74.9	$MAPbI_{3-x}Cl_x$	[361]
30	1.65	7.4	1010	11.8	62.2	$Cs_{0.05}(FA_{0.85}MA_{0.15})_{0.95}Pb(I_{0.85}Br_{0.15})_3$	[353]
31	1.69	11.9	1050	16.3	69.4	$MAPbI_{2.5}Br_{0.5}$	[352]
33	1.55	7.3	1037	13.4	52.5	$MAPbI_3$	[362]
34	1.62	11.7	990	15.9	74.6	$MAPbI_{3-x}Cl_x$	[361]
36	1.79	10.3	1080	14.6	65.5	$MAPbI_2Br$	[352]
37	1.62	10.8	1010	14.7	73.1	$MAPbI_{3-x}Cl_x$	[361]
37	1.57	7.8	970	11.6	69.6	$MAPbI_{3-x}Cl_x$	[354]
38	1.63	10.7	1060	13.0	77.6	$MAPbI_3$	[359]
41	1.90	8.8	1110	12.8	62.2	$MAPbI_{1.5}Br_{1.5}$	[352]
42	1.63	10.3	1000	13.6	75.6	$MAPbI_{3-x}Cl_x$	[361]
45	1.64	8.5	960	12.6	73.5	$MAPbI_{3-x}Cl_x$	[361]
46	1.57	3.6	1030	5.4	64.4	$MAPbI_{3-x}Cl_x$	[354]
47	1.63	4.5	880	8.2	63.0	$MAPbI_3$	[363]
66	2.62	1.1	1000	2.1	52.9	$Cs_2AgBiBr_6$	[364]
68	2.35	7.8	1550	6.7	72.0	$FAPbBr_{2.43}Cl_{0.57}$	[44]
72	2.62	1.5	960	2.1	74.3	$Cs_2AgBiBr_6$	[364]
72	3.03	0.2	1110	0.6	35.4	$MAPbCl_3$	[365]
73	2.62	1.6	970	2.2	73.1	$Cs_2AgBiBr_6$	[364]
73	2.84	0.5	1260	0.9	44.9	$MAPbCl_{2.4}Br_{0.6}$	[365]
74	2.62	1.5	970	2.2	71.1	$Cs_2AgBiBr_6$	[364]

Table 18. Best transparent and semitransparent organic research solar cell performance parameters as a function of the average visible transmittance and the device absorber bandgap energy (from *EQE* spectrum).

AVT [%]	E_g [eV]	*PCE* [%]	V_{oc} [mV]	J_{sc} [mA cm^{-2}]	*FF* [%]	Active material	Ref.
1	**1.40**	**13.3**	**810**	**24.6**	**66.5**	**PM6:Y6**	[366]
2	1.66	7.6	770	15.6	63.3	PBDTTT-C-T:$PC_{71}BM$	[367]
3	**1.40**	**12.6**	**800**	**24.5**	**64.5**	**PM6:Y6**	[366]
6	**1.47**	**12.0**	**870**	**19.6**	**70.4**	**PM7/PTTtID-Cl/IT-4F**	[368]
8	**1.73**	**7.3**	**860**	**12.1**	**69.6**	**DTDCPB:C_{70}**	[366]
9	1.42	14.2	854	23.0	72.3	PM6:Y6	[369]
11	1.66	7.1	760	14.5	64.4	PBDTTT-C-T:$PC_{71}BM$	[367]
13	1.42	13.3	853	21.7	71.9	PM6:Y6	[369]
14	**1.40**	**13.6**	**850**	**21.1**	**75.8**	**PM6:Y6**	[370]
14	**1.41**	**12.0**	**844**	**19.6**	**72.8**	**PM6:Y6:C6**	[313]
15	1.52	8.9	772	18.3	63.0	PTB7-Th:FNIC1	[371]
16	**1.95**	**2.9**	**540**	**9.7**	**55.4**	**P3HT-PCBM**	[372]
17	1.39	12.6	810	21.2	73.2	PBDB-T-2F:Y6	[373]
18	1.39	11.7	810	20.7	69.6	PBDB-T-2F:Y6	[373]
19	1.42	12.4	852	20.4	71.4	PM6:Y6	[369]
20	1.42	12.3	817	20.6	73.0	PM6:Y6	[374]
21	**1.41**[a)]	**13.8**	**820**	**25.3**	**66.5**	**PM6:N3**	[375]
25	1.34	11.0	750	20.9	70.0	PCE-10:A078	[376]
25	1.40	10.2	736	20.3	68.3	PTB7-Th:FOIC	[377]
26	1.40	12.9	825	21.6	72.4	PBDB-T-2F:Y6	[378]
28	**1.41**[a)]	**8.9**	**810**	**16.8**	**65.1**	**PM6:N3**	[375]
28	1.66	5.6	760	11.9	61.9	PBDTTT-C-T:$PC_{71}BM$	[367]
29	**1.41**[a)]	**7.8**	**800**	**15.2**	**64.7**	**PM6:N3**	[375]
30	1.35	10.8	718	21.9	68.7	PTB7-Th:IEICO-4F	[379]
34	1.40	9.1	733	18.5	67.1	PTB7-Th:FOIC	[377]
36	1.37	8.8	680	18.0	71.9	PCE-10:BT-CIC:TT-FIC	[380]
36	1.86	6.9	890	11.6	66.5	PSEHTT:ICBA	[381]
37	1.86	6.1	890	10.2	66.8	PSEHTT:ICBA	[381]
38	**1.33**	**5.7**	**700**	**12.4**	**66.2**	**PTB7-Th:IEICO-4F**	[382]
39	1.86	4.9	880	8.3	67.9	PSEHTT:ICBA	[381]
42	**1.35**	**9.6**	**690**	**26.1**	**53.2**	**PTB7-Th:IEICO-4F**	[383]
43	1.34	8.1	730	16.3	68.1	PCE-10:A078	[376]
44	1.37	8.0	680	16.2	72.6	PCE-10:BT-CIC:TT-FIC	[380]
46	1.34	10.8	750	20.4	70.6	PCE-10:A078	[376]
47	1.34	7.1	730	14.3	68.0	PCE-10:A078	[376]
47	1.86	2.4	860	4.1	68.2	PSEHTT:ICBA	[381]
49	1.37	7.2	670	14.8	72.6	PCE-10:BT-CIC:TT-FIC	[380]
50	1.38	8.3	746	16.7	66.8	PTB7-Th:FOIC:$PC_{71}BM$	[384]
51	1.39	7.4	749	14.7	66.7	PTB7-Th:FOIC:$PC_{71}BM$	[384]
53	1.86	1.8	890	3.8	54.8	PSEHTT:ICBA	[381]
53	1.32	5.7	750	10.6	69.5	DPP2T:IEICO-4F	[385]
60	**1.32**	**9.1**	**680**	**22.6**	**59.1**	**PTB7-Th:IEICO-4F**	[43]
60	1.33	3.9	749	7.3	70.2	DPP2T:IEICO-4F	[385]
62	1.33	5.9	690	12.9	66.0	PTB7-Th:6TIC-4F	[44]
73	1.50	1.2	990	1.5	81.0	CO_i8DFIC	[386]
84	2.81	0.4	520	1.3	65.0	PBMMA:PEMA:$(TBA)_2Mo_6Cl_{14}$	[387]
86	1.52	0.4	500	1.2	66.0	Cy7	[388]

[a)] E_g taken from absorbance.

Table 19. Best semitransparent dye sensitized research solar cell performance parameters as a function of the average visible transmittance and the device absorber bandgap energy (from *EQE* spectrum).

AVT [%]	E_g [eV]	*PCE* [%]	V_{oc} [mV]	J_{sc} [mA cm^{-2}]	*FF* [%]	Sensitizing dye	Ref.
1	2.00	5.2	780	12.4	53.7	N719	[389]
9	2.00	4.5	780	10.3	56.0	N719	[389]
9	1.82	4.3	720	9.9	60.0	N719+SDA	[390]
10	2.01	5.2	770	11.9	57.0	N719	[390]
10	2.00	4.9	765	11.4	56.1	N719	[389]
13	1.68	10.1	851	14.9	80.2	SGT-021	[391][a]
14	1.68	9.9	850	14.9	78.5	SGT-021	[391][a]
15	1.68	9.6	850	14.7	77.2	SGT-021	[391][a]
17	1.68	9.8	855	15.1	75.5	SGT-021	[391][a]
18	**2.00**	**8.6**	**750**	**16.7**	**68.4**	**N719 (EtOH)**	[45]
23	1.82	4.2	650	9.9	64.0	N719+SDA	[390]
23	2.01	3.6	650	8.2	68.0	N719	[390]
24	**2.00**	**7.8**	**794**	**17.4**	**56.3**	**N719 (EtOH)**	[45]
25	1.82	2.6	650	5.6	71.0	N719+SDA	[390]
27	**1.77**	**3.7**	**521**	**10.7**	**65.8**	**NPI**	[392]
30	2.19	1.5	640	3.3	70.0	N719	[390]
31	**2.23**	**6.4**	**698**	**13.5**	**67.9**	**TPA-1 (EtOH)**	[45]
33	**2.30**	**6.1**	**711**	**12.5**	**68.3**	**TPA-2 (EtOH)**	[45]
36	**2.23**	**6.1**	**766**	**14.5**	**54.7**	**TPA-1 (EtOH)**	[45]
37	**2.46**	**3.5**	**648**	**8.0**	**67.5**	**Cz-2**	[393]
38	**2.31**	**5.7**	**769**	**13.6**	**54.2**	**TPA-2 (EtOH)**	[45]
43	1.95	7.8	720	15.3	70.8	PdTPBP/BPEA	[394][b]
69	**1.39**	**3.1**	**422**	**11.2**	**65.6**	**VG20-C_{16}**	[395]
76	**1.41**	**2.3**	**406**	**8.6**	**65.9**	**VG20-C_{16}**	[395]

[a]Selective absorption-like EQE spectrum; [b]E_g calculated from transmittance spectrum.

Table 20. Best semitransparent research solar cell performance parameters as a function of the average visible transmittance and the device absorber bandgap energy (from *EQE* spectrum) for emerging inorganic technologies.

AVT [%]	E_g [eV]	*PCE* [%]	V_{oc} [mV]	J_{sc} [mA cm^{-2}]	*FF* [%]	Absorber/technology	Ref.
1	**1.46**	**3.0**	**475**	**14.6**	**42.8**	**$Cu_2ZnSn(S,Se)_4$**	[396]
8	**1.83**	**3.4**	**679**	**12.1**	**42.0**	**Sb_2S_3**	[397]

Table 21. Best semitransparent research solar cell performance parameters as a function of the average visible transmittance and the device absorber bandgap energy (from *EQE* spectrum) for established inorganic technologies.

AVT [%]	E_g [eV]	*PCE* [%]	V_{oc} [mV]	J_{sc} [mA cm^{-2}]	*FF* [%]	Absorber/technology	Ref.
2	1.23	10.0	640	23.3	66.9	CIGS	[398]
5	**1.26**	**9.8**	**630**	**22.9**	**67.6**	**CIGS**	[399]
7	**1.92**	**6.6**	**881**	**11.8**	**63.7**	**a-Si:H**	[400]
9	1.30	9.8	630	20.9	74.1	CIGS	[398]
9	1.28	6.5	597	22.9	46.5	CIGS	[401]
11	**1.34**	**8.4**	**620**	**20.4**	**66.3**	**CIGS**	[399]
16	1.83	7.5	810	14.2	65.3	a-Si:H	[402]
17	1.83	7.7	810	14.1	67.3	a-Si:H	[402]
18	2.05	5.9	720	14.1	58.3	a-SiGe:H	[403]
18	1.50	5.9	710	14.6	57.4	CIGS	[404]
19	1.87	7.3	820	13.1	67.6	a-Si:H	[402]
19	**1.30**	**6.9**	**640**	**16.6**	**64.7**	**CIGS**	[399]
19	1.34	6.5	580	17.5	63.5	CIGS	[398]
20	1.64	1.7	495	8.9	40.8	CIGS	[405]
22	2.05	5.5	760	12.3	58.6	a-Si:H	[403]
23	1.92	6.0	830	10.6	68.2	a-Si:H	[402]
24	1.68[a]	6.9	920	10.7	70.3	a-Si:H	[406]
37	1.54	0.4	101	14.7	27.2	CdTe	[407]
41	**2.17**	**1.1**	**596**	**3.9**	**47.3**	**a-Si:H**	[408]

[a]E_g taken from absorption spectrum.

7.4. Operational Stability Tables of Emerging Research Solar Cells (Tables 22–25)

Table 22. Most stable perovskite research solar cells in terms of the stability test energy yield for 200 and 1000 h under simulated 1 sun illumination as a function of the device bandgap energy (from *EQE* spectrum).

E_g [eV]	0 h *PCE* [%]	200 h *PCE* [%]	1000 h *PCE* [%]	E_{200h} [Wh cm^{-2}]	E_{1000h} [Wh cm^{-2}]	Absorber	Ref.	Comments[a]
1.53	**23.5**	**20.9**	–	**4.3**	–	**α-$FAPbI_3$**	[13]	**MPP, N2, w-LED, 35 °C**
1.54	**23.02**	**20.9**	**19.4**	**4.3**	**20.4**	**$FAPbI_3$/FGCs**	[409]	**MPP, AM1.5G, N_2, 60 °C**
1.57	21.8	22.0	21.8	4.2	22.0	$Cs_{0.05}(FA_{0.92}MA_{0.08})_{0.95}Pb(I_{0.92}Br_{0.08})_3$	[85]	MPP, AM1.5G, N_2, 40 °C, UV-f
1.57	20.6	20.2	20.2	4.1	20.1	$FA_xCs_{1-x}PbI_3$	[410]	MPP, w-LED, Ar, 55–60 °C
1.58	19.2	19.3	18.4	3.9	19.0	$(FA_{0.83}MA_{0.17})_{0.95}Cs_{0.05}Pb(I_{0.9}Br_{0.1})_3$	[411]	OC, AM1.5G, encapsulation, 70–75 °C
1.59	17.1	11.6	9.5	2.8	11.1	$MA_{0.85}Gua_{0.15}PbI_3$	[412]	MPP, AM1.5G, Ar, 60 °C
1.60	**21.8**	**21.4**	**19.8**	**4.3**	**20.9**	**$CsMAFAPbI_3$:PPP**	[24]	**MPP, encapsulation, air, AM1.5G, 75 °C**
1.60	**21.3**	**21.1**	**21.3**	**4.2**	**21.2**	**$CsMAFAPbI_3$:PPP**	[24]	**MPP, encapsulation, air, AM1.5G, 45 °C**
1.60	19.6	19.6	18.8	3.9	19.4	$Cs_{0.05}FA_{0.81}MA_{0.14}PbI_{2.55}Br_{0.45}$	[413]	MPP-R_L, AM1.5G, encapsulation, 50–70% RH, 65 °C
1.61	18.1	11.9	13.6	2.6	13.0	$MA_{0.75}Gua_{0.25}PbI_3$	[412]	MPP, AM1.5G, Ar, 60 °C
1.62	**21.1**	**19.9**	**18.0**	**4.0**	**19.1**	**$Cs_{0.04}(FA_{0.84}MA_{0.16})_{0.96}Pb(I_{0.84}Br_{0.16})_3$**	[302]	**MPP, AM1.5G, N_2, 40 °C**
1.63	**20.0**	**16.8**	**11.8**[b]	**3.5**	**15.1**	**$Cs_{0.05}FA_{0.79}MA_{0.16}PbBr_{0.51}I_{2.49}$**	[414]	**MPP, AM1.5G, N_2, 25 °C**
1.63	**21.0**	**19.7**	**19.4**[b]	**3.9**	**19.6**	**$Cs_{0.05}FA_{0.81}MA_{0.14}PbI_{2.55}Br_{0.45}$/FGCs**	[409]	**MPP, AM1.5G, N_2, 60 °C**
1.64	20.1	17.8	–	3.7	–	$Cs_{0.1}(MA_{0.17}FA_{0.83})_{0.9}Pb(I_{0.83}Br_{0.17})_3$	[415]	MPP, w-LED, N_2, 25 °C
1.64[c]	19.7	17.2	–	3.5	–	$Cs_{0.5}(FA_{0.83}MA_{0.17})_{0.95}Pb(I_{0.83}Br_{0.17})_3$	[416]	MPP, w-LED, N_2, 20 °C
1.66	13.0	14.7	13.0	2.8	14.1	$Cs_{0.17}FA_{0.83}Pb(Br_{0.17}I_{0.83})_3$	[417]	MPP, AM1.5G, 40% RH, 35 °C
1.69	6.8	6.7	–	1.3	–	$CsSn_{0.5}Ge_{0.5}I_3$	[101]	MPP†, AM1.5G, N_2, 45 °C
1.74	12.9	13.4	–	2.7	–	$CsPbI_3$	[418]	OC, AM1.5G, N_2, 25 °C, UV-f

[a]Abbreviations: MPP, maximum power point (tracking during test); OC, open-circuit (condition during test); UV-f, ultraviolet light filter; w-LED, white light spectrum light emitting diode source; RH, relative humidity; MPP-R_L, the cell is connected to the load resistance which matches the initial maximum power point; [b]Extrapolated value; [c]E_g taken from PL peak.

Table 23. Most stable organic research solar cells in terms of the stability test energy yield for 200 and 1000 h under simulated 1 sun illumination as a function of the device bandgap energy (from *EQE* spectrum).

E_g [eV]	0 h *PCE* [%]	200 h *PCE* [%]	1000 h *PCE* [%]	E_{200h} [Wh cm^{-2}]	E_{1000h} [Wh cm^{-2}]	Active material	Ref.	Comments[a]
1.56	7.8	7.2	6.8	1.5	7.0	PBDB-T:ITIC-2F	[419]	OC, w-LED, N_2, 40 °C, UV-f
1.57	5.0	5.0	4.7	1.0	4.8	P3HT:o-IDTBR	[420]	OC, AM1.5G, N_2, UV-f
1.61	**5.1**	**4.9**	**4.9**	**1.1**	**4.9**	**Dyad 4**	[421,422]	**OC, w-LED, N_2, 30 °C**
1.66	8.0	7.4	7.0	1.5	7.3	PBDB-T:ITIC-Th	[419]	OC, w-LED, N_2, 40 °C, UV-f
1.70	8.7	8.1	–	1.6	–	PBDB-T:IDTBR	[423]	OC, AM1.5G, N_2, 35–40 °C
1.84	5.9	5.6	5.4	1.1	5.6	PBDB-T:PCBM	[419]	OC, w-LED, N_2, 40 °C, UV-f
1.94	3.7	3.7	3.7	0.7	3.7	P3HT-PCBM	[424]	OC, AM1.5G, air

[a]Abbreviations: OC, open-circuit (condition during test); UV-f, ultraviolet light filter; w-LED, white light spectrum light emitting diode source.

Table 24. Most stable dye sensitized research solar cells in terms of the stability test energy yield for 200 and 1000 h under simulated 1 sun illumination as a function of the device bandgap energy (from *EQE* spectrum).

E_g [eV]	0 h *PCE* [%]	200 h *PCE* [%]	1000 h *PCE* [%]	E_{200h} [Wh cm^{-2}]	E_{1000h} [Wh cm^{-2}]	Sensitizing dye	Ref.	Comments[a]
1.59	9.0	9.0	8.2	1.8	8.7	TF-tBu_C3F7	[425]	OC, AM1.5G, 65 °C
1.75	6.5	6.7	6.3	1.4	6.6	N719	[426]	OC, AM1.5G, 35 °C, UV-f
1.77	6.3	5.8	4.8	1.3	5.5	Z907	[427]	OC, w-LED, 20 °C
1.78	9.3	9.9	7.9	1.9	9.2	N719	[428]	OC, AM1.5G, 50 °C
1.83	8.4	8.3	–	1.7	–	MK2	[425]	OC, w-LED
1.85	8.0	8.3	8.3	1.4	8.1	N719	[429]	OC, AM1.5G
2.07	5.8	6.5	5.9	1.3	6.2	D35	[430]	OC, AM1.5G, 60 °C

[a]Abbreviations: OC, open-circuit (condition during test); UV-f, ultraviolet light filter; w-LED, white light spectrum light emitting diode source.

Table 25. Most stable tandem research solar cells in terms of the stability test energy yield for 200 and 1000 h under simulated/equivalent 1 sun illumination as a function of the device bandgap energies (from *EQE* spectra) of the absorber materials.

Bottom E_g [eV]	Top E_g [eV]	0 h *PCE* [%]	200 h *PCE* [%]	1000 h *PCE* [%]	E_{200h} [Wh cm^{-2}]	E_{1000h} [Wh cm^{-2}]	Bottom absorber material	Top absorber material	Ref.	Comments[a]
							Perovskite/perovskite			
1.26	**1.82**	**24.4**	**24.3**	**19.3**[b]	**4.9**	**21.8**[b]	**FSA:$MA_{0.3}FA_{0.7}Pb_{0.5}Sn_{0.5}I_3$**	**$FA_{0.8}Cs_{0.2}Pb(I_{0.6}Br_{0.4})_3$**	[11]	**MPP, encapsulation, air, 30–50% RH, AM1.5G, no UV-f, 54–60 °C**
1.26	**1.82**	**21.2**	**20.6**	**19.8**	**4.2**	**20.7**	**$Cs_{0.05}MA_{0.45}FA_{0.5}Pb_{0.5}Sn_{0.5}I_3$**	**$Cs_{0.4}FA_{0.6}PbI_{1.95}Br_{1.05}$**	[260]	**MPP-R_L, encapsulation, air, AM1.5G, room T**
1.27	1.72	23.1	22.2	20.4	4.7	21.4	$(FASnI_3)_{0.6}(MAPbI_3)_{0.4}$	$Cs_{0.05}FA_{0.8}MA_{0.15}PbI_{2.55}Br_{0.45}$	[47]	MPP, AM1.5G
							GaAs/perovskite			
1.42	1.85	24.1	23.9	22.1[b]	4.76	23.3[b]	GaAs	$FA_{0.80}MA_{0.04}Cs_{0.16}Pb(I_{0.50}Br_{0.50})_3$	[256]	MPP, air 20–25% RH, AM1.5G, room T, UV-f
							CIGS/perovskite			
1.10	1.65	22.0	19.9	18.4[b]	4.1	19.4[b]	CIGS	$Cs_{0.09}FA_{0.77}MA_{0.14}Pb(I_{0.86}Br_{0.14})_3$	[257]	MPP, air 20% RH, 30 °C

[a]Abbreviations: MPP, maximum power point (tracking during test); UV-f, ultraviolet light filter; RH, relative humidity; MPP-R_L, the cell is connected to the load resistance which matches the initial maximum power point; MA, methylammonium; FA, formamidinium; [b]Extrapolated value.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

R.R.L. is a cofounder, director, and a part owner of Ubiquitous Energy, Inc., a company working to commercialize transparent photovoltaic technologies. All other authors declare no competing financial interest.

Keywords

bandgap energy, emerging photovoltaics, flexible photovoltaics, photovoltaic device operational stability, tandem solar cells, transparent and semitransparent solar cells

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Osbel Almora graduated of Physics from the University of Havana, Cuba, in 2013 and received his Ph.D. in 2020 from both the Universitat Jaume I of Castelló, Spain, and the Friedrich-Alexander Universität Erlangen-Nürnberg (FAU), in Germany. His main research interests are the characterization and modeling of energy materials and devices, e.g., perovskite solar cells, and more recently he focused on the development of optoelectronic characterization techniques, such as the light intensity modulated impedance spectroscopy (LIMIS). On December 4, 2019, he presented the initiating concept for the "Emerging PV reports" during a seminar at FAU.

Derya Baran received her Ph.D. from Friedrich-Alexander University Erlangen-Nuremberg, Germany in 2014. She worked at Forschungszentrum Jülich, Germany and the Center for Plastic Electronics, Imperial College London, UK prior to joining KAUST as an assistant professor in 2017. Her research group, the organic/Hybrid materials for energy applications lab (OMEGALAB) focuses on solution processable organic/hybrid soft materials for electronic devices including solar cells and thermoelectric devices.

Guillermo C. Bazan received his B.Sc. (*summa cum laude*) from the University of Ottawa. His Ph.D. studies were carried out at Massachusetts Institute of Technology (MIT) under the guidance of Nobel Laureate Richard R. Schrock. He was a postdoctoral associate at the California Institute of Technology with Professor John E. Bercaw. Gui joined the University of Rochester in 1992, and the University of California, Santa Barbara in 1998, where he held appointments in the Departments of Chemistry and Biochemistry and Materials. In 2020, Gui moved to the National University of Singapore, as a member of the Chemistry and Chemical and Biomolecular Engineering Departments.

Christian Berger received the M.Sc. Degree in Computer Science in 2016 from the Friedrich-Alexander University Erlangen-Nuremberg, Germany where he is currently pursuing his Ph.D. His research focuses on the automation of scientific laboratory processes by combining mechanical engineering, electrical engineering and computer science. As part of the Research Team High Throughput Materials and Devices at the Helmholtz Institute Erlangen-Nürnberg he is the lead architect of AMANDA (Autonomous Materials and Device Application Platform).

Carlos I. Cabrera received his Ph.D. in Physics from the Autonomous University of Zacatecas (UAZ), Mexico, in 2018, working on computational modeling of quantum heterostructure solar cells. He joined the Collaboratory for Epitaxy of Nanomaterials (CEN) at Boise State University as a visiting graduate research assistant, modeling self-assembled quantum dots (QD) nanostructures. He then joined the Autonomous University of the State of Morelos, as a postdoctoral research fellow. He is currently a professor at the Academic Unit of Science and Technology of Light and Matter (LUMAT-UAZ), and his research interests include solar cells, self-assembled QD nanostructures, and 2D materials for optoelectronic applications.

Kylie R. Catchpole is professor in the Research School of Electrical, Energy and Materials Engineering at the Australian National University. She has research interests in solar cells and solar fuels as well as the broader energy transition.

Sule Erten-Ela received her Ph.D. degree in 2004 from the Ege University in Turkey. She received a full professor position in 2015 in the Ege University-Solar Energy Institute. Şule Erten-Ela has been the Head of the Energy Department since 2016. Since 2019, she has been working as the director of Solar Energy Institute at Ege University. She is currently working as a professor at the Ege University, Institute of Solar Energy, Department of Energy.

Fei Guo received his Ph.D. in Material Science from Friedrich-Alexander University Erlangen-Nuremberg, Germany in 2015. After a year's postdoctoral training at the group of Prof. Christoph J. Brabec, he joined Jinan University as a full professor in March 2017. His current research interests focus on printed optoelectronic devices based on perovskites and organic semiconductors.

Jens Hauch received the B.A. degree from the University of Illinois at Urbana–Champaign, Champaign, IL, USA, in 1992, and the Ph.D. degree from the University of Texas at Austin, Austin, TX, USA, in 1998, both in physics. Since 2002, he has been active in the development of PV technologies in various positions at Siemens AG, Konarka Technologies, Energie Campus Nuremberg and Bavarian Center for Applied Energy Research (ZAE Bayern). Currently he is the head of the Research Unit "High Throughput Methods in Photovoltaics" at the Helmholtz Institute Erlangen-Nuremberg for Renewable Energies.

Anita W. Y. Ho-Baillie is the John Hooke Chair of Nanoscience at the University of Sydney and an Australian Research Council Future Fellow. She completed her Bachelor of Engineering on Co-op scholarship (2001) and Ph.D. (2005) at University of New South Wales. She is a highly cited researcher in 2019 and 2020. Her research interests include engineering of solar materials and devices at nanoscale for high performance durable single junction and multijunction tandem cells for a wide range of applications.

T. Jesper Jacobsson obtained a Ph.D. in Inorganic Chemistry at Uppsala University in 2014 with a project focusing on ZnO quantum dots and CIGS-based devices for solar hydrogen production. After his Ph.D., he has worked as a postdoc at École polytechnique fédérale de Lausanne (EPFL), Cambridge University, Uppsala University and at Helmholtz Zentrum Berlin with experimental development of perovskite solar cells. He is now a group leader at Nankai University.

Rene A. J. Janssen is a university professor in chemistry and physics at the Eindhoven University of Technology (TU/e) where he has researched molecular semiconductor materials and their application to organic and perovskite solar cells. His work combines organic and polymer synthesis, optical spectroscopy, electrochemistry, and morphological studies with the design, fabrication, and optoelectronic characterization of devices with the aim of enhancing performance levels.

Thomas Kirchartz is a professor in the department of Electrical Engineering and Information Technology at the University Duisburg-Essen (since 2013). In addition, he is the head of the department of Analytics and Simulation and the group for organic and hybrid solar cells at the Research Centre Jülich (Institute for Energy and Climate Research). Previously he was a junior research fellow at Imperial College London (2010–2013) and received a Dr.Ing. from RWTH Aachen (2009). His research interests include the fundamental understanding of photovoltaic devices, their characterization and simulation and the development of solution-processable solar cells.

Nikos Kopidakis is a research scientist at NREL and the technical lead of the PV Cell and Module performance group. He has over 20 years of experience in PV research, including silicon, dye-sensitized and organic PV. His interests cover the performance characterization of PV cells and modules of any size and technology and new measurement techniques for novel and emerging PV. He has previously worked on new materials for PV applications and in spectroscopic techniques for characterizing their photophysics.

Yongfang Li is a professor in the Institute of Chemistry, Chinese Academy of Sciences (ICCAS) and at the Soochow University. He received his Ph.D. degree in the department of Chemistry from Fudan University in 1986, followed by postdoctoral research at ICCAS from 1986 to 1988. He became a staff in 1988 and was promoted to professor in 1993 in ICCAS. He was elected as a member of the Chinese Academy of Sciences in 2013. His present research field is photovoltaic materials and devices for polymer solar cells.

Maria A. Loi is full professor and chair of Photophysics and OptoElectronics at the University of Groningen, the Netherlands. She studied Physics at the University of Cagliari in Italy where she received her Ph.D. (2001). Before joining the University of Groningen in 2006 she has been member of the Linz Institute for Organic Solar cells, of the University of Linz, Austria and of the Institute for Nanostructured Materials of the Italian National Research Council in Bologna. Her current research interest focuses on the understanding of the physical properties of new semiconductors and of optoelectronic devices made with them.

Richard R. Lunt is the Johansen Crosby endowed professor at Michigan State University in the Departments of Chemical Engineering and Materials Science and Physics. He earned his B.S. from the University of Delaware (2000) and his Ph.D. from Princeton University (2010). He then worked as a postdoctoral researcher at MIT (2011). His group focuses on understanding and exploiting excitonic photophysics and molecular crystal growth to develop unique thin film optoelectronic devices. He is known for his pioneering work in developing transparent solar cells and is cofounder of Ubiquitous Energy Inc., which is working to commercialize transparent solar cells.

Xavier Mathew has been a senior scientist and professor at the Instituto de Energías Renovables (IER) of the Universidad Nacional Autónoma de México (UNAM) since 1998. His research interests include materials for photovoltaic applications and in particular devices based on CdTe and perovskites.

Michael D. McGehee is a professor in the Chemical and Biological Engineering Department at the University of Colorado Boulder. He is the associate director of the Materials Science and Engineering Program and has a joint appointment at the National Renewable Energy Lab. He was a professor in the Materials Science and Engineering Department at Stanford University for 18 years and a senior fellow of the Precourt Institute for Energy. His current research interests are developing new materials for smart windows and solar cells. He received his B.Sc. from Princeton University and his Ph.D. from the University of California, Santa Barbara.

Jie Min received his M.S. degree (2011) under the supervision of Prof. Yongfang Li at the Institute of Chemistry, Chinese Academy of Sciences (ICCAS) as a joint-training Master student, and obtained his Ph.D. (2015) under the supervision of Prof. Christoph J. Brabec from Friedrich-Alexander Universität Erlangen-Nürnberg (FAU). After more than one year of postdoctoral research in Prof. Brabec's group, he joined Wuhan University as a full professor in 2017. His current research focuses on the development of organic materials and stable devices for the industrialization of next-generation photovoltaics.

David B. Mitzi is the Simon family professor at Duke University, with appointments to the Departments of Mechanical Engineering and Materials Science and Chemistry. He received his B.Sc. in Electrical Engineering and Engineering Physics from Princeton University (1985) and his Ph.D. in Applied Physics from Stanford University (1990). Prior to joining the faculty at Duke (2014), Dr. Mitzi spent 23 years at IBM's Watson Research Center, where his focus was on the search for and application of new electronic materials, including organic–inorganic perovskites and inorganic materials for photovoltaic, LED, transistor, and memory applications.

Mohammad K. Nazeeruddin received his Ph.D. degree in Inorganic Chemistry from Osmania University Hyderabad, India. Currently, he is a professor of Chemistry at Swiss Federal Institute of Technology, Lausanne, and his research focuses on perovskite and dye-sensitized solar cells and light-emitting diodes. His group is involved in developing stable perovskite solar cells by compositional and interface engineering. He was appointed as World Class University (WCU) professor at Korea University, and Adjunct Professor at King Abdulaziz University, Jeddah.

Jenny Nelson is a professor of physics at Imperial College London, where she has researched novel varieties of material for use in solar cells since 1989. Her current research is focused on understanding the properties of molecular and hybrid semiconductor materials and their application to solar energy conversion. This work combines fundamental electrical, spectroscopic, and structural studies of molecular electronic materials with numerical modeling and device studies, for optimizing the performance of solar cells and other devices. She also works with the Grantham Institute for Climate Change at Imperial to explore the mitigation potential of renewable energy technologies.

Ana F. Nogueira obtained her Bachelor in Chemistry from the University of Sao Paulo (1996) and Master (1998) and Ph.D. in Chemistry from the University of Campinas (2001). She worked as a postdoctorate fellow at the Imperial College, UK, (2001–2002) and as visiting researcher at Stanford University (2017–2018). She is currently a professor in the Chemistry Institute at Universidade Estadual de Campinas (UNICAMP) and director of the Center for Innovation on New Energies (CINE). Her research focuses on the development of functional (nano)materials and their application in solar energy conversion. She has experience on perovskite solar cells, perovskite quantum materials, and dense energy carriers.

Ulrich W. Paetzold is a tenure-track professor for next generation photovoltaics at Karlsruhe Institute of Technology (KIT). He was a doctoral student at Forschungszentrum Jülich and received his Ph.D. in Physics from Rheinisch-Westfälische Technische Hochschule (RWTH) Aachen University, then continued as a postdoc at Interuniversity Microelectronics Centre (IMEC) in Leuven. His research focuses on the interaction between light and structured matter for the purpose of engineering novel optical concepts and nanophotonic materials for solar energy harvesting. He is particularly interested in perovskite thin-film photovoltaics and perovskite based multijunction photovoltaics.

Nam-Gyu Park is a professor and SKKU-Fellow at the School of Chemical Engineering, Sungkyunkwan University (SKKU). He received his B.S., M.S., and Ph.D. degrees from Seoul National University (SNU) in 1988, 1992, and 1995, respectively. He worked at Institut de Chimie de la Matière Condensée de Bordeaux & Le Centre National de la Recherche Scientifique (ICMCB-CNRS), France, and National Renewable Energy Laboratory (NREL), USA, from 1996 to 1999 as a postdoctoral researcher. He worked as the director of Solar Cell Research Center at the Korea Institute of Science and Technology (KIST) in Korea before joining SKKU as a full professor in 2009. He is the pioneer of the solid-state perovskite solar cell, discovered in 2012.

Barry P. Rand earned a B.E. in electrical engineering from The Cooper Union in 2001. Then he received M.A. and Ph.D. degrees in electrical engineering from Princeton University, in 2003 and 2007, respectively. He is in the Department of Electrical Engineering and Andlinger Center for Energy and the Environment at Princeton University, currently as an associate professor. His research interests highlight the border between electrical engineering, materials science, chemistry, and applied physics, covering electronic and optoelectronic thin-films and devices.

Uwe Rau is currently director of the Institute for Energy and Climate Research-5 (Photovoltaics) at Research Centre Jülich. He is also professor at RWTH Aachen, Faculty of Electrical Engineering and Information Technology, where he holds the chair of photovoltaics. Previously, he was senior researcher at the University Stuttgart as well as post doc at the University Bayreuth and at the Max-Planck-Institute for Solid State Research in Stuttgart. His research interest covers electronic and optical properties of semiconductors and semiconductor devices, especially characterization, simulation, and technology of solar cells and solar modules.

Henry J. Snaith is a Professor of Physics and Group Leader of the Photovoltaics and Optoelectronics Device group at the University of Oxford. He has pioneered the development of hybrid materials for energy and photovoltaics through an interdisciplinary combination of materials synthesis, device development, advanced optoelectronic characterizations, and theoretical studies. He has created new materials with advanced functionality and enhanced understanding of fundamental mechanisms. He is the cofounder and chief scientific officer of Oxford PV, a successful startup company founded to commercialize the perovskite solar cell technology.

Eva Unger is a young investigator group leader at Helmholtz Zentrum Berlin (Germany) and holds an assistant professor position at the Department of Chemistry at Lund University (Sweden). She has a Ph.D. degree from Uppsala University (Sweden) where she worked on Excitonic Dye Solar Cells. During her postdoctoral research at Stanford University (USA) she investigated dynamic hysteresis phenomena in hybrid Perovskite Solar Cell devices. Her current research focuses on scalable process development for the manufacturing of larger area Perovskite Solar Cells and the rationalization of material formation mechanisms from solutions to solid state thin films.

Lídice Vaillant-Roca is the head of the Photovoltaic Research Laboratory at the University of Havana, Cuba. She received her Ph.D. in 2008 from both the University of Havana, and the University of Parma, Italy. She was a postdoc researcher at ISEFraunhofer and Albert-Ludwigs-Universitat, Freiburg (2011) and invited professor at the Nime Universite, France, and the Politecnico di Torino, Italy (2017). Her research focuses on the study of novel materials and low-cost fabrication techniques to obtain and improve the performance of thin film and nanostructured solar cells.

Hin-Lap Yip is a professor in the Department of Materials Science and Engineering and the Hong Kong Institute for Clean Energy at the City University of Hong Kong. He got his B.Sc. and M.Phil. degrees in Materials Science from the Chinese University of Hong Kong, and completed his Ph.D. degree in Materials Science & Engineering in 2008 at the University of Washington, Seattle. From 2013 to 2020, he was a faculty in the State Key Laboratory of Luminescent Materials and Devices and the School of Materials Science and Engineering in South China University of Technology. His current research focuses on the use of an integrated approach combining materials, interface, and device engineering to improve both polymer and perovskite optoelectronic devices.

Christoph J. Brabec received his Ph.D. (1995) from Linz University, Austria and joined the group of Nobel Prize laureate Alan Heeger at University of California Santa Barbara (USA) for a sabbatical. He joined the SIEMENS research labs (project leader, 2001), Konarka (chief technology officer, 2004), the Erlangen-Nuremberg-University (professor for material science, 2009), the ZAE Bayern e.V. (scientific director, 2010–2020), the Interdisciplinary Center for Nanostructured Films (spokesman, 2013–2016), the Forschungszentrum Julich (director, 2018–2023) and the University of Groningen (honorary professor, 2018–2023). His research interests include all aspects of solution processing organic, hybrid, and inorganics semiconductor devices with a focus on photovoltaics and renewable energy systems.