Device Performance of Emerging Photovoltaic Materials (Version 1)

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*

Emerging photovoltaics (PVs) focus on a variety of applications complementing large scale electricity generation. Organic, dye-sensitized, and some perovskite solar cells are considered in building integration, greenhouses, wearable, and indoor applications, thereby motivating research on flexible, transparent, semitransparent, and multi-junction PVs. Nevertheless, it can be very time consuming to find or develop an up-to-date overview of the state-of-the-art performance for these systems and applications. Two important resources for recording research cells efficiencies are the National Renewable Energy Laboratory chart and the efficiency tables compiled biannually by Martin Green and colleagues. Both publications provide an effective coverage over the established technologies, bridging research and industry. An alternative approach is proposed here summarizing the best reports in the diverse research subjects for emerging PVs. Best performance parameters are provided as a function of the photovoltaic bandgap energy for each technology and application, and are put into perspective using, e.g., the Shockley–Queisser limit. In all cases, the reported data correspond to published and/or properly described certified results, with enough details provided for prospective data reproduction. Additionally, the stability test energy yield is included as an analysis parameter among state-of-the-art emerging PVs.

1. Introduction

Photovoltaic (PV) technologies are one of the best strategies for sustainable production of electricity based on renewable sources. Solar cells harvest the energy of incident photons to produce usable electricity with the highest possible power conversion efficiency (PCE). Moreover, from every component of a PV system one expects the best performance, long-term operational lifetime, low production costs and low environmental hazard. These criteria are the focus for the PV research community in order to meet the requirements for the industry and the market, in agreement with eco-friendly policies.

Cutting-edge scientific achievements are typically published in prestigious academic journals with high impact factors. However, the increasing number of journals, academic articles and in some cases even editorial policies for increasing impact factors, enhance the complexity...
associated with identifying the state-of-the-art in each subject. In the case of PV research, the community has identified the PCE measured under standard test conditions as the most common widely used metric for comparing the performance of solar cells. The PCE is determined by extracting the maximum output power (P(out)) from the measured current density-voltage (J–V) characteristic under standard incident one sun illumination (P = 100 mW cm−2 of global AM1.5 spectrum) at 25 °C (IEC 60904-3: 2008, ASTM G-173-03 global). The P(out) value can be expressed in terms of the short-circuit current density (Jsc), the open-circuit voltage (Voc), and the fill factor (FF) from the illuminated J–V characteristic, via

\[
P_{\text{cell}} = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{V_{oc} J_{sc} FF}{P_{in}}
\]

(1)

By using the Shockley–Queisser (SQ) detailed balance limit,[1] one can estimate the maximum PCE of a single-junction-like PV solar cell as a function of the illumination, the temperature and the bandgap of the absorber material. This can be of interest to compare with the measured PCE of any given PV cell.

Long-term stability is another important metric for photovoltaic materials and devices. However, the study of degradation of most PV devices from first and second generations, like silicon and inorganic thin film solar cells, has always been predominantly an industrial concern rather than being of academic interest. One simple reason for this could be the stable performance lifetimes larger than 10 years commonly exhibited by these devices.[2–3] In contrast, most typical academic research projects are funded for 2–3 years. Furthermore, other very active research frontiers like the lowering of costs and the reduction of negative environmental impacts would be difficult to parameterize before the industrial stage; finding standard metrics for fairly identifying the “cheapest” and “healthiest” PV devices are challenging tasks for the future.

The absolute certified PCE records for most prominent PV technologies have been successfully increasing, mostly during the last three decades, as biannually summarized in the “Solar cell efficiency tables” by Green et al.[4–6] since 1993, and with more immediacy in National Renewable Energy Laboratory (NREL)’s “Best research-cell efficiency chart.”[7] The tables from Green et al. are the more comprehensive reference, listing state-of-the-art values for performance parameters: PCE, Voc, Jsc, and FF of certified devices. They also present the J–V curves under standard illumination conditions and external quantum efficiency (EQE) for each new report. These data are effective for tracking progress in technologies like Si solar cells, where a significant number of reports come from industry, while maintaining confidentiality. Also, first and second generation in PVs have been significantly optimized, and retain some general design concepts and the core absorbing materials. Academically, this means that one can still grasp some general idea of the devices’ working principles and fabrication technologies, even if complete details are missing. With a similar philosophy, NREL’s chart is the community’s go-to representation for the timeline evolution of PVs. However, for further and more in-depth analysis, one is missing the underlying data behind each data point on the graph. The sheer amount of information on a single slide, which is one major attraction of the NREL chart, makes it on the other hand problematic to use on slides without zooming into the areas of interest. Moreover, the confidential nature of certificates, which both, Green et al. tables and NREL’s chart are relying on, has created a need for discussions in the academic community on the value of “reported-before-published” updates. The rise of new and emerging PV technologies, mainly during the last decade, resulting in numerous materials research and development diversifications, have even increased the necessity to conduct and resolve these discussions.

Emerging photovoltaic technologies include but are not limited to devices like 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 or chalcogenides, or silicides. Typically, these technologies do not correspond to single absorber materials, but to families of materials, and in some cases the device architectures must be varied due to essential scientific or technological design criteria. Therefore, reported-before-published updates for emerging PVs in both, Green et al. tables and NREL’s chart, often impede a minimal understanding of what the materials, structures and working principles for each reported cell are, constituting a shortcoming for reproducibility. Moreover, the focus of emerging PVs is not only based on supplying green electricity to the grid. The research on emerging solar cell technologies is particularly targeting integration into buildings, greenhouses, airplanes, sails, automobiles, fabrics or indoor applications which require flexible and semitransparent devices. Some of these applications must sacrifice PCE in order to obtain added functionality (such as flexibility, low weight or transparency). Thus, state-of-the-art devices in these contexts would never make it to the lists of best research cells per technologies.

Each new material class or emerging PV technology may reveal new phenomena that were previously unknown. In the case of perovskite devices, the PCE measured with the standard certification procedure has been proven to be unreliable due to the presence of capacitive responses caused by mobile-ion movements responding within the measurement time. This phenomenon is usually known as hysteresis in the J–V curve[8–11] and it has motivated the introduction of maximum power point (MPP) tracking protocols in order to validate the actual power that can be extracted from the cell in more realistic conditions.[12,13] Given such phenomena, which may occur for any new emerging technology, it is of utmost importance to constantly report the most complete and detailed data set on record efficiency devices.

In addition, long-term performance stability represents a key focus of research in emerging photovoltaics, especially for organic and hybrid materials, which are susceptible to faster degradation pathways. In practice, one can already get a good evaluation of stability by performing inline tests under 1 sun illumination intensity at 65 °C for 200 h or at 85 °C for 1000 h, i.e., 8 days or 6 weeks respectively. Particularly, 200 h can be a more suitable time scale for the typical duration of academic research projects and specially for newer emerging PVs. Interestingly, a parameter which summarizes the overall device performance, including both efficiency and stability, is
the extracted energy density during the test time $\tau$, herein also referred as the stability test energy yield (STYE), resulting from computing the integral

$$E_{STY} = \int_0^\tau P_{in} \, dt = \int_0^\tau P_{in} \times \text{PCE} \, dt \tag{2}$$

where $P_{in}$ is the incident light intensity (e.g., 100 mW cm$^{-2}$) and the STYE can be taken for 200 and 1000 h as $E_{STY200}$ and $E_{STY1000}$, respectively. The similar concept of lifetime energy yield (LEY) has previously been introduced for the time the PCE does reach 80% of the initial value ($T_{80}$), denoting the corresponding integral (2) as $E_{T80}$.[14,15] Note that $E_{T80}$ is a very practical metric when $T80 < 200$ h and/or $T80 < 1000$ h, but it can be misleading for more stable or PCE increasing cells. Additionally, one can also use the SQ limit[1] to estimate the maximum STYE as $E_{STY} = P_{in} \times \text{PCE}_{SQ} \times \tau$ for a device with SQ limited efficiency. This stability test of duration $\tau$. Moreover, for devices with similar ranges of efficiency, it is also useful to check the degradation rate $\text{DR}_\tau = \partial \text{PCE}/\partial t$ as a function of time in case inline monitoring data are available. Alternatively, in case of offline measurements, one can sample the initial and final states in a stability test, resulting in an overall degradation rate

$$\text{DR}_\tau = \frac{\text{PCE}(\tau) - \text{PCE}(0)}{\tau} \tag{3}$$

most conveniently presented in units of percentage per day. For instance, one can take $DR_{200}$ and $DR_{1000}$ as the overall degradation rates for 200 and 1000 h, respectively.

However, probably because of the absence of institutions offering degradation certificates, there is no international reference for state-of-the-art achievements in this category. A most beneficial movement during the last years was the establishment of the so-called ISOS protocols, which regulate the lifetime reporting conditions of emerging PV technologies.[16] In parallel, efforts around the ISOS protocols have led to a technical specification for the testing protocol of photovoltaic devices enabled by nanomaterials. With the IEC TS 62876-2-1:2018,[17] for the first time a standard has been developed that defines the most significant testing protocols for stability. However, these guidelines do not take away the necessity of independent institutions being able to verify lifetime observations of emerging record devices, which are probably 10 years or more away from larger scale outdoor testing. Especially, the large number of interdependent testing conditions complicates the comparative analysis of degradation studies in the literature due to diverse measurement conditions, equipment, or environmental controls. The presentation of data in normalized plots, which is interesting to display trends but not the overall power output as a function of time for of emerging cells, can also complicate stability analysis.

In this work, a new reference and overview for already-published best emerging photovoltaic research cells is presented. The PCE values for each PV technology are presented as a function of the photovoltaic device bandgap energy $E_{gap}$, as defined in Equation (5). Similarly, the best performing flexible, transparent, and semitransparent PVs and best achievements in stability for emerging solar cells are summarized. In most of the cases, the data will be shown in relation to the Shockley–Queisser detailed balance limit,[1] as we believe that the SQ limit as a function of absorber’s bandgap represents the most appropriate benchmark for emerging PV technologies. This survey is intended to be updated periodically, summarizing the latest advances in emerging PV research.

2. Inclusion Criteria

The main objective of the present survey is to provide the PV research community with a resource for the reproduction of best achievements in emerging PVs and the analysis of the current research results and trends. With that motivation, each report must fulfill certain requirements before it can be accepted for inclusion in the graphs and tables in the following sections. These selection criteria may evolve with time, in accord with best practices and tools developed by the research community.

2.1. Best Efficiency Cells Criteria

As a main rule, the reported efficiency should correspond to an original published or already accepted (available DOI) article in a peer-reviewed journal indexed in the ISI-Web-of-Knowledge Journal-Citation-Reports (Clarivate Analytics). The article should include an experimental section with a description of the device structure, fabrication methods and relevant measurement conditions, with enough detail provided to allow the reproduction of the results.

The published/accepted articles must include the $J-V$ curve validating the PCE values and the EQE spectrum,[18,19] sometimes referred to as the incident photon-to-collected-electron conversion efficiency (IPCE). This is true for both PVs and luminescent solar concentrators (LSC). Unpublished certified efficiencies will be considered only in two cases. First, those included in Green’s et al. efficiency tables[21] will be incorporated as illustrative references. Otherwise, the authors may provide a digital copy of the certification and the experimental description and validation of the bandgap value (EQE spectrum), as would be expected for a publication. The latter information would be incorporated as supporting information if the reported efficiency is ultimately incorporated into the charts. Similarly, the reproduction of results in laboratories different to those of the authors in the original paper will be highlighted upon receipt of the corresponding information.

The $J-V$ curves should be measured under standard illumination conditions (1 sun = 100 mW cm$^{-2}$ illumination intensity of AM1.5G spectrum $Γ_{AM1.5G}$).[20] The manuscript or its supporting information must explicitly reflect the values for $V_{oc}$, $J_{sc}$, FF, PCE as well as the associated surface area of the device. Regarding the latter, the considered type of area should be clarified (total, aperture or designated as defined in the efficiency tables version 39).[22] And we strongly suggest the use of masks with known aperture. In addition, the type of solar simulator (e.g., AAA, ABA), the corresponding standard (IEC 60904–9)[23] ASTM E 927-05,[23] JIS C 8912-1998,[24] brand and model should
be mentioned, as well as the measurement temperature, atmospheric conditions (e.g., air, N₂, Ar), and whether light soaking was included and for how long. We also encourage the reporting of PCE with an MPP tracking (i.e., “stabilized efficiency” after 5 min) measurement, which is specifically important for recording the performance of PSCs, or for related technologies for which device stability and hysteresis⁶,⁸,⁹ are known to be issues. For these devices the voltage scan rate, direction and method (continuous/dynamic)²⁵,²⁶ shall be given. In case of significant hysteresis (≥0.1%), and provided the two scan directions, only the lowest PCE value shall be considered.

The mandatory EQE spectra at short-circuit are typically expressed as a function of the photon wavelength λ, which allows the calculation of the theoretical photocurrent under 1 sun illumination intensity of AM1.5G spectrum (Γ_AM1.5G) according to the integral

\[ J_{sc} = \frac{q}{h c} \int \text{EQE}(\lambda) \lambda \Gamma_{AM1.5G}(\lambda) \, d\lambda \]  

(4)

where \( q \) is the elementary charge, \( h \) is the Planck’s constant, \( c \) the speed of light, and \( \Gamma_{AM1.5G}(\lambda) \) is typically in units of \( W \, m^{-2} \, nm^{-1} \).

The agreement between \( J_{sc} \) from the \( J-V \) curve and that after Equation (4) from the EQE spectrum (up to 10% of deviation) is a minimal validation required for non-certified PCE reports. In addition, the EQE is also the essential measurement technique for estimating the bandgap energy value \( E_g \) of the device.

The photovoltaic bandgap is here defined as the inflection point of the EQE spectra in the region of the absorption threshold²⁷,²⁸ typically between 20% and 80% of the maximum EQE. This definition is the most appropriate for the evaluation of the SQ limit²⁷,²⁸ and, unlike the optical bandgap, here the aim is to characterize the complete process from charge carrier generation to current extraction, considering losses in the internal quantum efficiency. Additionally, the EQE measurement is relatively simple, the necessary equipment being generally available in the PV laboratories and the data are frequently provided in the literature.

The \( E_g \) value (the smallest photovoltaic bandgap in the system, if there are more than one) would be expected explicitly in the article and endorsed with the EQE spectrum analysis. This is expected for both PV and LSC alike. The inflection point can be directly calculated from the data, or a corresponding interpolation, by locating the maximum in the spectra derivative \( \partial \text{EQE}/\partial E \), or \( \partial \text{EQE}/\partial \lambda \). Alternatively, our preferred procedure has been the one-step fitting of the EQE spectra in the region around the bandgap wavelength \( \lambda_g \) (inflection point) to the step-like sigmoid function

\[ \text{EQE}(\lambda) = \frac{A_m}{1 + \exp \left[ \frac{2.63 (\lambda - \lambda_m) / \lambda_g}{1} \right]} \]  

(5)

where \( A_m \) and \( \lambda_m \) are fitting parameters related with the maximum EQE just after the step and the slope during the step, respectively. On the latter, note that \( \lambda_m \) expresses the broadening of the absorption threshold in the EQE spectrum, being optimal below 50 nm (like in Figure 1) and indicating a graded profile as \( \lambda_m \) approaches and exceeds 100 nm. The device bandgap is defined as

\[ E_g = \frac{hc}{\lambda_g} \]  

(6)

and the fitting and \( \lambda_g \) estimation procedures are illustrated in Figure 1. Nevertheless, despite reporting an \( E_g \) value using a technique different than EQE not necessary relates to the corresponding SQ limit, some other methods can be considered additionally, such as the device optical bandgap from typical linear fits for absorption Tauc plots,¹⁰,¹¹ and Gaussian fits in photoluminescence (PL) and/or electroluminescence (EL) spectra. Importantly, in any case the \( E_g \) value must relate to the full device, e.g., one could use optical transmission measurements on thin film cells before the evaporation of the metallic electrodes, but not on the single absorber film without selective layers. In addition, the measurement conditions should be specified, i.e., the equipment model and brand, as well as the temperature and atmosphere for the measurement.

For each \( E_g \) value, the best published PCE value with a bandgap resolution of 10 meV will be taken. For transparent and semitransparent PVs, the corresponding evidence for the average visible transmittance (AVT) should be provided by plotting the transmittance curve as a function of wavelength (as measured for the entire device without a reference sample).¹⁰ Reports on flexible substrates should include the thickness and type of the substrate.

Flexible and/or transparent/semitransparent properties should likewise be expressed in the manuscript, or in the supporting information (when relevant), and supported with at least one figure illustrating the transparency/flexibility. The substrate for flexible cells should be thinner than 250 µm,
where EQE(λ) and T(λ) become equal as the internal quantum efficiency (IQE) approaches unity—this substitution is made since the absorbance spectrum A(λ) is notoriously difficult to measure directly. We note that a number of articles have reported photon balances with EQE(λ) + T(λ) > 100%, indicating that either the EQE (thus $j_{sc}$) or T (thus AVT) are overestimated.

As a summary, Table 1 presents a list of minimal information that should be included in a manuscript, or the corresponding supporting information, to be eligible for incorporation in the below charts. Importantly, independent of possible inclusion, these guidelines should also be considered important general guidelines for reliable reporting of PV performance metrics.

Table 1. List of items and/or information to include in the manuscripts, or supporting information, for the published article where the achievement in efficiency and/or stability of the research solar cell is first presented. Requirements (i–iii) are mandatory for all cases and iv (a–c) are only required for certain cases.

| No. | Information | Figure/data |
|-----|-------------|-------------|
| i   | Efficiency under standard test conditions (1 sun AM1.5G illumination, 25 °C):  |
|     | Performance parameter values from $J−V$ curve (PCE, $V_{oc}$, $J_{sc}$, and FF using Equation (1)).  |
|     | Area (surface area and type: total, aperture or designated).  |
|     | Solar simulator (type, standard, model and brand).  |
|     | Measurement conditions (temperature, air or N₂-atmosphere, whether a black matte background was used).  |
| ii  | Photovoltaic bandgap:  |
|     | $E_g$ or $\lambda_g$ and $\lambda$ values (from EQE fitting using equation (5)).  |
|     | $j_{sc}$ value from EQE (using Equation (4)).  |
|     | Used instrument for EQE (model and brand).  |
|     | Measurement conditions (temperature, air or N₂-atmosphere, whether a black matte background was used).  |
|     | Additional methods can also be reported (e.g., Absorption Tauc plot).  |
| iii | Absorber material:  |
|     | Experimental section: description of structure and fabrication procedure allowing reproduction of the results.  |
| iv.a | Photostability test:  |
|     | Degradation conditions (e.g., MPP, OC, SC).  |
|     | Illumination spectrum (e.g., AM1.5G, UV filter model and brand).  |
|     | Illumination intensity (e.g., 100 mW cm⁻², provide information on how intensity was tracked).  |
|     | Measurement conditions: temperature, atmosphere (air with RH or inert N₂/Ar), instrument (model & brand or self-made).  |
|     | Integrated output energy for 200 and 1000 h under 1 sun illumination ($E_{200h}$ and $E_{1000h}$ using Equation (2)).  |
|     | PCE (including EQE) after 200 and 1000 h (measured as in "i")  |
| iv.b | Transparent and semitransparent PV  |
|     | $ATV$ value (using equation (7) as determined by the calculator provided in "Data S1"[32] and the support section of emerging-pv.org).  |
|     | Aesthetics (e.g., CRI or $a^n$, $b^n$)  |
|     | PBCC value (using Equation (8)).  |
|     | Used instrument for $T$ and $R$ (model and brand)  |
|     | Measurement conditions (temperature, air or N₂-atmosphere, whether a black matte background was used)  |
| iv.c | Flexible PV  |
|     | Substrate thickness  |
|     | Minimum radius the solar cell was bent to without reducing <5% performance output  |
|     | Measurement conditions  |

© 2020 The Authors. Advanced Energy Materials published by Wiley-VCH GmbH
2.2. Best Stability Cells Criteria

The recommended stability test should be 1000 h under 1 sun AM1.5G illumination, at a temperature of 85 °C, nitrogen atmosphere and MPP-tracking condition. The usage of UV filters, either external or internal ones, their brand, type and cut off wavelength, must be reported together with the brand and type of the light source. Alternative testing conditions may only vary in temperature, time or atmosphere. When testing in conditions other than dry nitrogen, the type of packaging or protection utilized must be denoted. Further, information on the bias is essential. Degradation should be done under MPP conditions. In case of other conditions, such as short-circuit (SC), open-circuit (OC) or constant bias voltage, it is important to report that.

The main criteria for presenting the best research cells in terms of overall performance stability would be the STEY value from the integral in Equation (2), during the degradation test. An example of the stability test and the energy integration is illustrated in Figure 2 for a 1000 h test. The best reports for STEY would be presented for each effective device absorption bandgap in two main categories: 200 and 1000 h stability tests, i.e., \( E_{200h} \) and \( E_{1000h} \), respectively.

In addition, the PCE values before and after 200 or 1000 h of stability testing (measured under standard illumination conditions), as well as EQE verification, should be provided. This option of providing only the PCE before and after the stability test, rather than the full time-dependent data, can be useful for those PV labs with difficulties in the instrumentation of MPP-tracking algorithms and automatic device performance monitoring during the stability test.

The PCE versus time degradation plots should preferably be in efficiency units (not normalized). At a minimum, normalized inline stability plots should be accompanied by the \( J-V \) curve under standard 1 sun AM1.5G illumination intensity before the beginning of the degradation test (and after 200 and/or 100 h). In all cases, the measurement conditions (degradation state, illumination intensity and spectrum, atmosphere, temperature, details for the instrumentation) should be provided in the manuscript or in the supporting information of the published article.

The \( E_g \) value for each report should be indicated in the manuscript, or supporting information, of the published article, similarly to the procedure outlined in the previous section. To sum up, the last row in Table 1 comments on the required information to be considered for inclusion in future versions of this survey.

Overall, these inclusion criteria encourage the generalization of best practices in the description and reproduction of published academic results. For this first version of the survey, the rules have been applied with some discretion, but with clear expectations to gain in rigor and robustness as they evolve with the involvement of the community and the support of electronic automated systems.

2.3. Discarding Rules

“Reporting Device Efficiency of Emerging PV Materials” is planned as an open access database following the FAIR principles. This implies that the data must be findable, accessible, inter-operable and reusable. A major concern is of course the quality of the data. We believe that the following principles are sufficient to maintain the highest standard in collecting data on new materials:

First, PCE values without explicit description of the \( J-V \) measurement conditions (i.e., light intensity, spectrum, suitably described cell area, and measurement instrument) nor EQE spectrum must be discarded. Specifically, differences of more than 10% between \( J_{sc} \) from \( J-V \) and EQE are considered as a discarding argument. For differences of between 5% and 10%, the lower efficiency value (i.e., associated with the lower \( J_{sc} \) value) shall be reported.

Second, the reports can also be discarded in the absence of evidence for evaluating the photovoltaic bandgap \( E_g \). Similarly, this applies with the values of AVT, substrate thickness/bending radius and \( E_{200h}/E_{1000h} \), for the transparent, flexible, and stability categories, respectively.

2.4. Tie Rules

Aiming to summarize the best achievements in not-necessarily certified-PCEs for emerging PV technologies, as published in academic articles, this survey focuses on the most efficient photovoltaic materials. Accordingly, there are two main uncertainties, associated with the reports on PCE and \( E_g \). The latter would always be considered as ±10 meV by default. Exceptionally, larger \( E_g \) uncertainties could be considered for devices with significantly gradual EQE absorption onset.

For PCE values, the PCE uncertainty would always be considered as ±0.5% by default. Then, at the same \( E_g \), only a second uncertified PCE record can be included if its average value is within ±0.5% of the best cell at \( E_g \) and/or above some PCE for the records in the range \( E_g \pm 10 \) meV. Certified and uncertified records will be considered as separate categories. Thus, up to four reports can be included at the
same $E_g$ (two certified and two uncertified) if the above rule is fulfilled.

For the photostability tests, the $E_{200h}$ and $E_{5000h}$ values would follow a $\pm 1$ Wh cm$^{-2}$ rule, similar to the PCE values, in addition to the $E_g \pm 10$ meV earlier mentioned. The best semitransparent PVs will be considered as the highest PCE at each AVT (±5%), and each $E_g$ value (±10 meV). Analogously to the above rules, at both the same AVT and $E_g$, only a second PCE record can be included if its average value is within ±0.5% of the best cell at AVT and $E_g$, and/or above some PCE for the records in the ranges AVT ±5% and $E_g$ ±10 meV.

Importantly, these would be the tie rules for inclusion in the final tables for each article version. Full data, including all the available records at each $E_g$, is intended to be accessible in the online database website emerging-pv.org, with visualization tools permitting customizable selections.

2.5. Inclusion Methods

The data to be included in the following versions of this survey can be incorporated via several methods. Primarily, we will systematically check in the literature for new developments. On the other hand, we urge the research community to take an active role in the future updates of these reviews, by following one of three approaches. First, the authors can submit data through a template in the online website emerging-pv.org (see the Supporting Information). This is a dedicated database collector under development which is intended to provide data visualization functionalities in the future. Second, the authors can send an email to report@emerging-pv.org with the attached data (see form in the online website emerging-pv.org). Finally, we also recommend including the form as a table in the supporting information of the published papers and/or in stable online websites for future automatic digital collection of the data.

3. Highest Efficiency Research Solar Cells

The best absolute achievements in emerging photovoltaics are summarized in Figure 3 as a function of the photovoltaic bandgap, along with some established technologies and the Shockley–Queisser$^{[3]}$ theoretical performance limit for a single junction assuming radiative emission from the front and rear side of the solar cell (solid line in Figure 3a).$^{[29]}$ Notably, only PSCs and established technologies such as silicon and thin film CdTe and CIGS exceed the 55% of the SQ limit (dotted line in Figure 3a), and only GaAs-based single junction devices exceed 85% of the SQ limit (dashed line in Figure 3a). However, excepting some lower-PCE-CIGS-cells, these devices have well-localized $E_g$ values below 1.55 eV, which limits the $V_{oc}$, as presented in Figure 3b, and ultimately the color tunability of the cells for some applications.

PSCs can be realized in a broader range of $E_g$ values, which is achieved by the modification of the perovskite composition. In this regard, one can identify four main regions or report clusters in Figure 3. Below 1.5 eV, tin-based PSCs struggle to overcome the 10% PCE. It is known that these devices still suffer from considerable nonradiative recombination due to morphology issues and band alignment mismatch, which affects mainly $V_{oc}$ and FF, as in Figure 3b,c. Lead-free PSCs represents a prioritized research direction, which may benefit all PV applications, in particular the indoor and wearable sectors. Nevertheless, aiming for a “taller efficiency roof,” some devices have already been reported PCE exceeding 20% at $E_g$ of ≈1.25 eV and ≈1.4 eV by tuning the cations (e.g., formamidinium, Cs, Sn) and/or anion (e.g., Br, Cl) compositions in

![Figure 3.](image-url)

Figure 3. Highest efficiency solar cells: Performance parameters as a function of effective absorber bandgap for different photovoltaic technologies: a) power conversion efficiency, b) open-circuit voltage, c) fill factor, and d) short-circuit current density. Experimental data are summarized in Section 10.1 and the solid, dashed and dotted lines indicate 100%, 85%, and 55% of the theoretical Shockley–Queisser efficiency limit, respectively.
the perovskite with respect to the CH\textsubscript{3}NH\textsubscript{3}PbI\textsubscript{3}, herein called mixed perovskites.

High efficiency PSCs cluster around the region within 1.53 and 1.6 eV, which corresponds to the bandgaps for formamidinium (FA) and methylammonium (MA) lead iodide perovskites, FAPbI\textsubscript{3} and MAPbI\textsubscript{3}, respectively. These devices are the result of considerable optimizations regarding perovskite composition and morphology, and selective contacts, which at the moment report a certified PCE record of 25.2% efficiency. Interestingly, this “hero” perovskite-cell is closer to the photovoltage radiative limit than the best crystalline silicon cell, which is most likely related with the advantage of having a direct bandgap, a situation closer to that of the GaAs cell.

High photovoltage perovskite cells are enabled as the bromide substitutes for iodide in the perovskite composition. Here, several devices based on the organometallic FAPbBr\textsubscript{3} and MAPbBr\textsubscript{3}, and the inorganic CsPbBr\textsubscript{3} have already reported \textit{V\textsc{oc}} values higher than 1.5 V with efficiencies above 10%. The latter is ≈70% of SQ limit, while the \textit{J\textsc{sc}} seems to be almost at full SQ limit in Figure 3d. Interestingly, in the region between 1.95 and 2.3 eV several proofs of concept for new perovskite compositions have also been proposed.

Best organic solar cells seem to perform better as the \textit{E\textsc{g}} decreases from 1.9 to 1.3 eV in Figure 3a. This trend probably relates to the difficulty of OPVs to increase photovoltage, a presently limiting consequence of the donor–acceptor bulk heterojunction design. Figure 3b suggests that \textit{V\textsc{oc}} > 1.0 V is rarely reported for the most efficient OPV devices, independently of the active material’s bandgap. Moreover, \textit{FF} and \textit{J\textsc{sc}} follow the more typical trends in Figure 3c,d.

Dye sensitized solar cells are third in terms of overall PCE values, after PSCs and OPVs, but the second regarding the breadth of \textit{E\textsc{g}} values, after PSCs. This is relatively “expected” due to the significant potential-losses in these devices, which lowers the actual theoretical efficiency limit below the SQ traditional estimation.\textsuperscript{38} Moreover, several devices with efficiencies around 35% of SQ limit have been reported with \textit{E\textsc{g}} values from 1.4 to 2.4 eV, while best performing DSSCs show \textit{E\textsc{g}} values within 1.8–2.1 eV. Interestingly, in the latter range these devices are able to surpass OPVs in terms of \textit{V\textsc{oc}}. Importantly, some \textit{J\textsc{sc}} values in Figure 3d reach and even exceed the SQ limit, suggesting firstly that these particular cells are not properly suited to the single-junction SQ limit model and, secondly, that the presence of artifacts cannot be disregarded in the estimation \textit{J\textsc{sc}} from the \textit{J–V} curve and/or the \textit{E\textsc{g}} from the EQE. The latter can be particularly challenging for most of DSSCs where a graded EQE spectrum is found, instead of “straight” abrupt steps as in Figure 1. Furthermore, the kesterite family of emerging inorganic solar cells (CZTS), typically using Cu\textsubscript{2}ZnSn(S,Se)\textsubscript{4}, and the Sb\textsubscript{2}Se\textsubscript{3}-based devices are also presented in Figure 3. These more recently emerging technologies are showing best performances below 40% of the SQ limit, mainly because of large photocurrent losses.

The relative performance in terms of the SQ limit is better observed in Figure 4, by using the SQ performance ratio defined by Guillemoles et al.\textsuperscript{19} as

\[
\text{PCE}\textsuperscript{real} = \frac{\text{PCE}\textsuperscript{real}}{\text{PCE}\textsuperscript{SQ}} = \frac{\text{FF} \left( \text{V\textsc{oc}} \right)}{\text{FF} \left( \text{V\textsc{oc}} \right)} \cdot \frac{\text{FF} \left( \text{V\textsc{oc}} \right)}{\text{FF} \left( \text{V\textsc{oc}} \right)}
\]

where the “real” and “SQ” superscripts respectively indicate the experimental and ideal SQ limit values for each magnitude and the theoretical SQ fill factor comes from\textsuperscript{19}

\[
\text{FF}_{\text{SQ}} \left( \text{V\textsc{oc}} \right) = \frac{q \text{V\textsc{oc}}}{k_{\text{B}} T} \ln \left[ \frac{q \text{V\textsc{oc}}}{k_{\text{B}} T} + 0.72 \right] \left[ 1 + \frac{q \text{V\textsc{oc}}}{k_{\text{B}} T} \right]
\]

Figure 4. Percentage of SQ efficiency as Equation (9) limit for a) the most efficient cells for each PV technology and as a function of bandgap for b) PSCs, c) OPVs, and d) DSSCs. Experimental data are summarized in Section 10.1. No tie rules (see Section 2.4) were considered for this data selection, only the highest efficiency at each \textit{E\textsc{g}}.

\(2002774\)

© 2020 The Authors. Advanced Energy Materials published by Wiley-VCH GmbH
Subsequently, one can distribute the performance in logarithmic fractions that parameterize the losses of photovoltage, photocurrent, fill factor ($V_{oc}$) and fill factor (resistive), respectively. This concept is presented in Figure 4a for the best devices in each PV technology, and as a function of bandgap for the three main emerging PV technologies in Figure 4b–d. Comparing all the PV technologies, in Figure 4a, illustrates how most of highest efficiency inorganics (CTZSS, CdTe, CIGS, Si) and DSSCs mainly suffer from photovoltage loss. Also, best devices for a-Si:H, OPVs and, PSCs lose efficiency due to photovoltage and photocurrent fails similarly, while the GaAs hero cell would mainly need photocurrent optimization.

Comparing the three main emerging PV technologies, in Figure 4b–d, the parametrization indicates major photocurrent and photovoltage losses in OPVs and DSSCs, while most efficient PSCs are suffering more from resistive issues. Interestingly, for high bandgap PSCs, the best performing cells are almost as close to the SQ limit as those with a bandgap around that of MAPbI$_3$, and whilst the latter suffer from photocurrent losses, the high bandgap PSCs are mostly affected by photovoltage losses.

4. Flexible PVs: Best Research Solar Cells

The subject of flexible PVs has been recently tackled in several reviews,[40–47] here the focus is set on showing PCE versus $E_g$. The performance of flexible PV devices in Figure 5 seems to mirror the high-efficiency clusters for each technology in Figure 3. Obviously, it makes sense to take the most consolidated device designs when targeting further applications like fabrication of PVs on thinner flexible substrates.

For flexible PSCs,[41–43] the devices include mixed perovskites with well-established good-performing properties and $E_g$ within the range 1.47–1.65 eV. This focus has already allowed for reports with over 19% PCE, approaching 65% of the SQ limit (dashed line in Figure 5a). Interestingly, flexible PSCs provide the absolute photovoltage champions in Figure 5b, since $V_{oc} > 1.0$ V has not yet been achieved for the flexible GaAs cells. Notably, among established flexible PV technologies,[44] while GaAs remains the most efficient flexible single junction solar cell, flexible CIGS cells[45] significantly outperform other technologies (i.e., Si and CdTe devices).

Flexible OPVs[46] yield peak efficiency at $E_g \approx 1.4$ eV, with a reported PCE of above 15%, which is almost 50% of the SQ limit. However, most of the remaining emerging flexible PV technologies are below 10% PCE (below 40% of the SQ limit), including all the flexible DSSCs.[47] For the latter type of device, the use of the N719 dye sensitizer seems to be the most common approach.

5. Transparent and Semitransparent PVs: Best Research Solar Cells

Another particularly interesting subject in this survey is the development of transparent and semitransparent solar cells for applications such as PV-windows and PV-lamp cases. Integrated photovoltaics in an industry scale is one of the long-sought goals in the PV community to extend the reach of PV systems and to minimize the “food versus fuel” tradeoff.[48] Integrating power generation into our daily live is as such a tremendously important technological step to accelerate the energy transition from fossil to renewable. Transparent and semitransparent research cells have recently emerged to help fill this role and enable PV deployment in entirely new areas and applications. They have been reviewed recently by several authors,[49–55] and so here we present a comprehensive comparison between different technologies in Figure 6.

Figure 5. Flexible PVs: Best performance parameters as a function of absorber bandgap for various photovoltaic technologies: a) power conversion efficiency, b) open circuit voltage, c) fill factor, and d) short-circuit current density. Experimental data are summarized in Section 10.2 and the solid, dashed and dotted lines indicate 100%, 65%, and 50% of the theoretical Shockley–Queisser efficiency limit,[29] respectively.
A general classification of transparent and semitransparent solar cells separates i) non-wavelength selective (NWS), absorbing across the solar spectrum via spatially segmenting traditional PVs or by make traditional PVs ultrathin to enable partial light transmission; and ii) “wavelength selective” (WS), absorbing preferentially the invisible part of the solar spectrum via discrete molecular orbitals. This classification is important as each of these two approaches have fundamentally different SQ limits.\[34\]

Analogously to our previous analyses, Figure 6a presents the best efficiency research cells as a function of the \(E_g\) and the AVT. Note that, in contrast to opaque devices, here the SQ limit for NWS-PVs (blue surface in Figure 6a) is a function of both \(E_g\) and AVT\[34\] thus the 3D representation can be more useful in combination with the corresponding plane projections. Similarly to flexible PVs in Figure 5, most of the best reported transparent and semitransparent devices use previously optimized absorber materials (see absolute records in Figure 3), clustering around their respective \(E_g\) values. The latter is best appreciated in Figure 6b, where the light utilization efficiency (LUE = AVT \cdot PCE)\[55\] is presented as a function of the bandgap energy. For instance, one can see that the LUE values for most of the reports are below the SQ limit for 15% AVT (taking AVT as percentage and PCE as absolute). Complementary and irrespective of the \(E_g\) values, one can also display the LUE versus AVT and the corresponding SQ limit for NWS PVs as in Figure 6c, showing most of the reports below 55%.

Comparing with more traditional semitransparent thin film solar cells, like a-Si:H and CIGS, Figure 6 illustrates the advantage of emerging photovoltaics. The established inorganic technologies have been reported with efficiencies below
10% and AVT values less than 26%. Note that, despite some research on semitransparent CdTe cells,[50] to the knowledge of the authors, only one report with efficiency below 1% can be analyzed in terms of the corresponding AVT and $E_g$ values.

Semitransparent PSCs[52,53] have been reported with efficiencies ranging from 3.6% at 47% of AVT to PCE as high as 17.5% at 10% of AVT. Here the control of both absorber thickness and composition are typical strategies. Interestingly, unlike the absolute records in Figure 3 and the best flexible solar cells in Figure 5, PSCs are not such clear leaders for semitransparent and transparent applications. OPVs[54] present comparable and even larger PCE values than PSCs, for some transparency ranges, e.g. AVT > 40%. The PSCs fail to provide larger values of photocurrent in Figure 6e, while semitransparent OPVs show limitations for reporting $V_{oc}$ values ≥1.0 V in Figure 6f, for almost the entire AVT range. Semitransparent DSSCs, on the other hand, seem to remain in the “third position” with efficiencies hardly above 10% and mainly below 30% of AVT. OPVs offer a unique advantage in this category as they can enable the highest LUE of any transparent or semitransparent PV by exploiting wavelength selective absorption around the visible spectrum due to their molecular orbital nature. Accordingly, they have reached efficiencies ranging from 8.32% PCE at 50% AVT[56] to 1.2% at AVT of 75%.[57]

6. Stability in Emerging Research Solar Cells

The stability of emerging PVs is of paramount importance for the commercialization of any of these emerging technologies perhaps, despite being the subject with least extensive data, likely owing to the care and effort needed to undertake these studies effectively. Research publications on degradation of emerging PVs are not as many as one would possibly like[58–62] and, more troublingly, the proper description of the stability tests is not often found. Most reports present normalized analyses that focus only on trends, omitting the data regarding the initial performance parameters.

Figure 7. Most photostable emerging PVs for each technology: stability test energy yield for a) 200 h and d) 1000 h as a function of bandgap energy, final power conversion efficiency after b) 200 h and e) 1000 h as a function of the initial value, and overall degradation rate (Equation (3)) as a function of initial power conversion efficiency for c) 200 h and f) 1000 h. The experimental data is summarized in Section 10.4 and the solid, dot-dashed and dashed lines in (a,d) indicate 100%, 70% and 40% of the theoretical Shockley–Queisser limit,[29] respectively. The diagonal dot-dot-dashed lines in (b,e) indicate where the final efficiencies equal the initial ones. The positive values above the horizontal dotted line in (c,f) represent increase of PCE with respect to the initial values.
On the overall performance, the most stable PSCs in Figure 7 provide above twice more output energy than most of the presented OPVs and DSSCs during 200 and 1000 h under simulated 1 sun operation. However, the lack of well-described stability studies in OPVs performing above 15% PCE (see Figure 3) is admittedly a weak spot in this representation. Moreover, most stable PSCs are close to 70% of the SQ limit (dot-dashed line Figure 3a,d), while the rest of the technologies are below 40% (dashed line Figure 3a,d).

Interestingly, it is also evident that the first 200 h of operation can be significantly unstable for emerging photovoltaics. This is more evident by presenting the efficiencies after degradation and the degradation rate as a function of the initial PCE values. Final versus initial efficiencies (in Figure 7b,e) evidence how most of the devices keep or increase their efficiency during the first 200 h (dots above/over the x = y diagonal line) but later show significant losses within 1000 h of stability testing (dots below the x = y diagonal line). In terms of overall degradation rate, as defined in Equation (3), most of the cells degrade between two and eight times faster within the first 200 h than considering 1000 h of test (in Figure 7c,f). Interestingly, DSSCs show a more common trend to increase efficiency as operation time augments up to 1000 h, despite this rate of PCE increase is anyway diminished with time.

7. The Time Evolution

Most directly complementing NREL’s chart,[7] the publication year of the above presented reports are summarized in Figure 8 for each of the four previous sections. This representation is not only illustrating on the topicality of each research field/section, but also attempts to provide an eye-catching tool for the readers to identify possible missing reports.

The absolute best efficiency reports in Figure 8a show, in the first place, that most of the PV research is mainly focused on emerging rather than on established technologies. On the former technologies, OPV and PSCs with device bandgap energies within the range 1.35–1.61 eV seem to be “trending topic,” while just the opposite within 1.63–1.75 eV. Flexible and semitransparent device research, in Figure 8b,c respectively, suggest the OPV technology as the “hottest” among the emerging PVs. Interestingly, from Figure 8c it looks like the research community has been losing interest on semitransparent PSCs during the last 2 years. Finally, the stability reports (attending to our selection criteria for Figures 7 and 8d) have mostly been reported during the last 3 years over devices whose bandgap energy is currently “trending topic” (around 2 years later).

8. A Critical Outlook

Despite the interesting and useful content of the presented data and analyses, we are aware of several limitations and/or possibly critical issues, which will hopefully evolve into creative solutions for the future. First, some debate is to be expected regarding our inclusion criteria and methods. For instance, we neglect the evaluation of metrics for analyzing best achievements for low cost and environmentally friendly devices. Moreover, even for the categories described in Section 2, the large volume of online publications and the variegated structure of research articles may have hindered the inclusion of all the already available data in the literature. Hopefully, the summoning of the research community will contribute to correcting and updating future versions of this survey.

The certification and the reliability of the reported values is another vital subject in our discussion. Our intention here
is to motivate the community to discuss new and broader certification methods. Particularly, we highlight the impact of certified stability tests, while other procedures like the AVT evaluation could be certified as well. Ideally, we could provide in the future independent graphs with certified reports as abundant as the uncertified charts.

The data quality and specifically reproducibility is another of our major concerns. While hard to evaluate in this first version, we expect for those records with practical reproducibility to be updated and/or significantly approached in following versions of this survey. Hopefully, we would be able to include subsequent contributions from those authors who have reported achievements as good or better than those reviewed here, but were neglected due to the lack of description (e.g., no EQE, no AVT, no initial PCE in stability). In this regard, we intend to implement a “gold” category system for automatically labeling each report with the highest detail provided in the description for the database website emerging-pv.org. We further intend to provide information on the reproducibility and even introduce a “reproducibility factor,” e.g., in case several groups independently from each other can produce a specific result. We also intend to categorize data in terms of the production processing technology, highlighting differences in lab efficiency (spin coated in N2) versus industrial efficiency (printed in air). These and further specifications would allow the community to discern between poorly and adequately described reports, and hopefully motivate best practices.

The hysteresis in the J−V curve of PSCs \(^{60,63}\) is another intensely discussed issue for reports on best efficiencies. Even the certified reports may be affected by measurement artifacts if there is no appropriate MPP tracking \(^{13}\) or other stabilized J−V measurement such as low scan rate continuous sweep \(^{26}\) or dynamic asymptotic methods \(^{25}\). For instance, future “gold-reports” would include at least a 5 min MPP tracking test as a basic endorsement of the reported PCE values, along with the EQE spectrum and a second PCE value measured 24 h after the first J−V characteristic.

A convenient standard flexibility test for the PV devices is a pending discussion in the community. The focus in this survey would be for reporting initial device performance under bending and performance after a series of bending cycles (BC). For instance, an early proposal would be to measure the PCE under standard illumination conditions followed by an inline MPP tracking as a function of the minimum bending radius \(r_b\) and BC, until the PCE decreases 5% of the initial value (PCE\(_o\)). Alternatively, the J−V characteristic could be taken for the smaller \(r_b\) and after as many BC as possible, provided that the PCE is still >5% of PCE\(_o\). Thus, one could analyze the highest bendable efficiency HBE, = PCE\(_o\)/\(r_b\) and the bending efficiency lifetime BEL = PCE\(_o\) × BC. However, the bending geometry and bending rate could significantly modify the test outcomes, and also a selection of a maximum number of BC may be considered.

The stability test conditions are also a subject of discussion in the future. Among the several already existing standards \(^{16,17}\) as well as other possible alternatives, the PV research community is still missing a consensus on the most representative and practical protocols for evaluating the long-term performance of solar cells. The priority for the upcoming versions of this survey is to list an increased number of reports fulfilling our inclusion criteria. Subsequently, the goal would be to conduct more specific analyses attending different measurement conditions, targeting specific operating modes and/or the effects on each individual element of the devices.

Other emerging solar cells, including inorganic absorbers \(^{64}\) quantum dots \(^{65}\) and multi-junction devices will also be considered for inclusion in future versions of this survey. In each case, it is still pending to define the best categories and representations to be incorporated into the database website and the published articles.

9. Conclusions

In summary, the present review has illustrated the benefit of reporting power conversion efficiency as a function of the absorber material bandgap for the main emerging photovoltaic technologies: perovskite, organic and dye sensitized solar cells. Focused on the absorber materials, parametrized through the effective device bandgap, the absolute record efficiencies were shown to be led by the PSCs in the widest range of photovoltaic bandgap, competing with established technologies like silicon and thin film inorganics. The systematic development of high bandgap emerging photovoltaics serves as a guideline for the future implementation of tandem solar cells. Moreover, the best flexible solar cells were also summarized, indicating again some competition between PSCs and established technologies like CIGS. On the other hand, the best transparent and semitransparent research cells, with average visible transmittance values above and below 50%, respectively, are being led by two emerging technologies OPVs and PSCs that have already reported efficiencies significantly larger than those from CIGS and a-Si:H devices. Subsequently, we presented an initial sample of the output energy values from stability tests of emerging PV cells under 1 sun simulated illumination after 200 and 1000 h. Despite the limited and irregularity of the data, it can be seen that the behavior of high efficiency emerging PV technologies is encouraging. We hope this effort will help to grow and nurture a “forest of emerging PV materials” in every version of our best emerging research cells reports.

10. Tables (Tables 2–17)

The below tables 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 \(E_g\) were estimated by fitting the absorption threshold region of the corresponding EQE spectra to Equation (5), as illustrated with Figure 1 in Section 2.1.

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.
### Table 2. Best 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\(_{0.6}\)(MAPbI\(_3\))\(_{0.4}\) | [66] |
| 1.26       | 20.4   | 834             | 30.5            | 80.2  | GuaSCN:(FASnI\(_{0.6}\)(MAPbI\(_3\))\(_{0.4}\) | [67] |
| 1.26       | 19.0   | 888             | 28.8            | 74.5  | (FASnI\(_{0.6}\)(MAPbI\(_{0.34}\)(MAPbBr\(_{0.16}\)) | [68] |
| 1.27       | 20.9   | 827             | 31.4            | 80.5  | MA\(_2\)fA\(_0\)Pb\(_2\)Sn\(_{1.5}\)I\(_3\) | [69] |
| 1.28       | 20.3   | 850             | 30.2            | 79.1  | FA\(_{2.2}\)Cs\(_{0.8}\)Pb\(_2.5\)Sn\(_{1.5}\)I\(_3\) | [70] |
| 1.28       | 18.4   | 780             | 32.8            | 72.0  | Cs\(_{0.22}\)FA\(_{2.05}\)MA\(_{1.5}\)Sn\(_{1.5}\)Pb\(_{2.5}\)I\(_3\) | [71] |
| 1.29       | 16.0   | 771             | 29.3            | 70.8  | FASn\(_{1.5}\)Pb\(_{0.5}\)I\(_3\) | [72] |
| 1.29       | 15.9   | 770             | 26.5            | 78.0  | (FASnI\(_{1.5}\)(MAPbI\(_{0.34}\)(MAPbBr\(_{0.16}\)) | [73] |
| 1.30       | 13.8   | 660             | 29.0            | 72.1  | FA\(_2\)mA\(_{0.5}\)Pb\(_{2.5}\)Sn\(_{0.5}\)I\(_3\) | [74] |
| 1.31       | 5.0    | 420             | 23.8            | 50.3  | CsSnI\(_3\) | [75] |
| 1.31       | 7.1    | 486             | 22.9            | 64.0  | MaSnI\(_3\) | [76] |
| 1.31       | 14.1   | 740             | 26.7            | 71.4  | FA\(_{2.2}\)Cs\(_{0.8}\)Sn\(_{1.5}\)Pb\(_{2.5}\)I\(_3\) | [77] |
| 1.32       | 11.6   | 720             | 23.4            | 68.9  | MAPb\(_2\)Sn\(_{0.5}\)Br\(_{1.5}\)I\(_3\) | [78] |
| 1.34       | 10.0   | 767             | 20.5            | 63.6  | MAPb\(_2\)Sn\(_{0.5}\)I\(_3\) | [79] |
| 1.34       | 12.1   | 780             | 20.7            | 75.1  | MAPb\(_2\)Sn\(_{0.5}\)Br\(_{1.5}\)I\(_3\) | [78] |
| 1.35       | 16.3   | 780             | 26.5            | 79.0  | FAPb\(_2\)Sn\(_{0.5}\)I\(_3\) | [80] |
| 1.37       | 14.7   | 737             | 27.1            | 73.6  | FA\(_2\)mA\(_{2.5}\)Pb\(_{2.5}\)Sn\(_{0.5}\)I\(_3\) | [81] |
| 1.38       | 17.3   | 810             | 28.2            | 75.4  | FAPb\(_2\)Sn\(_{0.5}\)I\(_3\) | [82] |
| 1.38       | 15.2   | 800             | 26.2            | 72.5  | MAPb\(_2\)Sn\(_{0.5}\)I\(_3\) | [83] |
| 1.39       | 20.6   | 1020            | 26.6            | 76.0  | FA\(_2\)mA\(_{2.5}\)Pb\(_{2.5}\)Sn\(_{0.5}\)I\(_3\) | [84] |
| 1.40       | 8.2    | 745             | 17.8            | 61.8  | MAPb\(_2\)Sn\(_{0.5}\)I\(_3\) | [79] |
| 1.40       | 7.8    | 570             | 20.7            | 66.2  | MaSnI\(_3\) | [85] |
| 1.41       | 5.9    | 487             | 20.0            | 60.6  | FA\(_{3.2}\)RbSnI\(_3\) | [86] |
| 1.42       | 14.4   | 820             | 22.4            | 78.0  | MAPb\(_2\)Sn\(_{0.5}\)I\(_3\) | [87] |
| 1.43       | 10.4   | 772             | 20.3            | 66.4  | MAPb\(_2\)Sn\(_{0.5}\)I\(_3\) | [88] |
| 1.44       | 10.2   | 630             | 21.6            | 74.7  | FASnI\(_3\) | [89] |
| 1.44       | 9.4    | 605             | 21.1            | 73.4  | FA\(_2\)SnI\(_3\) | [89] |
| 1.42       | 13.2   | 840             | 20.3            | 78.0  | FA\(_{3.2}\)E\(_{0.2}\)E\(_{1.8}\)EDA\(_{0.4}\)SnI\(_3\) | [90] |
| 1.51       | 19.3   | 1047            | 23.8            | 77.5  | FA\(_{3}\)MAPbI\(_3\) | [91] |
| 1.52       | 22.0   | 1120            | 24.9            | 78.6  | FA\(_{3.2}\)MAPb\(_{0.1}\)PbI\(_3\) | [92] |
| 1.53       | 23.7   | 1144            | 26.7            | 77.6  | \(\alpha\)-FAPbI\(_3\)-MDACl\(_2\) | [93] |
| 1.53       | 23.3   | 1180            | 25.2            | 78.4  | FA\(_{3}\)MAPbI\(_3\) | [94] |
| 1.53       | 18.6   | 1050            | 24.1            | 73.5  | FAPbI\(_3\) | [95] |
| 1.53       | 21.6   | 1110            | 24.6            | 79.2  | FA\(_{0.6}\)Cs\(_{0.4}\)PbI\(_3\) | [96] |
| 1.54       | 24.6   | 1181            | 26.2            | 79.6  | FAPbI\(_3\) | [97] |
| 1.54       | 22.1   | 1105            | 25.0            | 80.3  | \(\alpha\)-FAPbI\(_3\)-MDACl\(_2\) | [98] |
| 1.55       | 21.5   | 1160            | 23.4            | 79.2  | Cs\(_{0.25}\)FA\(_{2.05}\)MA\(_{2.5}\)PbI\(_3\)-DAP | [99] |
| 1.56       | 25.2   | 1180            | 24.1            | 84.8  | \(\alpha\)-FAPbI\(_3\)-MDACl\(_2\) | [4] |
| 1.56       | 22.7   | 1145            | 24.9            | 79.9  | \(\alpha\)-FAPbI\(_3\)-MDACl\(_2\) | [100] |
| 1.56       | 20.9   | 1116            | 24.0            | 78.0  | \(\alpha\)-FAPbI\(_3\)-MDACl\(_2\) | [101] |
| 1.56       | 19.7   | 1075            | 23.7            | 77.3  | (MA\(_{0.7}\)FA\(_{0.3}\)EDA\(_{0.2}\)PbI\(_3\) | [102] |
Table 2. Continued.

| $E_g$ [eV] | PCE [%] | $V_{oc}$ [mV] | $J_{sc}$ [mA cm$^{-2}$] | FF [%] | Absorber perovskite | Ref. |
|-----------|---------|---------------|------------------------|--------|---------------------|-----|
| 1.57      | 23.0    | 1170          | 24.1                   | 81.6   | Cs$_{0.05}$(FA$_{0.92}$MA$_{0.08}$)$_{0.95}$Pb$_4$Br$_{12}$ | [36] |
| 1.57      | 22.3    | 1143          | 23.8                   | 82.0   | Cs$_{0.05}$(FA$_{0.92}$MA$_{0.08}$)$_{0.95}$Pb$_4$Br$_{12}$ | [36] |
| 1.57      | 20.6    | 1120          | 22.8                   | 80.5   | Cs$_{0.05}$(MAPbBr$_3$)$_{0.08}$ | [103] |
| 1.58      | 22.6    | 1116          | 24.2                   | 78.6   | Cs$_{0.05}$(FA$_{0.92}$Pb$_4$Br$_{12}$)$_{0.08}$ | [104] |
| 1.58      | 20.4    | 1125          | 23.3                   | 77.8   | Cs$_{0.05}$(FA$_{0.92}$Pb$_4$Br$_{12}$)$_{0.08}$ | [105] |
| 1.58      | 21.9    | 1120          | 24.2                   | 80.6   | Cs$_{0.05}$(FA$_{0.85}$MAPbBr$_3$)$_{0.15}$ | [106] |
| 1.59      | 21.1    | 1086          | 24.0                   | 81.0   | MAPb$_{3.5}$Sn$_{0.5}$Cs$_{0.5}$PbBr$_{1.5}$ | [107] |
| 1.59      | 21.0    | 1140          | 23.7                   | 77.7   | MAPb$_{3.5}$MA$_{0.5}$Pb$_4$Br$_{12}$ | [108] |
| 1.60      | 20.3    | 1130          | 23.2                   | 77.4   | MAPb$_1$Cl$_x$ | [109] |
| 1.61      | 20.5    | 1110          | 25.1                   | 73.5   | MAPb$_1$ | [106] |
| 1.61      | 21.6    | 1140          | 24.9                   | 76.1   | Cs$_{0.05}$(FA$_{0.85}$MAPbBr$_3$)$_{0.15}$ | [110] |
| 1.61      | 22.6    | 1200          | 24.0                   | 78.5   | Cs$_{0.05}$(FA$_{0.85}$MAPbBr$_3$)$_{0.15}$ | [111] |
| 1.62      | 21.7    | 1180          | 22.5                   | 81.7   | MAPb$_1$DAP | [99] |
| 1.63      | 20.3    | 1130          | 23.4                   | 76.8   | Cs$_{0.05}$(FA$_{0.85}$MAPbBr$_3$)$_{0.15}$ | [112] |
| 1.64      | 20.4    | 1140          | 23.6                   | 75.8   | Cs$_{0.05}$(FA$_{0.85}$MAPbBr$_3$)$_{0.15}$ | [110] |
| 1.65      | 16.2    | 1109          | 19.6                   | 74.2   | MAPb$_1$Br$_x$ | [113] |
| 1.66      | 10.4    | 904           | 16.3                   | 70.4   | MAPb$_1$Br$_{0.1}$ | [114] |
| 1.67      | 8.2     | 890           | 13.9                   | 65.8   | MAPb$_1$Br$_{0.1}$ | [115] |
| 1.68      | 20.7    | 1220          | 21.3                   | 79.7   | Cs$_{0.05}$(FA$_{0.85}$MAPbBr$_3$)$_{0.15}$ | [116] |
| 1.69      | 7.1     | 936           | 10.4                   | 63.0   | MAPb$_1$Br$_{0.2}$ | [117] |
| 1.70      | 16.9    | 1170          | 20.2                   | 71.5   | Cs$_{0.05}$(FA$_{0.85}$MAPbBr$_3$)$_{0.15}$ | [116] |
| 1.70      | 16.9    | 1170          | 20.2                   | 71.5   | Cs$_{0.05}$(FA$_{0.85}$MAPbBr$_3$)$_{0.15}$ | [116] |
| 1.71      | 12.5    | 1070          | 15.4                   | 75.5   | MAPb$_{3.5}$Cs$_{0.5}$Pb$_4$Br$_{12}$ | [118] |
| 1.72      | 18.6    | 1244          | 19.2                   | 77.9   | FA$_{0.85}$Cs$_{0.15}$Pb$_4$Br$_{12}$ | [119] |
| 1.72      | 17.1    | 1200          | 19.4                   | 73.5   | FA$_{0.85}$Cs$_{0.15}$Pb$_4$Br$_{12}$ | [120] |
| 1.74      | 18.3    | 1269          | 18.9                   | 76.3   | Rb$_{0.25}$Cs$_{0.75}$MAPb$_4$Br$_{12}$ | [121] |
| 1.75      | 19.8    | 1310          | 19.4                   | 78.0   | FA$_{0.85}$Cs$_{0.15}$Pb$_4$Br$_{12}$ | [122] |
| 1.76      | 18.5    | 1210          | 20.0                   | 76.4   | (FA$_{0.85}$MAPbBr$_3$)$_{0.15}$Cs$_{0.85}$Pb$_4$Br$_{12}$ | [123] |
| 1.77      | 18.6    | 1234          | 18.3                   | 82.5   | Cs$_{0.05}$(FA$_{0.85}$MAPbBr$_3$)$_{0.15}$ | [124] |
| 1.78      | 15.7    | 1210          | 18.4                   | 70.5   | Cs$_{0.05}$(FA$_{0.85}$MAPbBr$_3$)$_{0.15}$ | [116] |
| 1.79      | 19.0    | 1250          | 19.0                   | 80.0   | Cs$_{0.05}$(FA$_{0.85}$MAPbBr$_3$)$_{0.15}$ | [116] |
| 1.79      | 16.5    | 1284          | 17.2                   | 74.8   | Cs$_{0.05}$(FA$_{0.85}$MAPbBr$_3$)$_{0.15}$ | [119] |
| 1.80      | 13.7    | 1272          | 14.4                   | 75.0   | MAPb$_{4}$B$_{12}$ | [125] |
| 1.81      | 16.3    | 1220          | 17.0                   | 78.6   | FA$_{0.85}$Cs$_{0.15}$Pb$_4$Br$_{12}$ | [70] |
| 1.82      | 17.1    | 1100          | 21.0                   | 74.0   | FA$_{0.85}$Cs$_{0.15}$Pb$_4$Br$_{12}$ | [126] |
| 1.83      | 3.3     | 1020          | 5.7                    | 56.9   | Cs$_{0.05}$(FA$_{0.85}$MAPbBr$_3$)$_{0.15}$ | [127] |
| 1.83      | 8.6     | 1110          | 11.3                   | 68.4   | Cs$_{0.05}$(FA$_{0.85}$MAPbBr$_3$)$_{0.15}$ | [118] |
| 1.84      | 15.2    | 1260          | 15.6                   | 77.3   | Cs$_{0.05}$(FA$_{0.85}$MAPbBr$_3$)$_{0.15}$DAP | [99] |
| 1.85      | 15.0    | 1296          | 15.6                   | 74.2   | FA$_{0.85}$Cs$_{0.15}$Pb$_4$Br$_{12}$ | [119] |
| 1.86      | 17.0    | 1340          | 15.9                   | 79.8   | Cs$_{0.05}$(FA$_{0.85}$MAPbBr$_3$)$_{0.15}$DAP | [128] |
| $\varepsilon_g$ [eV] | PCE [%] | $V_{oc}$ [mV] | $J_{sc}$ [mA cm$^{-2}$] | FF [%] | Absorber perovskite | Ref. |
|----------------|--------|--------------|----------------|--------|-------------------|-----|
| 1.87 | 14.0 | 1280 | 14.0 | 78.1 | CsPb$_{0.8}$Ba$_{0.2}$I$_2$Br | [129] |
| 1.87 | 13.7 | 1220 | 14.6 | 76.8 | CsPb$_{0.95}$Eu$_{0.05}$I$_2$Br | [130] |
| 1.88 | 15.3 | 1250 | 15.4 | 79.0 | CsPbI$_2$Br | [131] |
| 1.89 | 15.6 | 1300 | 15.3 | 78.3 | CsPb$_{1-x}$Br(Ac)$_x$ | [132] |
| 1.90 | 16.1 | 1320 | 15.3 | 79.7 | CsPbI$_2$Br | [133] |
| 1.91 | 14.4 | 1312 | 15.6 | 70.1 | FA$_{0.15}$Cs$_{0.85}$Pb$_{1.2}$Br$_{1.8}$ | [119] |
| 1.91 | 13.5 | 1177 | 14.3 | 79.9 | CsPbI$_2$Br | [134] |
| 1.91 | 2.0 | 620 | 5.4 | 60.8 | MA$_3$Sn$_3$I$_4$+HI | [135] |
| 1.94 | 4.3 | 630 | 10.7 | 63.8 | Ag$_3$Bi$_4$ | [136] |
| 1.94 | 2.2 | 670 | 5.2 | 62.7 | AgBi$_3$ | [137] |
| 1.95 | 2.6 | 690 | 6.0 | 62.4 | AgBi$_3$ | [137] |
| 1.97 | 1.1 | 850 | 2.2 | 59.6 | Cs$_3$Bi$_2$I$_9$ | [138] |
| 1.98 | 8.3 | 1080 | 12.3 | 62.0 | CsPbBr$_2$ | [139] |
| 2.00 | 9.6 | 1183 | 11.2 | 72.3 | Cs$_{0.15}$FA$_{0.85}$Pb$_2$I$_2$Br$_{1.8}$ | [140] |
| 2.03 | 2.8 | 836 | 6.4 | 52.7 | MAPb$_2$(I$_{0.85}$Br$_{0.15}$)$_3$ | [115] |
| 2.04 | 10.3 | 1340 | 9.7 | 79.2 | MAPb$_2$(I$_{0.85}$Br$_{0.15}$)$_3$Cl$_{0.2}$Br$_{0.8}$ | [141] |
| 2.05 | 6.1 | 1450 | 5.4 | 77.1 | MAPbBr$_2$ | [142] |
| 2.09 | 10.2 | 1270 | 11.5 | 69.4 | CsPbBr$_2$ | [143] |
| 2.10 | 10.7 | 1261 | 11.8 | 72.0 | CsPbBr$_2$ | [144] |
| 2.11 | 9.2 | 1200 | 10.2 | 74.6 | GAI-DEE-CsPbI$_2$ | [145] |
| 2.14 | 3.1 | 650 | 8.1 | 58.4 | MASbS$_3$I$_2$ | [146] |
| 2.15 | 4.4 | 1084 | 6.3 | 64.8 | (FA$_{0.65}$MA$_{0.35}$Pb)$_2$(I$_{0.85}$Br$_{0.15}$)$_3$ | [147] |
| 2.19 | 2.0 | 1051 | 3.0 | 69.5 | (FA$_{0.65}$MA$_{0.35}$Pb)$_2$(I$_{0.85}$Br$_{0.15}$)$_3$ | [147] |
| 2.20 | 1.2 | 610 | 3.6 | 55.9 | Cs$_5$Sb$_3$I$_9$ | [148] |
| 2.27 | 10.6 | 1552 | 8.9 | 76.5 | FAPbBr$_3$ | [149] |
| 2.31 | 9.7 | 1458 | 8.12 | 81.9 | CsPbBr$_3$ | [150] |
| 2.32 | 10.1 | 1653 | 7.72 | 79.1 | MAPbBr$_3$ | [125] |
| 2.33 | 8.2 | 1470 | 7.3 | 76.1 | CsPbBr$_3$ | [131] |
| 2.34 | 9.7 | 1584 | 7.4 | 82.8 | CsPbBr$_3$ | [152] |
| 2.35 | 10.7 | 1622 | 7.9 | 83.5 | CsPbBr$_3$ | [153] |
| 2.35 | 10.6 | 1610 | 7.8 | 84.4 | CsSnBr$_3$ | [154] |
| 2.36 | 4.0 | 1130 | 5.5 | 63.6 | CsPb$_2$Br$_2$Cl$_{0.1}$ | [155] |
| 2.37 | 2.2 | 690 | 5.0 | 63.5 | MA$_3$Sb$_2$Cl$_3$I$_{3-x}$ | [156] |
| 2.38 | 8.1 | 1490 | 6.9 | 78.8 | CsPbBr$_3$ | [157] |
| 2.39 | 10.3 | 1580 | 8.2 | 80.0 | Cs$_{0.15}$Rb$_{0.85}$PbBr$_3$ | [158] |
| 2.42 | 1.1 | 870 | 2.9 | 43.0 | BdAPb$_4$ | [159] |
| 2.43 | 2.8 | 820 | 5.7 | 60.3 | CsPbBr$_3$ | [160] |
| 2.44 | 2.4 | 1140 | 3.4 | 60.9 | FAPbBr$_2$Cl$_{0.9}$ | [161] |
| 2.46 | 1.7 | 1060 | 3.9 | 40.2 | Cs$_3$AgBi$_3$Br$_6$ | [162] |
| 2.48 | 1.4 | 1060 | 2.5 | 52.0 | FAPbBr$_3$Cl | [161] |

*a) Exception included as a material highlight; b) Certified efficiency; MA: methylammonium; FA: formamidinium; c) Exception included as a PCE highlight but missing the absorber information.*
Table 3. Best 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 | [163] |
| 1.34       | 12.8    | 712            | 27.3                     | 65.9   | PTB7-Th:IEICO-4F | [164] |
| 1.34       | 9.7     | 695            | 19.8                     | 70.2   | PBDB-T-DPP:IEICO-4F | [165] |
| 1.35       | 14.3    | 802            | 26.8                     | 66.5   | PBDB-T:2Cl:I-TBP:4F:PC$_6$BM | [166] |
| 1.36       | 15.9    | 846            | 25.4                     | 74.1   | PM6:Y11       | [167]$^a$ |
| 1.37       | 13.6    | 820            | 26.5                     | 62.6   | PM6:Y6        | [168] |
| 1.38       | 17.3    | 841            | 26.2                     | 78.5   | PBDB-T:F:TBP-eC9 | [169]$^b$ |
| 1.39       | 18.2    | 859            | 27.7                     | 76.6   | D18:Y6       | [170]$^b$ |
| 1.39       | 17.0    | 858            | 77.6                     | 25.5   | PBDB-T:F:TBP-4Cl:12 | [171]$^b$ |
| 1.39       | 16.6    | 860            | 25.4                     | 76.3   | PBDB-T:F:AQux-2 | [172] |
| 1.40       | 17.0    | 840            | 26.0                     | 77.8   | PBDB-T:2F:Y6:PC$_{61}$BM | [173] |
| 1.40       | 17.1    | 834            | 26.4                     | 77.6   | PM6:Y6       | [174]$^b$ |
| 1.40       | 16.5    | 867            | 25.4                     | 75.0   | PBDB-T:F:TBP-4Cl | [175]$^a$ |
| 1.41       | 17.4    | 862            | 25.8                     | 77.9   | PM6:SeTIC4Cl:DI-p | [176]$^b$ |
| 1.42       | 15.6    | 834            | 24.9                     | 75.1   | PBDB-T:F:TBP-4F | [177] |
| 1.42       | 15.6    | 838            | 25.0                     | 74.4   | PM6:SeTIC4Cl:DI-p | [178] |
| 1.43       | 14.3    | 820            | 24.9                     | 70.0   | PM6:IDST-4F   | [179] |
| 1.44       | 13.6    | 920            | 21.4                     | 69.1   | PBDB-T:F:BTIC-F-m | [180] |
| 1.46       | 12.9    | 852            | 21.5                     | 70.6   | PM6:NC11      | [181] |
| 1.47       | 14.6    | 882            | 23.1                     | 71.7   | PBDB-T:2Cl:I-TBP-4Cl:4F:MF1 | [182] |
| 1.48       | 12.4    | 880            | 20.8                     | 67.7   | PBDB-T:IDT:EDOT:PC$_{61}$BM | [183] |
| 1.50       | 15.4    | 920            | 22.6                     | 74.1   | PM6:DTC4Cl    | [184] |
| 1.51       | 13.3    | 780            | 22.9                     | 75.0   | PM6:SeTIC4Cl:DI-p | [185] |
| 1.52       | 10.4    | 850            | 18.0                     | 68.0   | PBDB-T:IDT:EDOT:PC$_{61}$BM | [186] |
| 1.53       | 10.7    | 850            | 22.2                     | 56.7   | PM6:SeTIC4Cl:DI-p | [187] |
| 1.54       | 13.6    | 940            | 19.5                     | 73.8   | BTR:NIT1:PC$_{61}$BM | [188] |
| 1.55       | 12.0    | 840            | 19.5                     | 73.3   | PM6:IT-4F     | [189] |
| 1.56       | 12.1    | 826            | 20.9                     | 70.1   | PBDB-T:2F:IT-4F | [181] |
| 1.58       | 13.9    | 950            | 21.7                     | 67.4   | PM6:DTC4Cl    | [182] |
| 1.58       | 13.5    | 880            | 20.6                     | 74.33  | PBDB-T:SF:IT-4F | [183] |
| 1.61       | 13.4    | 940            | 20.2                     | 70.5   | PM6:DTC4Cl    | [182] |
| 1.61       | 12.1    | 916            | 18.1                     | 73.0   | PBDB-T:2Cl:MF1 | [180] |
| 1.62       | 11.0    | 793            | 19.4                     | 71.5   | b) | [187]$^a$ |
| 1.62       | 12.2    | 930            | 17.5                     | 75.0   | PTQ10:IDTPC   | [188] |
| 1.63       | 12.8    | 910            | 19.1                     | 73.6   | PTQ10:IDIC-2F | [189] |
| 1.64       | 12.9    | 960            | 17.4                     | 71.3   | PTQ10:IDIC    | [189] |
| 1.65       | 9.3     | 820            | 16.5                     | 68.7   | JS1:ITIC    | [190] |
| 1.66       | 12.1    | 815            | 20.3                     | 73.2   | b) | [191]$^b$ |
| 1.67       | 10.2    | 810            | 21.0                     | 59.9   | P4T1F:PC$_{61}$BM | [183] |
| 1.67       | 11.5    | 791            | 19.7                     | 73.7   | b) | [192]$^b$ |
| 1.68       | 12.0    | 1030           | 18.5                     | 63.0   | PBDDTTT:EFT:EHDITBR | [193] |
| 1.69       | 8.9     | 878            | 13.9                     | 72.9   | PBT1-C:NFA  | [194] |
| 1.70       | 11.1    | 867            | 17.8                     | 71.9   | b) | [195]$^b$ |
| 1.72       | 10.0    | 899            | 16.8                     | 66.4   | b) | [21]$^b$ |
| 1.79       | 7.5     | 1140           | 10.6                     | 62.1   | BDT-RBX:DT:PD14 | [196] |
| 1.79       | 6.2     | 1230           | 8.9                      | 56.6   | BDT-RBX:DT:SF:PD1      | [196] |
| 1.85       | 9.0     | 900            | 13.8                     | 72.9   | BTR:PC$_{61}$BM | [184] |
| 1.85       | 7.6     | 830            | 13.3                     | 69.1   | PBDB-T:PC$_{61}$BM | [181] |
| 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 | [166] |
| 2.01       | 3.7     | 592            | 10.4                     | 59.2   | P3HT:PCBM | [198] |

$^a$Certified efficiency; $^b$Exception included as a PCE highlight but missing the absorber information.
Table 4. Best 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 [%] | Dye sensitizer | Ref. |
|-----------|--------|---------------|------------------------|-------|----------------|------|
| 1.44      | 11.0   | 714           | 21.9                   | 70.3  |                     | [21] |
| 1.52      | 11.4   | 743           | 21.3                   | 71.9  |                     | [21] |
| 1.59      | 10.1   | 710           | 18.5                   | 76.9  | TF-tBu$_2$C$_3$F$_7$| [199]|
| 1.74      | 7.8    | 694           | 15.4                   | 72.7  | YD2             | [200]|
| 1.77      | 10     | 740           | 18.1                   | 74.7  | N719            | [201]|
| 1.80      | 6.5    | 663           | 13.3                   | 74.5  | SK7             | [200]|
| 1.82      | 6.4    | 680           | 13.1                   | 71.8  | AN-11          | [202]|
| 1.85      | 12.3   | 1020          | 15.2                   | 79.1  |                     | [4]  |
| 1.86      | 8.3    | 782           | 14.8                   | 71.7  | N719            | [203]|
| 1.87      | 9.1    | 1060          | 11.2                   | 76.7  | L351            | [204]|
| 1.88      | 7.8    | 730           | 14.3                   | 74.7  | TY4             | [201]|
| 1.89      | 8.5    | 580           | 21.3                   | 68.8  | N719+W2        | [203]|
| 1.93      | 11.2   | 1140          | 13.0                   | 75.6  | L350            | [204]|
| 1.97      | 3.0    | 600           | 6.3                    | 79.4  | AN-14          | [202]|
| 1.99      | 5.4    | 689           | 11.3                   | 69.5  | SK6             | [203]|
| 2.00      | 6.3    | 732           | 12.0                   | 71.7  | CW10+SK6      | [203]|
| 2.01      | 9.2    | 1160          | 11                     | 72.1  | L349            | [204]|
| 2.02      | 8.1    | 760           | 14.3                   | 75.0  | TY6             | [201]|
| 2.05      | 3.9    | 680           | 7.4                    | 77.5  | AN-12          | [202]|
| 2.09      | 6.9    | 780           | 11.6                   | 76.3  | TY3             | [201]|
| 2.12      | 5.8    | 739           | 10.8                   | 72.7  | CW10           | [203]|
| 2.23      | 5.8    | 760           | 10.2                   | 74.8  | MS3            | [201]|
| 2.32      | 5.3    | 1170          | 6.4                    | 70.8  | L348           | [204]|

*a)Exception included as a PCE highlight but missing the absorber information; b) Certified efficiency.

Table 5. Best research solar cells performance parameters as a function of device absorber bandgap energy (from EQE spectrum) for several inorganic emerging technologies.

| $E_g$ [eV] | PCE [%] | $V_{oc}$ [mV] | $J_{sc}$ [mA cm$^{-2}$] | FF [%] | Absorber material/technology | Ref. |
|-----------|--------|---------------|------------------------|-------|-------------------------------|------|
| 1.09      | 10.8   | 447           | 38.6                   | 62.6  | Cu$_2$ZnSn(S$_x$Se$_{1-x}$)$_4$ | [206]|
| 1.11      | 9.4    | 457           | 32.5                   | 63.3  | Cu$_2$ZnSnSe$_4$              | [207]|
| 1.12      | 9.5    | 460           | 31.1                   | 66.4  | Cu$_2$ZnSnSe$_4$              | [207]|
| 1.13      | 12.6   | 513           | 35.2                   | 69.8  | Cu$_2$ZnSn(S$_x$Se$_{1-x}$)$_4$| [208]|
| 1.13      | 11.1   | 460           | 34.5                   | 69.8  | Cu$_2$ZnSn(S$_x$Se$_{1-x}$)$_4$| [206]|
| 1.15      | 8.4    | 426           | 30.0                   | 65.7  | Cu$_2$ZnSnSe$_4$              | [207]|
| 1.22      | 7.5    | 413           | 28.9                   | 62.4  | Sb$_2$Se$_3$                 | [209]|
| 1.24      | 9.2    | 400           | 32.6                   | 70.6  | Sb$_2$Se$_3$                 | [210]|
| 1.27      | 4.8    | 370           | 27.3                   | 47.3  | Sb$_2$Se$_3$                 | [210]|
| 1.50      | 11.0   | 731           | 21.7                   | 69.3  | Cu$_2$ZnSnS$_4$              | [211]|
| 1.50      | 10.0   | 655           | 24.1                   | 63.3  | Sb$_2$(S$_x$Se$_{1-x}$)$_3$   | [212]|
| 1.52      | 8.73   | 664           | 20.6                   | 63.9  | (Cu$_{0.8}$Sb$_{0.2}$)$_{1.13}$Zn$_{0.3}$Cd$_{0.7}$S$_4$ | [213]|

*a)Certified efficiency.
Table 6. Best research solar cells performance parameters as a function of device absorber bandgap energy (from EQE spectrum) for 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                       | [214]$^a$ |
| 1.10       | 21.7    | 718           | 40.7            | 74.3  | CIGS                       | [191]$^a$ |
| 1.11       | 26.7    | 738           | 42.7            | 84.9  | Si (crystalline)            | [191]$^a$ |
| 1.13       | 22.9    | 744           | 38.8            | 79.5  | CIGS                       | [215]$^a$ |
| 1.14       | 21.0    | 757           | 35.7            | 77.6  | CIGS                       | [216]$^a$ |
| 1.15       | 23.4    | 734           | 39.6            | 80.4  | CIGS                       | [176]$^a$ |
| 1.30       | 16.3    | 762           | 31.4            | 68.1  | CIGS                       | [217]$^a$ |
| 1.42       | 29.1    | 1127          | 29.8            | 86.7  | GaAs                       | [218]$^a$ |
| 1.42       | 21.0    | 1062          | 30.3            | 79.4  | CdTe                       | [187]$^a$ |
| 1.48       | 18.3    | 857           | 27.0            | 77.0  | CdTe                       | [195]$^a$ |
| 1.60       | 10.2    | 896           | 16.4            | 69.8  | Si (amorphous)             | [187]$^a$ |
| 1.69       | 10.6    | 896           | 16.1            | 75.6  | Si (amorphous)             | [219]$^a$ |
| 1.85       | 10.1    | 886           | 16.8            | 67.0  | Si (amorphous)             | [220]$^a$ |

$^a$Certified efficiency.

10.2. Best Flexible Efficiency Research Solar Cells Tables

Table 7. Best flexible 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. |
|------------|---------|---------------|-----------------|-------|----------------------|------|
| 1.47       | 3.62    | 616           | 14.5            | 40.6  | (5-AVA)$_y$(MA)$_{1−y}$PbI$_3$ | [221]$^a$ |
| 1.54       | 18.3    | 1090          | 23.4            | 71.5  | FA$_{0.25}$Cs$_{0.05}$PbI$_3$ | [96]  |
| 1.54       | 18.2    | 1070          | 22.1            | 76.9  | FAPb$_{1−x}$Br$_x$      | [222] |
| 1.56       | 17.1    | 1101          | 22.1            | 75.4  | MA$_{0.25}$FA$_{0.75}$PbI$_3$ | [223] |
| 1.57       | 19.5    | 1110          | 23.1            | 76.0  | FA$_{0.34}$MA$_{0.66}$Cs$_{0.05}$PbI$_{0.85}$Br$_{0.15}$ | [224] |
| 1.59       | 19.3    | 1090          | 22.7            | 78.1  | MAPbI$_3$−NH4Cl          | [225] |
| 1.60       | 19.0    | 1090          | 21.8            | 80.0  | MAPbI$_3$                | [226] |
| 1.60       | 18.4    | 1103          | 22.5            | 74.2  | MAPbI$_3$−dimethylsulfide | [227] |
| 1.61       | 17.3    | 1062          | 21.7            | 74.9  | Cs$_{0.25}$FA$_{0.75}$MA$_{0.5}$PbI$_{0.85}$Br$_{0.15}$ | [228]$^b$ |
| 1.61       | 19.1    | 1135          | 21.2            | 79.2  | Cs$_{0.25}$FA$_{0.75}$MA$_{0.5}$PbI$_{0.85}$Br$_{0.15}$ | [229] |
| 1.62       | 18.0    | 1120          | 22.3            | 72.1  | Cs$_{0.25}$FA$_{0.75}$MA$_{0.5}$PbI$_{0.85}$Br$_{0.15}$ | [230] |
| 1.63       | 10.4    | 1030          | 19.2            | 52.8  | (FA$_{0.25}$MA$_{0.75}$MAPbI$_{0.25}$Br$_{0.75}$) | [231] |
| 1.65       | 11.2    | 940           | 18.4            | 64.9  | MAPbI$_3$                | [232] |
| 1.65       | 7.9     | 1090          | 10.8            | 70.7  | Cs$_{0.25}$FA$_{0.75}$MA$_{0.5}$PbI$_{0.85}$Br$_{0.15}$ | [233] |

$^a$ $E_g$ taken from absorption spectrum; $^b$ Certified efficiency; MA: methylammonium; FA: formamidinium.

Table 8. Best flexible 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 | [163] |
| 1.39       | 13.4    | 829           | 23.0            | 70.0  | PM6:Y6         | [234] |
| 1.40       | 15.2    | 832           | 25.1            | 73.0  | PBDB-T-2F:Y6   | [235] |
| 1.40       | 14.1    | 828           | 23.6            | 72.0  | PM6:Y6:PC$_{71}$BM | [236] |
| 1.55       | 12.0    | 840           | 19.5            | 73.3  | PM6:IT-4F      | [183] |
| 1.56       | 11.6    | 820           | 19.6            | 72.2  | PBDB-T:2F:IT-4F| [237] |
| 1.56       | 12.1    | 826           | 20.9            | 70.1  | PBDB-T:2F:IT-4F| [186] |
| 1.61       | 10.9    | 900           | 18.7            | 64.8  | PBDB-T:ITIC     | [186] |
| 1.63       | 9.2     | 770           | 16.0            | 74.7  | PTB7-Th:PC$_{71}$BM | [238] |
| 1.65       | 9.3     | 820           | 16.5            | 68.7  | J51:ITIC       | [190] |
| 1.65       | 8.2     | 890           | 13.4            | 68.6  | PBDB-T:ITIC    | [239] |
| 2.01       | 3.7     | 592           | 10.4            | 59.2  | P3HT:PCBM      | [198] |
Table 9. Best flexible 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 % | Dye sensitizer | Ref. |
|------------|---------|---------------|-----------------------|-------|----------------|------|
| 1.74       | 4.6     | 750           | 10.5                  | 58.0  | N719           | [240]|
| 1.75       | 7.6     | 732           | 15.0                  | 69.2  | N719           | [241]|
| 1.79       | 6.5     | 729           | 13.19                 | 68.0  | N719           | [242]|
| 1.81       | 6.3     | 754           | 12.3                  | 67.9  | (JH-1)0.4(SQ2)0.4 | [243]|
| 1.88       | 6.0     | 750           | 11.2                  | 71.0  | N719           | [244]|
| 1.94       | 4.2     | 710           | 10.3                  | 57.2  | N719           | [245]|
| 1.99       | 6.4     | 660           | 18.1                  | 53.4  | N719           | [240]|

Table 10. Best flexible research single-junction solar cells performance parameters as a function of device absorber bandgap energy (from EQE spectrum) for established and other emerging 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                        | [246]|
| 1.20       | 20.4    | 736           | 35.1                  | 78.9  | CIGS                        | [247]|
| 1.22       | 18.7    | 720           | 35.0                  | 74.4  | CIGS                        | [248]|
| 1.32       | 8.4     | 550           | 24.3                  | 63.0  | c-Si                        | [249]|
| 1.42       | 22.1    | 980           | 27.1                  | 83.4  | GaAs                        | [250]|
| 1.46       | 16.4    | 831           | 25.5                  | 77.4  | CdTe                        | [251]|
| 1.49       | 11.5    | 821           | 22.0                  | 63.9  | CdTe                        | [252]|
| 1.79       | 8.8     | 888           | 14.3                  | 70    | a-Si:H                      | [253]|
| 1.88       | 8.2     | 820           | 15.6                  | 64.0  | a-Si:H                      | [254]|

10.3. Best Transparent and Semitransparent Research Solar Cells Tables

Table 11. 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). MA: methylammonium; FA: formamidinium.

| AVT [%] | $E_g$ [eV] | PCE [%] | $V_{oc}$ [mV] | $J_{sc}$ [mA cm$^{-2}$] | FF % | Absorber | Ref. |
|---------|------------|---------|---------------|-----------------------|-------|----------|------|
| 3       | 1.53       | 12.2    | 1017          | 17.5                  | 68.5  | MAPbI$_3$ | [255]|
| 5       | 1.60       | 16.5    | 1080          | 20.6                  | 74.2  | MAPbI$_3$ | [256]|
| 5       | 1.61       | 12.0    | 960           | 19.2                  | 65.3  | MAPbI$_3$Cl$_x$ | [257]|
| 5       | 1.65       | 11.2    | 940           | 18.4                  | 64.9  | MAPbI$_3$ | [232]|
| 6       | 1.60       | 15.8    | 1100          | 19.3                  | 74.4  | MAPbI$_3$ | [258]|
| 7       | 1.55       | 13.6    | 988           | 20.4                  | 67.5  | MAPbI$_3$ | [259]|
| 10      | 1.59       | 17.5    | 1070          | 22.4                  | 73.1  | MAPbI$_3$ | [260]|
| 10      | 1.65       | 16.1    | 1060          | 20.4                  | 74.5  | Cs$_{0.05}$(FA$_{0.85}$MA$_{0.15}$)$_3$Pb(I$_{0.85}$Br$_{0.15}$)$_3$ | [261]|
| 12      | 1.60       | 13.2    | 1000          | 19.5                  | 67.8  | MAPbI$_3$ | [260]|
| 13      | 1.67       | 14.9    | 1100          | 19.8                  | 68.4  | MAPbI$_3$Br$_{0.5}$ | [260]|
| 14      | 1.57       | 13.0    | 970           | 19.1                  | 69.9  | MAPbI$_3$Cl$_x$ | [262]|
| 15      | 1.61       | 11.9    | 1000          | 17.8                  | 66.3  | MAPbI$_3$ | [260]|
| 16      | 1.76       | 13.7    | 1120          | 16.7                  | 73.4  | MAPbI$_3$Br | [260]|
| 17      | 1.65       | 12.8    | 1040          | 16.6                  | 74.1  | Cs$_{0.05}$(FA$_{0.85}$MA$_{0.15}$)$_3$Pb(I$_{0.85}$Br$_{0.15}$)$_3$ | [261]|
| 18      | 1.77       | 12.2    | 1110          | 15.1                  | 72.7  | MAPbI$_3$Br | [260]|
| 18      | 1.53       | 9.1     | 1017          | 14.6                  | 61.5  | MAPbI$_3$ | [255]|
| 19      | 1.55       | 8.8     | 941           | 13.7                  | 68.3  | MAPbI$_3$ | [255]|
| 20      | 1.63       | 14.7    | 1108          | 17.6                  | 75.2  | K$_2$Cs$_{0.05}$(FA$_{0.85}$MA$_{0.15}$)$_3$Pb(I$_{0.85}$Br$_{0.15}$)$_3$ | [263]|
| 21      | 1.63       | 14.2    | 1117          | 17.4                  | 73.2  | K$_2$Cs$_{0.05}$(FA$_{0.85}$MA$_{0.15}$)$_3$Pb(I$_{0.85}$Br$_{0.15}$)$_3$ | [263]|
| 21      | 1.63       | 11.0    | 1000          | 15.9                  | 69.2  | MAPbI$_3$ | [264]|
| 22      | 1.61       | 13.2    | 1073          | 17.2                  | 71.7  | K$_2$Cs$_{0.05}$(FA$_{0.85}$MA$_{0.15}$)$_3$Pb(I$_{0.85}$Br$_{0.15}$)$_3$ | [263]|

Adv. Energy Mater. 2021, 11, 2002774 2002774 (21 of 39) © 2020 The Authors. Advanced Energy Materials published by Wiley-VCH GmbH
Table 12. 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 [%] | Absorber Ref. |
|---------|------------|---------|--------------|-----------------------|--------|---------------|
| 2       | 1.66       | 12.3    | 1082         | 17.1                  | 66.6   | K$_2$Cu$_{0.5}$(FA$_{0.85}$MA$_{0.15}$)$_{0.5}$Pb$_2$(I$_{0.85}$Br$_{0.15}$)$_3$ [263] |
| 3       | 1.62       | 11.3    | 1040         | 15.1                  | 72.3   | MAPbI$_3$ [265] |
| 11      | 1.66       | 10.8    | 970          | 17.3                  | 64.4   | MAPbI$_2$Cl$_x$ [262] |
| 13      | 1.87       | 9.4     | 1120         | 13.6                  | 61.6   | MAPbI$_2$Br$_{1.5}$ [260] |
| 14      | 1.55       | 10.8    | 950          | 16.3                  | 69.7   | MAPbI$_3$ [266] |
| 16      | 1.63       | 10.2    | 1070         | 12.2                  | 78.1   | MAPbI$_3$ [267] |
| 17      | 1.60       | 12.1    | 1000         | 18.3                  | 66.2   | MAPbI$_3$ [260] |
| 18      | 1.60       | 8.5     | 964          | 13.1                  | 66.8   | MAPbI$_2$Cl$_x$ [268] |
| 19      | 1.57       | 8.1     | 1030         | 11.2                  | 70.2   | MAPbI$_2$Cl$_x$ [262] |
| 20      | 1.62       | 12.8    | 1030         | 16.5                  | 74.9   | MAPbI$_2$Cl$_x$ [269] |
| 21      | 1.65       | 7.4     | 1010         | 11.8                  | 62.2   | MAPbI$_2$Cl$_x$ [269] |
| 22      | 1.69       | 11.9    | 1050         | 16.3                  | 69.4   | MAPbI$_2$Br$_{1.5}$ [260] |
| 23      | 1.55       | 7.3     | 1037         | 13.4                  | 52.5   | MAPbI$_3$ [270] |
| 24      | 1.62       | 11.7    | 990          | 15.9                  | 74.6   | MAPbI$_2$Cl$_x$ [269] |
| 25      | 1.79       | 10.3    | 1080         | 14.6                  | 65.5   | MAPbI$_3$Br [260] |
| 26      | 1.62       | 10.8    | 1010         | 14.7                  | 73.1   | MAPbI$_2$Cl$_x$ [269] |
| 27      | 1.57       | 7.8     | 970          | 11.6                  | 69.6   | MAPbI$_2$Cl$_x$ [262] |
| 28      | 1.63       | 10.7    | 1060         | 13.0                  | 77.6   | MAPbI$_3$ [267] |
| 29      | 1.90       | 8.8     | 1110         | 12.8                  | 62.2   | MAPbI$_2$Br$_{1.5}$ [260] |
| 30      | 1.42       | 10.3    | 1000         | 13.6                  | 75.6   | MAPbI$_2$Cl$_x$ [269] |
| 31      | 1.64       | 8.5     | 960          | 12.6                  | 73.5   | MAPbI$_2$Cl$_x$ [269] |
| 32      | 1.57       | 3.6     | 1030         | 5.4                   | 64.4   | MAPbI$_2$Cl$_x$ [262] |
| 33      | 1.63       | 4.5     | 880          | 8.2                   | 63.0   | MAPbI$_3$ [271] |
| 34      | 2.62       | 1.1     | 1000         | 2.1                   | 52.9   | Cs$_2$AgBiBr$_4$ [272] |
| 35      | 2.35       | 7.8     | 1550         | 6.7                   | 72.0   | FA$\text{PbBr}_2$Cl$_{0.57}$ [161] |
| 36      | 2.62       | 1.5     | 960          | 2.1                   | 74.3   | Cs$_2$AgBiBr$_4$ [272] |
| 37      | 3.03       | 0.2     | 1110         | 0.6                   | 35.4   | MAPbCl$_3$ [273] |
| 38      | 2.62       | 1.6     | 970          | 2.2                   | 73.1   | Cs$_2$AgBiBr$_4$ [272] |
| 39      | 2.84       | 0.5     | 1260         | 0.9                   | 44.9   | MAPbCl$_3$Br$_3$ [273] |
| 40      | 2.62       | 1.5     | 970          | 2.2                   | 71.1   | Cs$_2$AgBiBr$_4$ [272] |

Table 11. Continued.
Table 13. 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 [%] | Active material | Ref. |
|---------|-----------|---------|--------------|----------------|-------|----------------|------|
| 1       | 2.00      | 5.2     | 780          | 12.4           | 53.7  | N719           | [287]|
| 9       | 2.00      | 4.5     | 780          | 10.3           | 56.0  | N719           | [287]|
| 9       | 1.82      | 4.3     | 720          | 9.9            | 60.0  | N719+SDA       | [288]|
| 10      | 2.01      | 5.2     | 770          | 11.9           | 57.0  | N719           | [288]|
| 10      | 2.00      | 4.9     | 765          | 11.4           | 56.1  | N719           | [288]|
| 13      | 1.68      | 10.1    | 851          | 14.9           | 80.2  | SGT-021        | [289]$^a$|
| 14      | 1.68      | 9.9     | 850          | 14.9           | 78.5  | SGT-021        | [289]$^a$|
| 15      | 1.68      | 9.6     | 850          | 14.7           | 77.2  | SGT-021        | [289]$^a$|
| 17      | 1.68      | 9.8     | 855          | 15.1           | 75.5  | SGT-021        | [289]$^a$|
| 23      | 1.82      | 4.2     | 650          | 9.9            | 64.0  | N719+SDA       | [288]|
| 23      | 2.01      | 3.6     | 650          | 8.2            | 68.0  | N719           | [288]|
| 24      | 2.00      | 3.5     | 786          | 7.3            | 60.9  | N719           | [287]|
| 25      | 1.82      | 2.6     | 650          | 5.6            | 71.0  | N719+SDA       | [288]|
| 30      | 2.19      | 1.5     | 640          | 3.3            | 70.0  | N719           | [288]|
| 43      | 1.95      | 7.8     | 720          | 15.3           | 70.8  | PdTPBP/BPEA    | [290]$^b$|

$^a$Selective absorption-like EQE spectrum; $^b$ $E_g$ calculated from transmittance spectrum.
Table 14. 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              | [291]|
| 9      | 1.30           | 9.8     | 630            | 20.9            | 74.1  | CIGS              | [291]|
| 16     | 1.34           | 6.5     | 597            | 22.9            | 46.5  | CIGS              | [292]|
| 17     | 1.64           | 1.7     | 495            | 8.9             | 40.8  | CIGS              | [293]|
| 22     | 2.05           | 5.5     | 760            | 12.3            | 58.6  | a-Si:H            | [294]|
| 23     | 1.92           | 6.0     | 830            | 10.6            | 68.2  | a-Si:H            | [293]|
| 24     | 1.68           | 6.9     | 920            | 10.7            | 70.3  | a-Si:H            | [296]|
| 26     | 1.50           | 5.9     | 710            | 14.6            | 57.4  | CIGS              | [297]|
| 43     | 1.53           | 0.4     | 101            | 14.7            | 27.2  | CdTe              | [298]|

\( E_g \) taken from absorption spectrum; AVT average transmittance.

10.4. Stability Tests Tables of Emerging Research Solar Cells

Table 15. 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). 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.

| \( E_g \) [eV] | 0 h PCE [%] | 200 h PCE [%] | 1000 h PCE [%] | \( E_{200h} \) [Wh cm\(^{-2}\)] | \( E_{1000h} \) [Wh cm\(^{-2}\)] | Absorber | Ref. | Comments |
|----------------|-------------|---------------|----------------|-----------------|-----------------|----------|------|----------|
| 1.57           | 21.8        | 22.0          | 21.8           | 4.2             | 22.0            | Cs\(_{0.05}\)(FA\(_{0.92}\)MA\(_{0.08}\))\(_{0.95}\)Pb\(_{0.92}\)Br\(_{0.08}\) | [36] | MPP, AM1.5G, N\(_2\), 40 °C, UV-f |
| 1.57           | 20.6        | 20.2          | 20.2           | 4.1             | 20.1            | FA\(_{0.95}\)Cs\(_{0.05}\)Pb\(_{0.95}\)Br\(_{0.05}\) | [299] | MPP, w-LED, Ar, 55–60 °C |
| 1.58           | 19.2        | 19.3          | 18.4           | 3.9             | 19.0            | (FA\(_{0.95}\)MA\(_{0.05}\))\(_{0.95}\)Cs\(_{0.05}\)Pb\(_{0.95}\)Br\(_{0.05}\) | [300] | OC, AM1.5G, encapsulation, 70–75 °C |
| 1.59           | 17.1        | 11.6          | 9.5            | 2.8             | 11.1            | MA\(_{0.95}\)Cs\(_{0.05}\)Pb\(_{0.95}\)Br\(_{0.05}\) | [301] | MPP, AM1.5G, Ar, 60 °C |
| 1.60           | 19.2        | 19.5          | 17.6           | 4.1             | 19.1            | MAPb\(_{0.1}\)Cl\(_{0.9}\) | [109] | OC, AM1.5G |
| 1.60           | 19.6        | 19.6          | 18.8           | 3.9             | 19.4            | Cs\(_{0.05}\)(FA\(_{0.95}\)MA\(_{0.05}\))\(_{0.95}\)Pb\(_{0.95}\)Br\(_{0.05}\) | [302] | MPP-R\(_L\), AM1.5G, encapsulation, 50–70% RH, 65 °C |
| 1.61           | 18.1        | 11.9          | 13.6           | 2.6             | 13.0            | MA\(_{0.95}\)Cs\(_{0.05}\)Pb\(_{0.95}\)Br\(_{0.05}\) | [301] | MPP, AM1.5G, Ar, 60 °C |
| 1.63           | 12.2        | 13.3          | 12.3           | 2.1             | 9.9             | (FA\(_{0.95}\)MA\(_{0.05}\))\(_{0.95}\)Cs\(_{0.05}\)Pb\(_{0.95}\)Br\(_{0.05}\) | [303] | 77 mW cm\(^{-2}\), MPP-R\(_L\), AM1.5G, RH=25%, 26 °C |
| 1.64           | 20.1        | 17.8          | –              | 3.7             | –               | Cs\(_{0.1}\)(MA\(_{0.9}\))\(_{0.95}\)Pb\(_{0.95}\)Br\(_{0.05}\) | [304] | MPP, w-LED, N\(_2\), 25 °C |
| 1.64           | 19.7        | 17.2          | –              | 3.5             | –               | Cs\(_{0.1}\)(FA\(_{0.95}\)MA\(_{0.05}\))\(_{0.95}\)Pb\(_{0.95}\)Br\(_{0.05}\) | [305] | MPP, w-LED, N\(_2\), 20 °C |
| 1.66           | 13.0        | 14.7          | 13.0           | 2.8             | 14.1            | Cs\(_{0.1}\)(FA\(_{0.95}\)Pb\(_{0.95}\)Br\(_{0.05}\))\(_{0.95}\) | [306] | MPP, AM1.5G, 40% RH, 35 °C |
| 1.69           | 6.8         | 6.7           | –              | 1.3             | –               | CsSn\(_{0.1}\)Ge\(_{0.1}\) | [117] | MPP\(_L\), AM1.5G, N\(_2\), 45 °C |
| 1.74           | 12.9        | 13.4          | –              | 2.7             | –               | CsPb\(_{0.1}\) | [307] | OC, AM1.5G, N\(_2\), 25 °C, UV-f |

\( E_g \) taken from PL peak; \( \text{MA} \): methylammonium; \( \text{FA} \): formamidinium.
Table 16. 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). OC: open-circuit (condition during test); UV-f: ultraviolet light filter; w-LED: white light spectrum light emitting diode source.

| $E_g$ [eV] | 0 h PCE [%] | 200 h PCE [%] | 1000 h PCE [%] | $E_{200h}$ [Wh cm$^{-2}$] | $E_{1000h}$ [Wh cm$^{-2}$] | Active material | Ref. | Comments |
|----------|------------|--------------|----------------|--------------------------|-----------------------------|----------------|------|---------|
| 1.56     | 7.8        | 7.2          | 6.8            | 1.5                      | 7.0                         | PBDB-T:ITIC-2F  | [308] | OC, w-LED, N$_2$, 40 °C, UV-f |
| 1.57     | 5.0        | 5.0          | 4.7            | 1.0                      | 4.8                         | P3HTo-IDTBR     | [309] | OC, AM1.5G, N$_2$, UV-f       |
| 1.66     | 8.0        | 7.4          | 7.0            | 1.5                      | 7.3                         | PBDB-T:ITIC-Th   | [308] | OC, w-LED, N$_2$, 40 °C, UV-f |
| 1.70     | 8.7        | 8.1          | –              | 1.6                      | –                           | PBDB-T:IDTBR     | [310] | OC, AM1.5G, N$_2$, 35–40 °C |
| 1.84     | 5.9        | 5.6          | 5.4            | 1.1                      | 5.6                         | PBDB-T:PCBM      | [308] | OC, w-LED, N$_2$, 40 °C, UV-f |
| 1.94     | 3.7        | 3.7          | 3.7            | 0.7                      | 3.7                         | P3HT-PCBM        | [311] | OC, AM1.5G, air               |

Table 17. 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). OC: open-circuit (condition during test); UV-f: ultraviolet light filter; w-LED: white light spectrum light emitting diode source.

| $E_g$ [eV] | 0 h PCE [%] | 200 h PCE [%] | 1000 h PCE [%] | $E_{200h}$ [Wh cm$^{-2}$] | $E_{1000h}$ [Wh cm$^{-2}$] | Dye sensitizer | Ref. | Comments |
|----------|------------|--------------|----------------|--------------------------|-----------------------------|----------------|------|---------|
| 1.59     | 9.0        | 9.0          | 8.2            | 1.8                      | 8.7                         | TF-tBu_C3F7     | [312] | OC, AM1.5G, 65 °C             |
| 1.75     | 6.5        | 6.7          | 6.3            | 1.4                      | 6.6                         | N719            | [313] | OC, AM1.5G, 35 °C, UV-f       |
| 1.77     | 6.3        | 5.8          | 4.8            | 1.3                      | 5.5                         | Z907            | [314] | OC, w-LED, 20 °C              |
| 1.78     | 9.3        | 9.9          | 7.9            | 1.9                      | 9.2                         | N719            | [315] | OC, AM1.5G, 50 °C             |
| 1.83     | 8.4        | 8.3          | –              | 1.7                      | –                           | MK2             | [312] | OC, w-LED                     |
| 1.85     | 8.0        | 8.3          | 8.3            | 1.4                      | 8.1                         | N719            | [316] | OC, AM1.5G                    |
| 2.07     | 5.8        | 6.5          | 5.9            | 1.3                      | 6.2                         | D35             | [317] | OC, AM1.5G, 60 °C             |

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

Acknowledgements
O.A. acknowledges the financial support from the VDI/VID Innovation + Technik GmbH (Project-title: PV-ZUM) and the SAOT funded by the German Research Foundation (DFG) in the framework of the German excellence initiative. C.J.B. acknowledges funding from DFG within INST 90/917-1 FUGC, the SFB 953 (DFG, project no. 182849149) and the ICG 2495 (Energy Conversion Systems—from Materials to Devices). C.J.B. further acknowledges the grants “ELF-PV—Design and development of solution processed functional materials for the next generations of PV technologies” (No. 44-6521a/20/4) and “Solar Factory of the Future” (FKZ 20.2-3410.5-4.5) and the SoTech Initiative by the Bavarian State Government. A.F.N. acknowledges support from FAPESP (Grant 2017/11986-5), Shell and the strategic importance of the support given by ANP (Brazil’s National Oil, Natural Gas and Biofuels Agency) through the R&D levy regulation. R.R.L. gratefully acknowledges support from the National Science Foundation under grant CBET-1702591. N.K. acknowledges funding by the US Department of Energy, Office of Energy Efficiency and Renewable Energy, Solar Energy Technologies Office, Agreement Number 34351. J.N. thanks the European Research Council for support under the European Union’s Horizon 2020 research and innovation program (grant agreement No 742708). Minor alterations were made to Figure 7c,f on March 18, 2021.

Conflict of Interest
R.R.L. is a co-founder, director, and a part owner of Ubiquitous Energy, Inc., a company working to commercialize transparent photovoltaic technologies. All other authors declare no competing financial interests.

Keywords
bandgap energy, emerging photovoltaics, flexible photovoltaics, photovoltaic device photostability, transparent and semitransparent solar cells

Received: August 28, 2020
Revised: November 9, 2020
Published online: December 4, 2020

[1] W. Shockley, H. J. Queisser, J. Appl. Phys. 1961, 32, 510.
[2] A. Ndiaye, A. Charki, A. Kobi, C. M. F. Kébé, P. A. Ndiaye, V. Sambou, Sol. Energy 2013, 96, 140.
[3] D. C. Jordan, S. R. Kurtz, Prog. Photovoltaics 2013, 21, 12.
[4] M. A. Green, E. D. Dunlop, J. Hohl-Ebinger, M. Yoshita, N. Kopidakis, A. W. Y. Ho-Baillie, Prog. Photovoltaics 2020, 28, 3.
[5] M. A. Green, K. Emery, Prog. Photovoltaics 1993, 1, 25.
[6] M. A. Green, E. D. Dunlop, J. Hohl-Ebinger, M. Yoshita, N. Kopidakis, X. Hao, Prog. Photovoltaics 2020, 28, 629.
[7] NREL’s Best Research-Cell Efficiency Chart, https://www.nrel.gov/pv/cell-efficiency.html (accessed: May 2020).
[8] E. L. Unger, E. T. Hoke, C. D. Bailie, W. H. Nguyen, A. R. Bowring, T. Heumuller, M. G. Christoforo, M. D. McGehee, Energy Environ. Sci. 2014, 7, 3690.
[9] H. J. Snaith, A. Abate, J. M. Ball, G. E. Eperon, T. Leijtens, N. K. Noel, S. D. Stranks, J. T. W. Wang, K. Wojciechowski, W. Zhang, J. Phys. Chem. Lett. 2014, 5, 1511.
[10] P. López-Varo, J. A. Jiménez-Tejada, M. García-Rosell, S. Ravishankar, G. Garcia-Belmonte, J. Bisquert, O. Almora, Adv. Energy Mater. 2013, 3, 1511.
[11] D.-H. Kang, N.-G. Park, Adv. Mater. 2019, 31, 1805214.
[12] N. Pellet, F. Giordano, M. Ibrahim Dar, G. Gregori, S. M. Zakeeruddin, J. Maier, M. Grätzel, Prog. Photovoltaics 2017, 25, 942.
such as the light intensity modulated impedance spectroscopy (LIMIS). On December 4, 2019, he recently he is been focused on the development of optoelectronic characterization techniques, and modeling of energy materials and devices, e.g., perovskite solar cells, and more.

Osbel Almora graduated of Physics from the University of Havana, Cuba, in 2013 and received his Ph.D. in 2020 from both the Universität 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 is 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, 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 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 & 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, 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 QD nanostructures. He then joined the CInC, Autonomous University of the State of Morelos, as a postdoctoral research fellow. He is currently a researcher at COZCyT 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 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. She completed her Bachelor of Engineering on Co-op scholarship (2001) and Ph.D. (2005) at University of New South Wales. Her research interests include engineering of solar materials and devices at nanoscale for high performance durable single junction and multi junction tandem cells for a wide range of applications. Her achievements include setting several solar cell energy efficiency world records and reporting of highly durable perovskite solar cells passing the International Electrotechnical Commission terrestrial photovoltaic module (IEC61215) standard damp heat and thermal cycling tests.
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 EPFL, Cambridge University, and Uppsala University with experimental development of perovskite solar cells. He is currently working at Helmholtz Zentrum for Materials and Energy in Berlin where he aims at gathering and classifying all published perovskite device data and developing standards and digital infrastructure for reporting new solar cell data.

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 opto-electronic 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, dyesensitized 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 & 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 post-doctoral 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 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 leads the research group Advanced Optics and Materials 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 RWTH Aachen University, then continued as a postdoc at IMEC in Leuven. His research focusses 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 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 BE 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 focusses 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 State Key Laboratory of Luminescent Materials and Devices and the Materials Science and Engineering (MSE) Department in South China University of Technology (SCUT). 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 MSE in 2008 at the University of Washington, Seattle. He joined SCUT in 2013 as full Professor. 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 UC Santa Barbara (USA) for a sabbatical. He joined the SIEMENS research labs (project leader, 2001), Konarka (CTO, 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.