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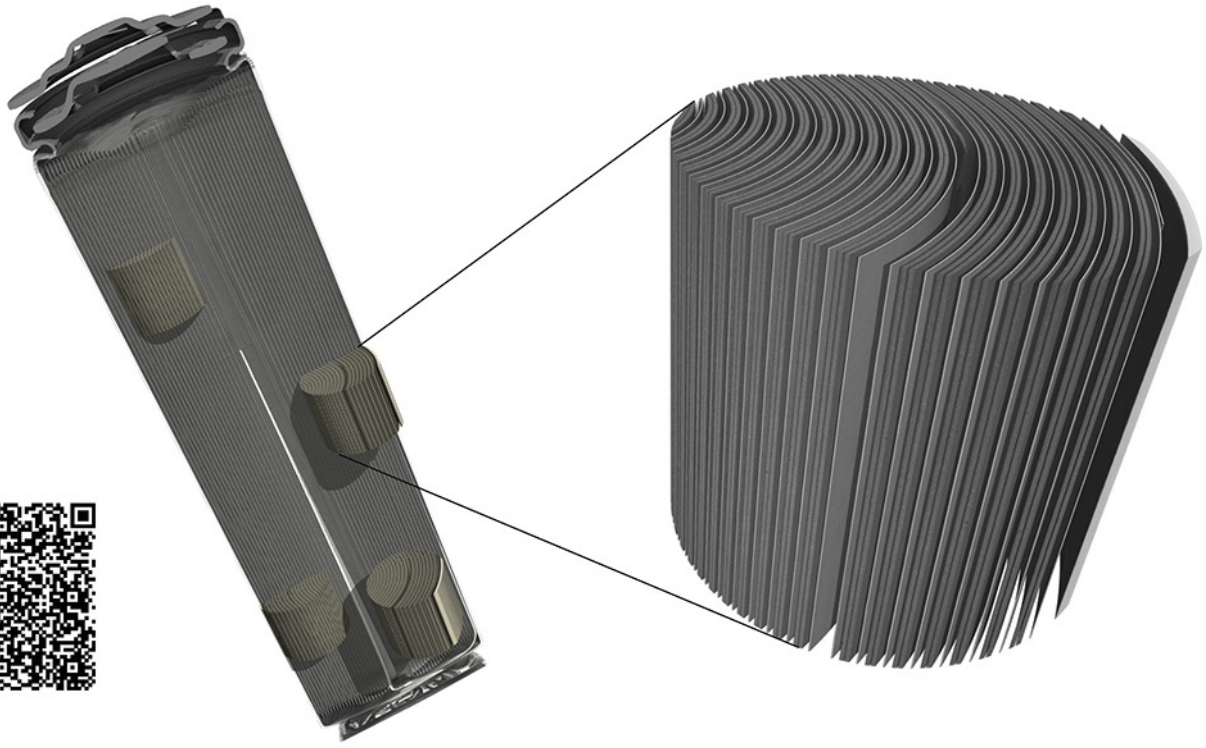

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Device Performance of Emerging Photovoltaic Materials (Version 1)

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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

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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_{in} = 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 (J_{sc}), the open-circuit voltage (V_{oc}), and the fill factor (FF) from the illuminated J–V characteristic, via

$$\mathrm{PCE} = \frac{P_{out}}{P_{in}} = \frac{V_{oc}\, J_{sc}\, \mathrm{FF}}{P_{in}} \quad (1)$$

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, V_{oc}, J_{sc}, 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 τ, herein also referred as the stability test energy yield (STEY), resulting from computing the integral

$$E_\tau = \int_0^\tau P_{\text{out}}\,\mathrm{d}t = \int_0^\tau P_{\text{in}}\ \text{PCE}\,\mathrm{d}t \tag{2}$$

where P_{in} is the incident light intensity (e.g., 100 mW cm^{-2}) and the STEY can be taken for 200 and 1000 h as $E_{200\text{h}}$ and $E_{1000\text{h}}$, 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 (T80), 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 STEY as $E_{\tau,\text{SQ}} = P_{\text{in}}\,\text{PCE}_{\text{SQ}}\,\tau$ for a device with SQ limited efficiency PCE_{SQ} during a stability test of duration τ. Moreover, for devices with similar ranges of efficiency, it is also useful to check the degradation rate $\text{DR} = \partial\text{PCE}/\partial t$ 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 $\text{DR}_{200\text{h}}$ and $\text{DR}_{1000\text{h}}$ 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_g, 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[4] 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 $\Gamma_{\text{AM1.5G}}$).[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),[21] 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,[22] 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, N_2, A_r), 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 hysteresis[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 ($\Gamma_{AM1.5G}$) according to the integral

$$J_{sc} = \frac{q}{h\,c} \int \mathrm{EQE}(\lambda)\cdot\lambda\cdot\Gamma_{AM1.5G}(\lambda)\,\mathrm{d}\lambda \tag{4}$$

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 threshold,[27,28] typically between 20% and 80% of the maximum EQE. This definition is the most appropriate for the evaluation of the SQ limit[1,29] and, unlike the optical bandgap, here the aim is to characterize the complete process from charge charrier 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 photoactive 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 $\partial\mathrm{EQE}/\partial\mathrm{E}$, or $\partial\mathrm{EQE}/\partial\lambda$. Alternatively, our preferred procedure has been the one-step fitting of the EQE spectra in the region around the bandgap wavelength λ_g (inflection point) to the step-like sigmoid function

$$\mathrm{EQE}\,(\lambda) = \frac{A_m}{1+\exp\left[2.63\left(\lambda-\lambda_g\right)/\lambda_s\right]} \tag{5}$$

where A_m and λ_s are fitting parameters related with the maximum EQE just after the step and the slope during the step, respectively. On the latter, note that λ_s 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 λ_s approaches and exceeds 100 nm. The device bandgap is defined as

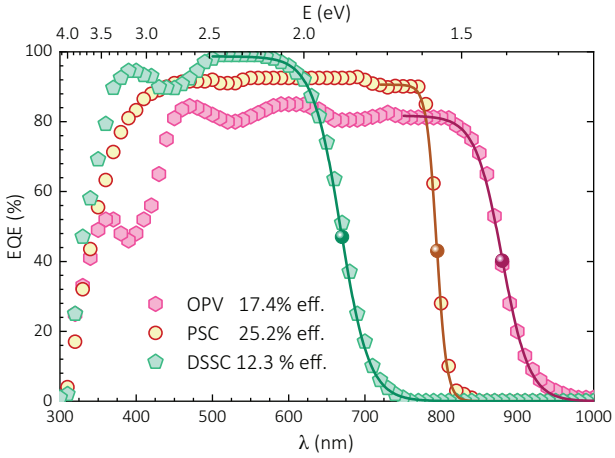

Figure 1. Experimental (data points) external quantum efficiency spectra for certified record organic, perovskite and dye sensitized solar cells as reported in Green's et al. tables.[4] Copyright 2019, John Wiley & Sons, Ltd. The lines are the fits to Equation (5) in the regions of the photovoltaic bandgap and the solid circles indicate the λ_g values: 880, 795, and 670 nm for OPV, PSC, and DSSC, respectively. Likewise, the corresponding λ_s values are 45, 17, and 49 nm.

$$E_g = \frac{hc}{\lambda_g} \tag{6}$$

and the fitting and λ_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,[30,31] 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).[32] 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,

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 value and type: total, aperture or designated). •Solar simulator (type, standard, model and brand). •Measurement conditions (temperature, air or N_2-atmosphere, whether a black matte background was used).	*J –V* curve plot
ii	Photovoltaic bandgap: •E_g or λ_g and λ_s 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 N_2-atmosphere, whether a black matte background was used). •Additional methods can also be reported (e.g., Absorption Tauc plot).	EQE – λ spectrum
iii	Absorber material: Experimental section: description of structure and fabrication procedure allowing reproduction of the results.	Optional figure/data
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 N_2/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")	Non-normalized PCE – *t* degradation record
iv.b	Transparent and semitransparent PV • *AVT* 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**, *b**)) • PBCC value (using Equation (8)) • Used instrument for *T* and *R* (model and brand) • Measurement conditions (temperature, air or N_2-atmosphere, whether a black matte background was used)	$T-\lambda$ and $R-\lambda$ spectra
iv.c	Flexible PV • Substrate thickness • Minimum radius the solar cell was bent to without reducing <5% performance output • Measurement conditions	Cross section/ bending picture

for which a measurement evidence should be presented (e.g., microscopy, profilometry). Additionally, an estimation of the minimum bending radius for which the PCE is larger than 5% of that without bending should be provided.

For transparent and semitransparent devices, many of the key protocols for measuring, analyzing, validating, and reporting have recently been outlined.[32,33] When measuring the *J–V*, a black matte background should be placed behind the device to prevent a double pass reflection. The transmittance spectrum $T(\lambda)$ of the device, measured without a reference sample, should be provided to validate the average visible transmittance, defined as[34]

$$\mathrm{AVT} = \frac{\int T(\lambda) P(\lambda) \Gamma_{\mathrm{AM1.5G}}(\lambda) \mathrm{d}\lambda}{\int P(\lambda) \Gamma_{\mathrm{AM1.5G}}(\lambda) \mathrm{d}\lambda} \tag{7}$$

where $P(\lambda)$ is the photopic response of the human eye.[35] Moreover, the aesthetic properties of transparent and semitransparent cells should be reported, including the color rendering index (CRI) and/or the CIELab color coordinates (*a**, *b**). These parameters can be directly obtained using $T(\lambda)$, $\Gamma_{\mathrm{AM1.5G}}(\lambda)$ and the reflectance spectrum $R(\lambda)$ (note that a calculator for these metrics is provided in "Data S1"[32] and the support section of emerging-pv.org) and are directly utilized by various industries including the window industry. Finally, it is necessary to provide a photon balance consistency check (PBCC) to assure that none of the optical measurements (EQE(λ) or $T(\lambda)$) are mismeasured or misreported. In units of percentage, the photon balance must satisfy

$$\mathrm{PBCC} = \mathrm{EQE}(\lambda) + T(\lambda) + R(\lambda) \leq 100\% \tag{8}$$

where $\mathrm{EQE}(\lambda) \leq A(\lambda)$ and becomes equal as the internal quantum efficiency (IQE) approaches unity—this substitution is made since the absorbance spectrum $A(\lambda)$ is notoriously difficult to measure directly. We note that a number of articles have reported photon balances with $\mathrm{EQE}(\lambda) + T(\lambda) > 100\%$, 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.

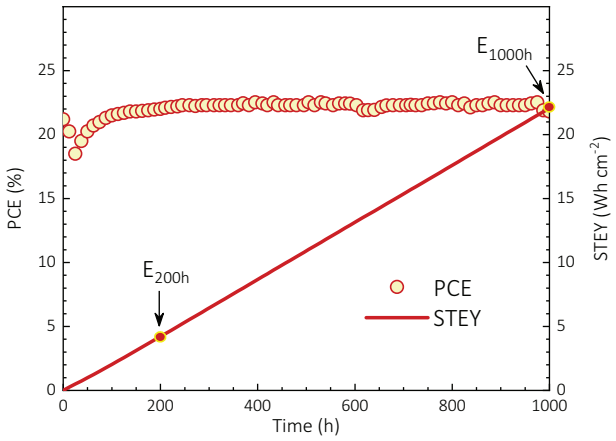

Figure 2. Stability test: efficiency (left axis) and stability test energy yield (right axis) for 1000 h under 1 sun AM1.5G illumination with MPP tracking. The data resemble that from a PSC reported by Zheng et al.[36]

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.[37] 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 ±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_{1000h} values would follow a ±1 Wh cm^{-2} rule, similar to the PCE values, in addition to the E_g ±10 meV earlier mentioned. The best semitransparent PVs will be considered as the highest PCE at each AVT (±1%), 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 ±1% 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[1] 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

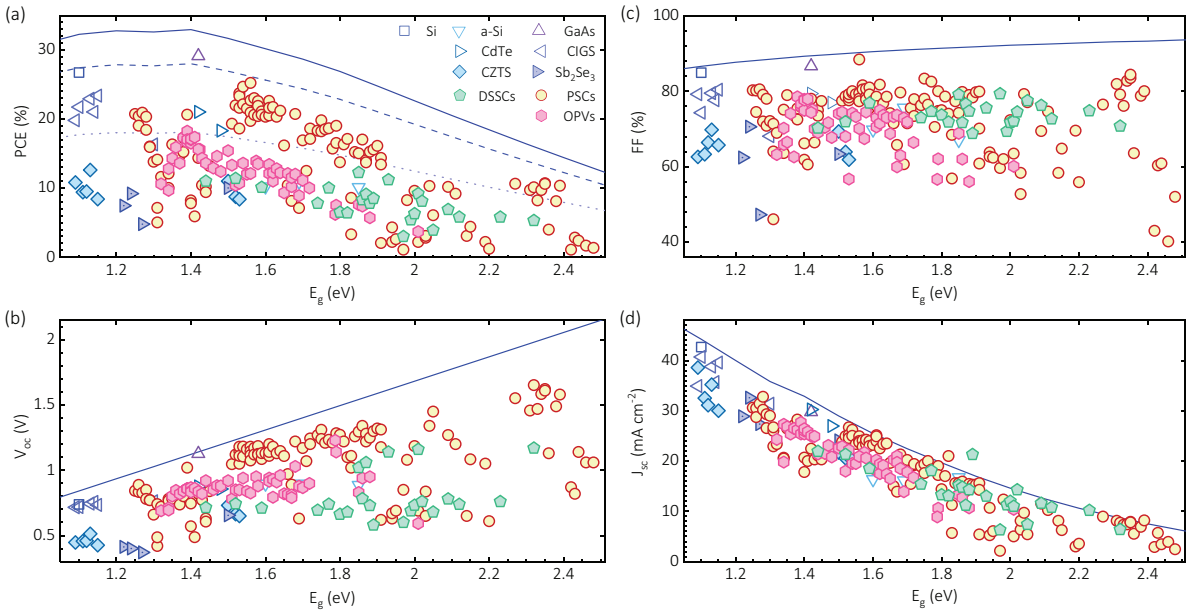

Figure 3. Highest efficiency solar cells: Performance parameters as a function of effective absorber bandgap for different photovoltaic technologies: a) power conversion efficiency, b) open-circuit voltage, c) fill factor, and d) short-circuit current density. Experimental data are summarized in Section 10.1 and the solid, dashed and dotted lines indicate 100%, 85%, and 55% of the theoretical Shockley–Queisser efficiency limit,[29] respectively.

the perovskite with respect to the $CH_3NH_3PbI_3$, 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, $FAPbI_3$ and $MAPbI_3$, 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 $FAPbBr_3$ and $MAPbBr_3$, and the inorganic $CsPbBr_3$ have already reported V_{oc} values higher than 1.5 V with efficiencies above 10%. The latter is ≈70% of SQ limit, while the J_{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 E_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 $V_{oc} > 1.0$ V is rarely reported for the most efficient OPV devices, independently of the active material's bandgap. Moreover, FF and J_{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 E_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.[38] Moreover, several devices with efficiencies around 35% of SQ limit have been reported with E_g values from 1.4 to 2.4 eV, while best performing DSSCs show E_g values within 1.8–2.1 eV. Interestingly, in the latter range these devices are able to surpass OPVs in terms of V_{oc}. Importantly, some J_{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 J_{sc} from the $J-V$ curve and/or the E_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 $Cu_2ZnSn(S,Se)_4$, and the Sb_2Se_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.[39] as

$$\frac{\mathrm{PCE}^{\mathrm{real}}}{\mathrm{PCE}^{\mathrm{SQ}}} = \frac{J_{\mathrm{sc}}^{\mathrm{real}}}{J_{\mathrm{sc}}^{\mathrm{SQ}}} \frac{V_{\mathrm{oc}}^{\mathrm{real}}}{V_{\mathrm{oc}}^{\mathrm{SQ}}} \frac{\mathrm{FF}_0\left(V_{\mathrm{oc}}^{\mathrm{real}}\right)}{\mathrm{FF}_0\left(V_{\mathrm{oc}}^{\mathrm{SQ}}\right)} \frac{\mathrm{FF}^{\mathrm{real}}}{\mathrm{FF}_0\left(V_{\mathrm{oc}}^{\mathrm{real}}\right)} \tag{9}$$

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[39]

$$\mathrm{FF}_0\ (V_{\mathrm{oc}}) = \frac{\frac{qV_{\mathrm{oc}}}{k_{\mathrm{B}}T} - \ln\left[\frac{qV_{\mathrm{oc}}}{k_{\mathrm{B}}T} + 0.72\right]}{1+\frac{qV_{\mathrm{oc}}}{k_{\mathrm{B}}T}} \tag{10}$$

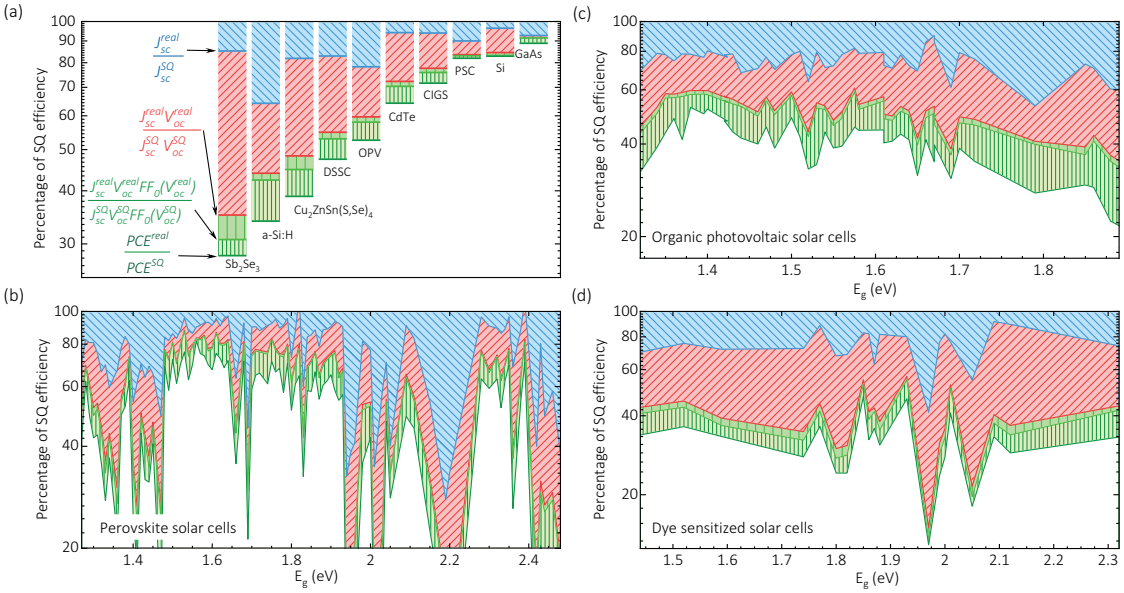

Figure 4. Percentage of SQ efficiency as Equation (9) limit for a) the most efficient cells for each PV technology and as a function of bandgap for b) PSCs, c) OPVs, and d) DSSCs. Experimental data are summarized in Section 10.1. No tie rules (see Section 2.4) were considered for this data selection,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

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**.

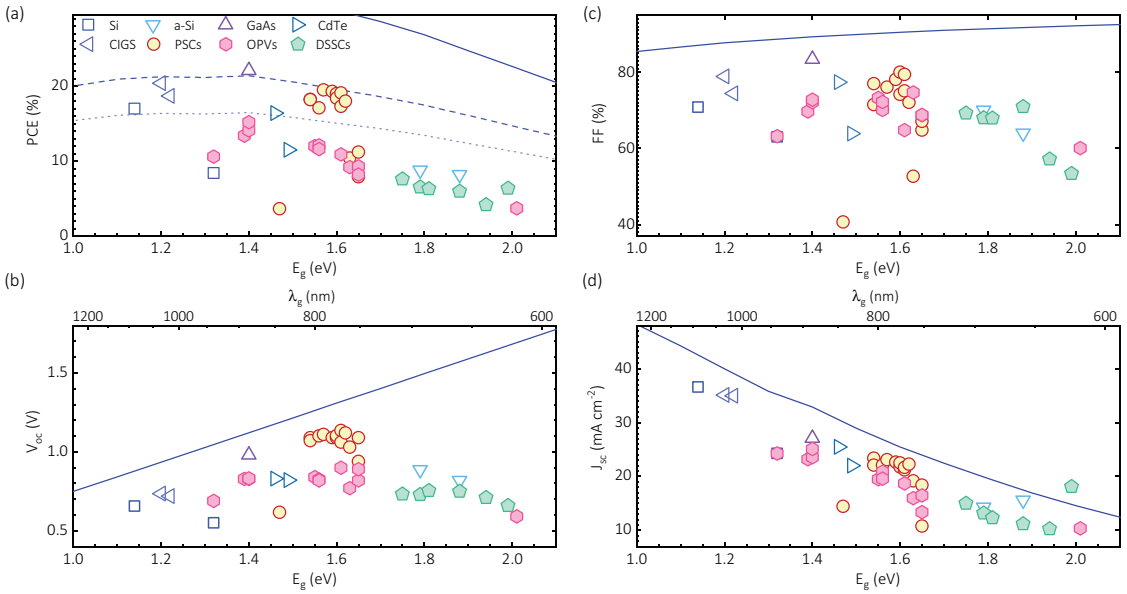

Figure 5. Flexible PVs: Best performance parameters as a function of absorber bandgap for various photovoltaic technologies: a) power conversion efficiency, b) open circuit voltage, c) fill factor, and d) short-circuit current density. Experimental data are summarized in Section 10.2 and the solid, dashed and dotted lines indicate 100%, 65%, and 50% of the theoretical Shockley–Queisser efficiency limit,[29] respectively.

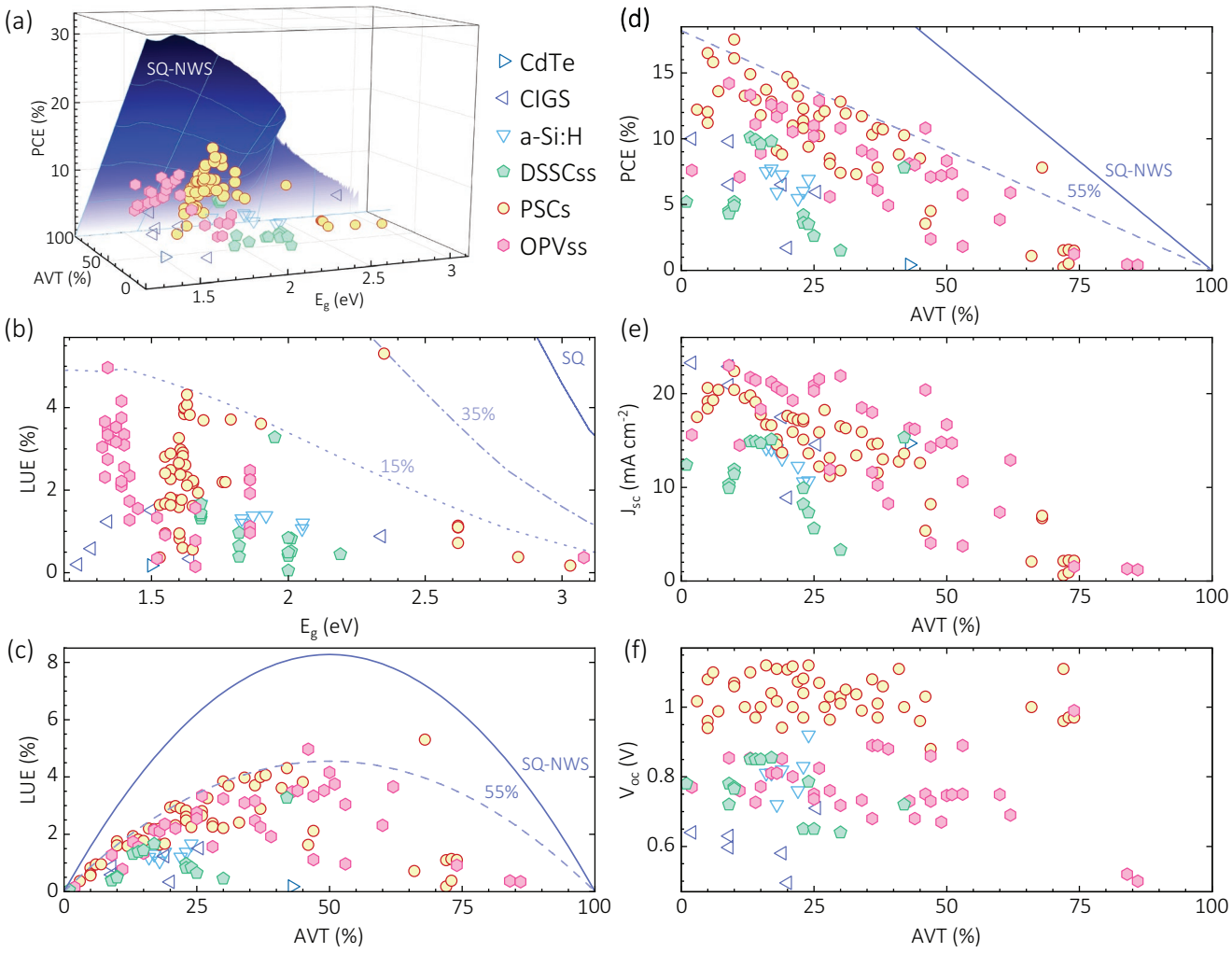

Figure 6. Best performing transparent and semitransparent PVs: a) highest power conversion efficiency as a function of device bandgap energy and average visible transmittance (3D representation); corresponding light utilization efficiency versus b) photovoltaic bandgap energy and c) average visible transmittance; and d) power conversion efficiency, e) short-circuit current density and f) open-circuit voltage as a function of average visible transmittance. Experimental data are summarized in Section 10.3. The blue surface in (a) indicates the theoretical Shockley–Queisser limit for non-wavelength selective PVs and the dotted, dash-dotted, dashed and solid lines in (b–d) indicate the corresponding projected 15%, 35%, 55%, and 100%, respectively. Note that the right most PSC point in (b,c) only has a CRI of 62, whereas most of the OPV devices are typically between a CRI of 80–95.

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 · 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.

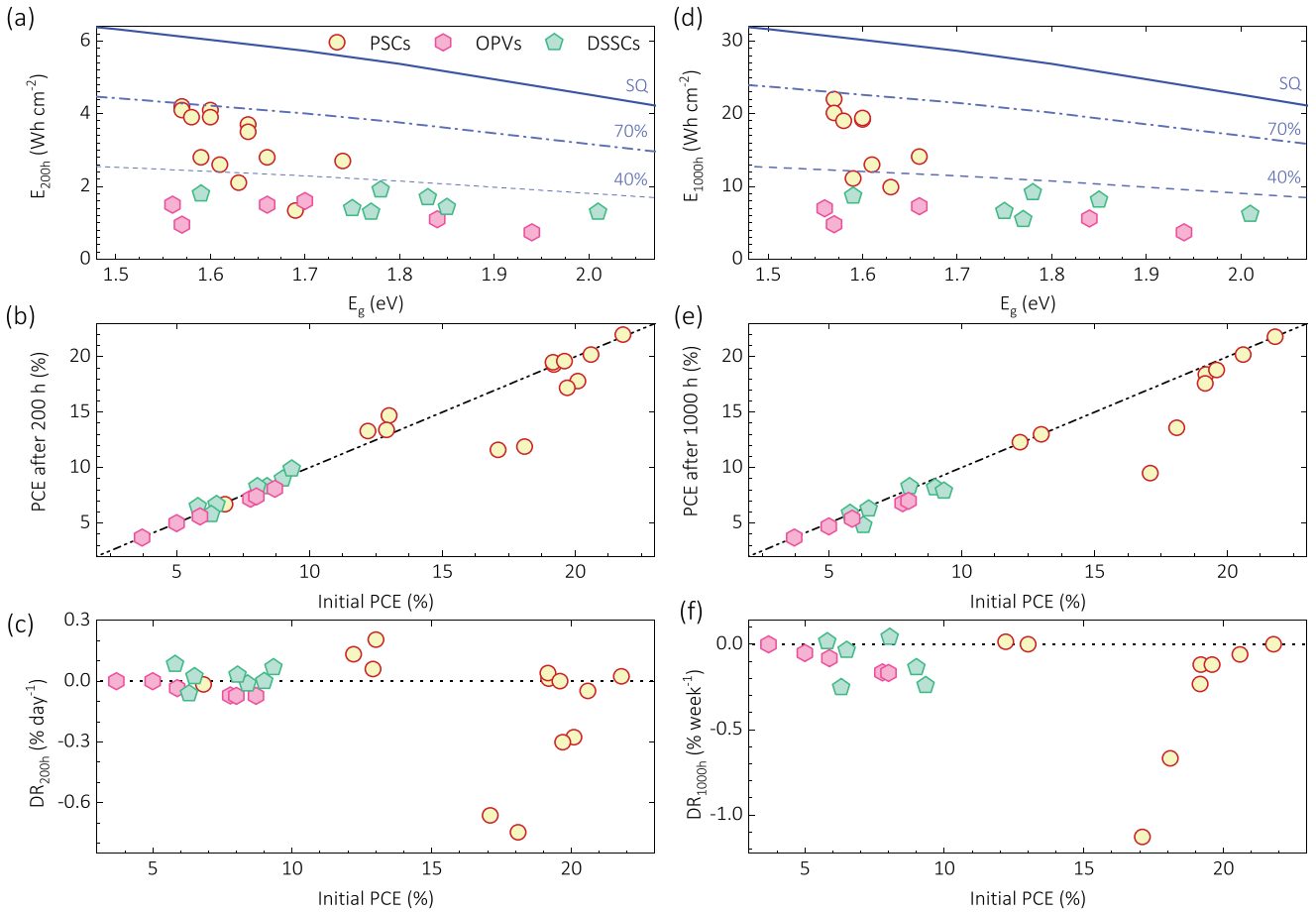

Figure 7. Most photostable emerging PVs for each technology: stability test energy yield for a) 200 h and d) 1000 h as a function of bandgap energy, final power conversion efficiency after b) 200 h and e) 1000 h as a function of the initial value, and overall degradation rate (Equation (3)) as a function 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

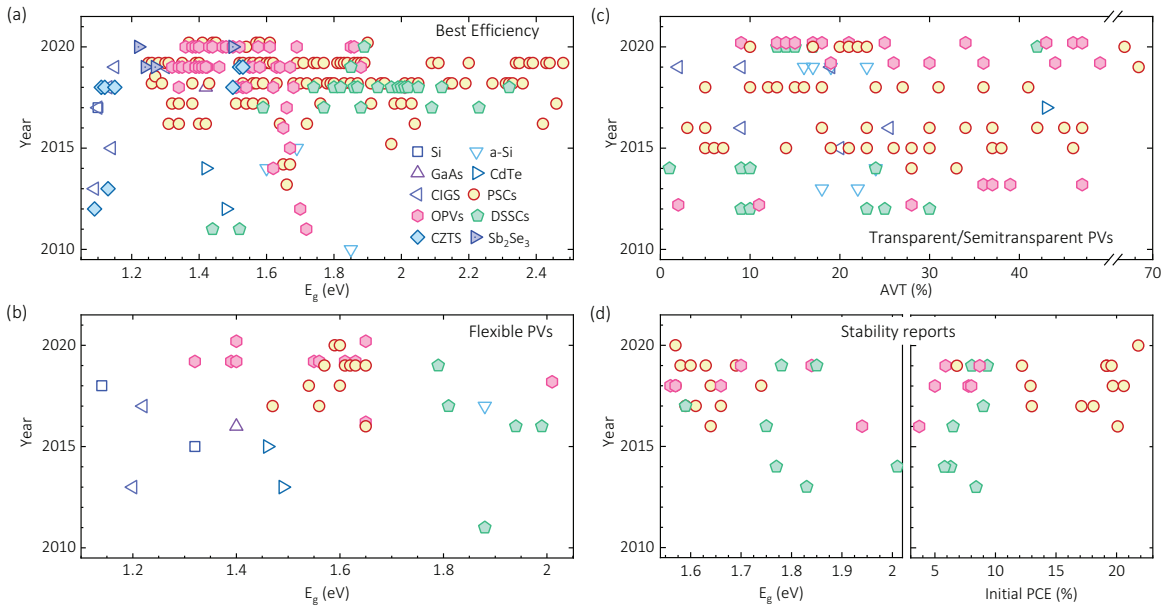

Figure 8. Publication year of the reports summarized in previous sections: a) absolute highest efficiency solar cells, b) best flexible, and c) semitransparent/transparent devices, and d) stability reports.

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 reproduce a specific result. We also intend to categorize data in terms of the production processing technology, highlighting differences in lab efficiency (spin coated in N_2) 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[9,63] 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_0). 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_0. Thus, one could analyze the highest bendable efficiency $HBE_r = PCE_0 / r_b$ and the bending efficiency lifetime $BEL = PCE_0 \times BC$. 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 stablished 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.

10.1. Highest Efficiency Research Solar Cells Tables

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	$(FASnI_3)_{0.6}(MAPbI_3)_{0.4}$	[66]
1.26	20.4	834	30.5	80.2	GuaSCN:$(FASnI_3)_{0.6}$(MAPbI$_3$)$_{0.4}$	[67]
1.26	19.0	888	28.8	74.5	$(FASnI_3)_{0.6}(MAPbI_3)_{0.34}$(MAPbBr$_3$)$_{0.06}$	[68]
1.27	20.9	827	31.4	80.5	$MA_{0.3}FA_{0.7}Pb_{0.5}Sn_{0.5}I_3$	[69]
1.28	20.3	850	30.2	79.1	$FA_{0.5}MA_{0.45}Cs_{0.05}Pb_{0.5}Sn_{0.5}I_3$	[70]
1.28	18.4	780	32.8	72.0	$Cs_{0.025}FA_{0.475}MA_{0.5}Sn_{0.5}Pb_{0.5}I_3$	[71]
1.29	16.0	771	29.3	70.8	$FASn_{0.5}Pb_{0.5}I_3$	[72]
1.29	15.9	770	26.5	78.0	$(FASnI_3)_{0.6}(MAPbI_3)_{0.3}$(MAPbBr$_3$)$_{0.1}$	[73]
1.30	13.8	660	29.0	72.1	$FA_{0.5}MA_{0.5}Pb_{0.5}Sn_{0.5}I_3$	[74]
1.31	5.0	420	23.8	50.3	$CsSnI_3$	[75][a)]
1.31	7.1	486	22.9	64.0	$MASnI_3$	[76][a)]
1.31	14.1	740	26.7	71.4	$FA_{0.75}Cs_{0.25}Sn_{0.5}Pb_{0.5}I_3$	[77]
1.32	11.6	720	23.4	68.9	$MAPb_{0.4}Sn_{0.6}I_{2.8}Br_{0.2}$	[78]
1.34	10.0	767	20.5	63.6	$MAPb_{0.4}Sn_{0.6}I_3$	[79]
1.34	12.1	780	20.7	75.1	$MAPb_{0.4}Sn_{0.6}I_{2.6}Br_{0.4}$	[78]
1.35	16.3	780	26.5	79.0	$FAPb_{0.7}Sn_{0.3}I_3$	[80]
1.37	14.7	737	27.1	73.6	$FA_{0.3}MA_{0.7}Pb_{0.7}Sn_{0.3}I_3$	[81]
1.38	17.3	810	28.2	75.4	$FAPb_{0.75}Sn_{0.25}I_3$	[82]
1.38	15.2	800	26.2	72.5	$MAPb_{0.75}Sn_{0.25}I_3$	[83]
1.39	20.6	1020	26.6	76.0	$FA_{0.7}MA_{0.3}Pb_{0.7}Sn_{0.3}I_3$	[84]
1.40	8.2	745	17.8	61.8	$MAPb_{0.6}Sn_{0.4}I_3$	[79]
1.40	7.8	570	20.7	66.2	$MASnI_3$	[85]
1.41	5.9	487	20.0	60.6	$FA_{1-x}Rb_xSnI_3$	[86]
1.42	14.4	820	22.4	78.0	$MAPb_{0.75}Sn_{0.25}I_3$	[87]
1.43	10.4	772	20.3	66.4	$MAPb_{0.7}Sn_{0.3}I_3$	[88]
1.44	10.2	630	21.6	74.7	$FASnI_3$	[89]
1.44	9.4	606	21.1	73.4	$FASnI_3$	[89][b)]
1.42	13.2	840	20.3	78.0	$(FA_{0.9}EA_{0.1})_{0.98}EDA_{0.01}SnI_3$	[90]
1.51	19.3	1047	23.8	77.5	$FA_{0.6}MA_{0.4}PbI_3$	[91]
1.52	22.0	1120	24.9	78.6	$FA_{0.85}MA_{0.15}PbI_3$	[92]
1.53	23.7	1144	26.7	77.6	α-FAPbI$_3$:MDACl$_2$	[93][b)]
1.53	23.3	1180	25.2	78.4	$FA_{1-x}MA_xPbI_3$	[94][b)]
1.53	18.6	1050	24.1	73.5	$FAPbI_3$	[95][a)]
1.53	21.6	1110	24.6	79.2	$FA_{0.95}Cs_{0.05}PbI_3$	[96]
1.54	24.6	1181	26.2	79.6	$FAPbI_3$	[97][b)]
1.54	22.1	1105	25.0	80.3	$(FAPbI_3)_{0.9}(MAPbBr_3)_{0.1}$	[98][b)]
1.55	21.5	1160	23.4	79.2	$Cs_{0.05}FA_{0.70}MA_{0.25}PbI_3$-DAP	[99]
1.56	25.2	1180	24.1	84.8	[c)]	[4][b)]
1.56	22.7	1145	24.9	79.9	$(FAPbI_3)_{0.95}(MAPbBr_3)_{0.05}$	[100][b)]
1.56	20.9	1116	24.0	78.0	$(FAPbI_3)_{1-x}(MAPbBr_3)_x$	[101][b)]
1.56	19.7	1075	23.7	77.3	$(MA_{0.7}FA_{0.3})_{0.97}EDA_{0.015}PbI_3$	[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	$Cs_{0.05}(FA_{0.92}MA_{0.08})_{0.95}Pb(I_{0.92}Br_{0.08})_3$	[36]
1.57	22.3	1143	23.8	82.0	$Cs_{0.05}(FA_{0.92}MA_{0.08})_{0.95}Pb(I_{0.92}Br_{0.08})_3$	[36][b)]
1.57	20.6	1120	22.8	80.5	$(FAPbI_3)_{1-x}(MAPbBr_3)_x$	[103]
1.58	22.6	1186	24.2	78.6	$(FAPbI_3)_{0.92}(MAPbBr_3)_{0.08}$	[104][b)]
1.58	20.4	1125	23.3	77.8	$Cs_{0.05}(FAPbI_3)_{0.85}(MAPbBr_3)_{0.15}$	[105]
1.58	21.9	1120	24.2	80.6	$FA_{0.15}MA_{0.85}PbI_3$	[106]
1.59	21.1	1086	24.0	81.0	$MAPb_{0.9}Sn_{0.05}Cu_{0.05}I_{2.9}Br_{0.1}$	[107]
1.59	21.0	1140	23.7	77.7	$FA_{0.85}MA_{0.15}Pb(I_{0.85}Br_{0.15})_3$	[108][b)]
1.60	20.3	1130	23.2	77.4	$MAPbI_{3-x}Cl_x$	[109][b)]
1.61	20.5	1110	25.1	73.5	$MAPbI_3$	[106][b)]
1.61	21.6	1140	24.9	76.1	$Cs_{0.05}(MA_{0.17}FA_{0.83})_{0.95}Pb(I_{0.83}Br_{0.17})_3$	[110]
1.61	22.6	1200	24.0	78.5	$Cs_{0.07}Rb_{0.03}FA_{0.765}MA_{0.135}PbI_{2.55}Br_{0.45}$	[111]
1.62	21.7	1180	22.5	81.7	$MAPbI_3$-DAP	[99]
1.63	20.3	1130	23.4	76.8	$Cs_{0.05}FA_{0.76}MA_{0.19}PbBr_{0.6}I_{2.4}$	[112]
1.64	20.4	1140	23.6	75.8	$Cs_{0.05}(MA_{0.17}FA_{0.83})_{0.95}Pb(I_{0.83}Br_{0.17})_3$	[110]
1.65	16.2	1109	19.6	74.2	$MAPbI_{1-x}Br_x$	[113][b)]
1.66	10.4	904	16.3	70.4	$MAPb(I_{0.87}Br_{0.13})_3$	[114]
1.67	8.2	890	13.9	65.8	$MAPb(I_{0.88}Br_{0.12})_3$	[115]
1.68	20.7	1220	21.3	79.7	$Cs_{0.05}MA_{0.15}FA_{0.8}Pb(I_{0.75}Br_{0.25})_3$	[116]
1.69	7.1	936	10.4	63.0	$MAPb(I_{0.74}Br_{0.26})_3$	[117]
1.70	16.9	1170	20.2	71.5	$Cs_{0.2}FA_{0.8}Pb(I_{0.75}Br_{0.25})_3$	[116]
1.71	12.5	1070	15.4	75.5	$MA_{0.85}Cs_{0.15}Pb(I_{0.85}Br_{0.15})_3$	[118]
1.72	18.6	1244	19.2	77.9	$FA_{0.17}Cs_{0.83}PbI_{2.2}Br_{0.8}$	[119]
1.72	17.1	1200	19.4	73.5	$FA_{0.83}Cs_{0.17}Pb(I_{0.6}Br_{0.4})_3$	[120]
1.74	18.3	1269	18.9	76.3	$Rb_{0.05}Cs_{0.095}MA_{0.1425}FA_{0.7125}PbI_2Br$	[121]
1.75	19.8	1310	19.4	78.0	$FA_{0.83}Cs_{0.17}Pb(I_{0.6}Br_{0.4})_3$	[122]
1.76	18.5	1210	20.0	76.4	$(FA_{0.83}MA_{0.17})_{0.95}Cs_{0.05}Pb(I_{0.6}Br_{0.4})_3$	[123]
1.77	18.6	1234	18.3	82.5	$CsPbI_{3-x}Br_x$	[124]
1.78	15.7	1210	18.4	70.5	$Cs_{0.17}FA_{0.83}Pb(I_{0.6}Br_{0.4})_3$	[116]
1.79	19.0	1250	19.0	80.0	$Cs_{0.12}MA_{0.05}FA_{0.83}Pb(I_{0.6}Br_{0.4})_3$	[116]
1.79	16.5	1284	17.2	74.8	$FA_{0.17}Cs_{0.83}PbI_{1.8}Br_{1.2}$	[119]
1.80	13.7	1272	14.4	75.0	$MAPbBrI_2$	[125]
1.81	16.3	1220	17.0	78.6	$FA_{0.6}Cs_{0.4}Pb(I_{0.65}Br_{0.35})_3$	[70]
1.82	17.1	1100	21.0	74.0	$FAPbI_{1.5}Br_{1.5}/CsPbI_{1.5}Br_{1.5}$	[126]
1.83	3.3	1020	5.7	56.9	Cs_2TiBr_6	[127][a)]
1.83	8.6	1110	11.3	68.4	$MA_{0.85}Cs_{0.15}Pb(I_{0.65}Br_{0.35})_3$	[118]
1.84	15.2	1260	15.6	77.3	$Cs_{0.2}FA_{0.8}Pb(I_{0.6}Br_{0.4})_3$-DAP	[99]
1.85	15.0	1296	15.6	74.2	$FA_{0.17}Cs_{0.83}PbI_{1.5}Br_{1.5}$	[119]
1.86	17.0	1340	15.9	79.8	$CsPb(I_{0.75}Br_{0.25})_3$-0.5FAOAc	[128]

Table 2. Continued.

E_g [eV]	PCE [%]	V_{oc} [mV]	J_{sc} [mA cm^{-2}]	FF [%]	Absorber perovskite	Ref.
1.87	14.0	1280	14.0	78.1	$CsPb_{0.8}Ba_{0.2}I_2Br$	[129]
1.87	13.7	1220	14.6	76.8	$CsPb_{0.95}Eu_{0.05}I_2Br$	[130]
1.88	15.3	1250	15.4	79.0	$CsPbI_2Br$	[131]
1.89	15.6	1300	15.3	78.3	$CsPbI_{2-x}Br(Ac)_x$	[132]
1.90	16.1	1320	15.3	79.7	$CsPbI_2Br$	[133]
1.91	14.4	1312	15.6	70.1	$FA_{0.17}Cs_{0.83}PbI_{1.2}Br_{1.8}$	[119]
1.91	13.5	1177	14.3	79.9	$CsPbI_2Br$	[134]
1.91	2.0	620	5.4	60.8	$MA_3Sb_2I_9$+HI	[135][b)]
1.94	4.3	630	10.7	63.8	Ag_3BiI_6	[136]
1.94	2.2	670	5.2	62.7	$AgBiI_4$	[137]
1.95	2.6	690	6.0	62.4	$AgBiI_5$	[137]
1.97	1.1	850	2.2	59.6	$Cs_3Bi_2I_9$	[138]
1.98	8.3	1080	12.3	62.0	$CsPbIBr_2$	[139]
2.00	9.6	1185	11.2	72.3	$Cs_{0.15}FA_{0.85}Pb(I_{0.3}Br_{0.7})_3$	[140]
2.03	2.8	836	6.4	52.7	$MAPb(I_{0.41}Br_{0.59})_3$	[115]
2.04	10.3	1340	9.7	79.2	$MAPb(I_{0.3}Br_{0.7})_xCl_{3-x}(Br)$	[141]
2.05	6.1	1450	5.4	77.1	$MAPbIBr_2$	[142]
2.09	10.2	1270	11.5	69.4	$CsPbIBr_2$	[143]
2.10	10.7	1261	11.8	72.0	$CsPbIBr_2$	[144]
2.11	9.2	1200	10.2	74.6	GAI-DEE-$CsPbIBr_2$	[145]
2.14	3.1	650	8.1	58.4	$MASbSI_2$	[146]
2.15	4.4	1084	6.3	64.8	$(FA_{0.85}MA_{0.15}Pb(I_{0.85}Br_{0.15})_3)$ R = 0.7	[147]
2.19	2.0	1051	3.0	69.5	$(FA_{0.85}MA_{0.15}Pb(I_{0.85}Br_{0.15})_3)$ R = 0.56	[147]
2.20	1.2	610	3.6	55.9	$Cs_3Sb_2I_9$	[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	$CsPbBr_3$	[151]
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	$CsPbBr_{2.9}I_{0.1}$	[155]
2.37	2.2	690	5.0	63.5	$MA_3Sb_2Cl_xI_{9-x}$	[156]
2.38	8.1	1490	6.9	78.8	$CsPbBr_3$	[157]
2.39	10.3	1580	8.2	80.0	$Cs_{0.91}Rb_{0.09}PbBr_3$	[158]
2.42	1.1	870	2.9	43.0	$BdAPbI_4$	[159]
2.43	2.8	820	5.7	60.3	$CsPb_2Br_5$	[160]
2.44	2.4	1140	3.4	60.9	$FAPbBr_{2.1}Cl_{0.9}$	[161]
2.46	1.7	1060	3.9	40.2	$Cs_2AgBiBr_6$	[162]
2.48	1.4	1060	2.5	52.0	$FAPbBr_2Cl$	[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	PBDTT-DPP:IEICO-4F	[165]
1.35	14.3	802	26.8	66.5	PBDB-T-2Cl:BTP-4F:$PC_{61}BM$	[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-TF:BTP-eC9	[169][a]
1.39	18.2	859	27.7	76.6	D18:Y6	[170][a]
1.39	17.0	858	77.6	25.5	PBDB-TF:BTP-4Cl-12	[171][a]
1.39	16.6	860	25.4	76.3	PBDB-TF:AQx-2	[172]
1.40	17.0	840	26.0	77.8	PBDB-T-2F:Y6:$PC_{71}BM$	[173]
1.40	17.1	834	26.4	77.6	PM6:Y6	[174][a]
1.40	16.5	867	25.4	75.0	PBDB-TF:BTP-4Cl	[175][a]
1.41	17.4	862	25.8	77.9	[b]	[4][a]
1.42	15.6	834	24.9	75.1	PBDB-TF:BTP-4F	[175]
1.42	15.6	838	25.0	74.4	[b]	[176][a]
1.43	14.3	820	24.9	70.0	PM6:IDST-4F	[177]
1.44	13.6	920	21.4	69.1	PBDB-TF:BTIC-F-m	[178]
1.46	12.9	852	21.5	70.6	PM6:N-C11	[179]
1.47	14.6	882	23.1	71.7	PBDB-T-2Cl:BP-4F:MF1	[180]
1.48	12.4	880	20.8	67.7	PBDB-T:IDT-EDOT:$PC_{71}BM$	[181]
1.50	15.4	920	22.6	74.1	PM6:DTTC-4Cl	[182]
1.51	13.3	780	22.9	75.0	PM6:SeTIC4Cl-DIO	[183]
1.52	10.4	850	18.0	68.0	PBDB-T:IDT-EDOT:$PC_{71}BM$	[181]
1.53	10.7	850	22.2	56.7	PM6:SeTIC4Cl	[183]
1.54	13.6	940	19.5	73.8	BTR:NITI:$PC_{71}BM$	[184]
1.55	12.0	840	19.5	73.3	PM6:IT-4F	[185]
1.56	12.1	826	20.9	70.1	PBDB-T-2F:IT-4F	[186]
1.58	13.9	950	21.7	67.4	PM6:DTTC-4F	[182]
1.58	13.5	880	20.6	74.53	PBDB-T-SF:IT-4F	[173]
1.61	13.4	940	20.2	70.5	PM6:DTC-4F	[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	J51:ITIC	[190]
1.66	12.1	815	20.3	73.2	[b]	[191][a]
1.67	10.2	810	21.0	59.9	P4TIF:$PC_{61}BM$	[183]
1.67	11.5	791	19.7	73.7	[b]	[192][a]
1.68	12.0	1030	18.5	63.0	PBDTTT-EFT:EHIDTBR	[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][a]
1.72	10.0	899	16.8	66.4	[b]	[21][a]
1.79	7.5	1140	10.6	62.1	BDT-ffBX-DT:PDI4	[196]
1.79	6.2	1230	8.9	56.6	BDT-ffBX-DT:SFPDI	[196]
1.85	9.0	900	13.8	72.9	BTR:$PC_{71}BM$	[184]
1.85	7.6	830	13.3	69.1	PBDB-T:$PC_{71}BM$	[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:PC61BM	[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	[a)]	[21][b)]
1.52	11.4	743	21.3	71.9	[a)]	[21][b)]
1.59	10.1	710	18.5	76.9	TF-tBu_C_3F_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	[a)]	[4][b)]
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	[205]
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	$Cu_2ZnSn(S,Se)_4$	[206]
1.11	9.4	457	32.5	63.3	$Cu_2ZnSnSe_4$	[207]
1.12	9.5	460	31.1	66.4	$Cu_2ZnSnSe_4$	[207]
1.13	12.6	513	35.2	69.8	$Cu_2ZnSn(S,Se)_4$	[208][a)]
1.13	11.1	460	34.5	69.8	$Cu_2ZnSn(S,Se)_4$	[206][a)]
1.15	8.4	426	30.0	65.7	$Cu_2ZnSnSe_4$	[207]
1.22	7.5	413	28.9	62.4	Sb_2Se_3	[209]
1.24	9.2	400	32.6	70.6	Sb_2Se_3	[210]
1.27	4.8	370	27.3	47.3	Sb_2Se_3	[210]
1.50	11.0	731	21.7	69.3	Cu_2ZnSnS_4	[211][a)]
1.50	10.0	655	24.1	63.3	$Sb_2(S,Se)_3$	[212][a)]
1.52	8.73	664	20.6	63.9	$(Cu_{0.99}Ag_{0.01})_{1.85}(Zn_{0.8}Cd_{0.2})_{1.1}SnS_4$	[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 [%]	Voc [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]
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]
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 [%]	Voc [mV]	J_{sc} [mA cm^{-2}]	FF [%]	Absorber perovskite	Ref.
1.47	3.62	616	14.5	40.6	$(5\text{-AVA})_y(MA)_{1-y}PbI_3$	[221][a]
1.54	18.3	1090	23.4	71.5	$FA_{0.95}Cs_{0.05}PbI_3$	[96]
1.54	18.2	1070	22.1	76.9	$FAPbI_{3-x}Br_x$	[222]
1.56	17.1	1101	22.1	75.4	$MA_{0.7}FA_{0.3}PbI_3$	[223]
1.57	19.5	1110	23.1	76.0	$FA_{0.945}MA_{0.025}Cs_{0.03}Pb(I_{0.975}Br_{0.025})_3$	[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	$Cs_{0.05}FA_{0.81}MA_{0.14}PbI_{2.55}Br_{0.45}$	[228][b]
1.61	19.1	1135	21.2	79.2	$Rb_{0.01}K_{0.04}$ $(Cs_{0.05}(FA_{0.83}MA_{0.17})_{0.95})_{0.95}$ $(I_{0.83}Br_{0.17})_3$	[229]
1.62	18.0	1120	22.3	72.1	$Cs_{0.06}FA_{0.79}MA_{0.15}PbI_{2.55}Br_{0.45}$	[230]
1.63	10.4	1030	19.2	52.8	$(FAPbI_3)_{0.85}(MAPbBr_3)_{0.15}$	[231]
1.65	11.2	940	18.4	64.9	$MAPbI_3$	[232]
1.65	7.9	1090	10.8	70.7	$(\alpha\text{-}FAPbI_3)_{0.5}(MAPbI_2Br)_{0.5}$	[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	[185]
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	$(JH\text{-}1)_{0.6}(SQ2)_{0.4}$	[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	$MAPbI_{3-x}Cl_x$	[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	$Cs_{0.05}(FA_{0.85}MA_{0.15})_{0.95}Pb(I_{0.85}Br_{0.15})_3$	[261]
12	1.60	13.2	1000	19.5	67.8	$MAPbI_3$	[260]
13	1.67	14.9	1100	19.8	68.4	$MAPbI_{2.5}Br_{0.5}$	[260]
14	1.57	13.0	970	19.1	69.9	$MAPbI_{3-x}Cl_x$	[262]
15	1.61	11.9	1000	17.8	66.3	$MAPbI_3$	[260]
16	1.76	13.7	1120	16.7	73.4	$MAPbI_2Br$	[260]
17	1.65	12.8	1040	16.6	74.1	$Cs_{0.05}(FA_{0.85}MA_{0.15})_{0.95}Pb(I_{0.85}Br_{0.15})_3$	[261]
18	1.77	12.2	1110	15.1	72.7	$MAPbI_2Br$	[260]
18	1.53	9.1	1017	14.6	61.5	$MAPbI_3$	[255]
19	1.55	8.8	941	13.7	68.3	$MAPbI_3$	[259]
20	1.63	14.7	1108	17.6	75.2	$K_xCs_{0.05}(FA_{0.85}MA_{0.15})_{0.95}Pb(I_{0.85}Br_{0.15})_3$	[263]
21	1.63	14.2	1117	17.4	73.2	$K_xCs_{0.05}(FA_{0.85}MA_{0.15})_{0.95}Pb(I_{0.85}Br_{0.15})_3$	[263]
21	1.63	11.0	1000	15.9	69.2	$MAPbI_3$	[264]
22	1.61	13.2	1073	17.2	71.7	$K_xCs_{0.05}(FA_{0.85}MA_{0.15})_{0.95}Pb(I_{0.85}Br_{0.15})_3$	[263]

Table 11. Continued.

AVT [%]	E_g [eV]	PCE [%]	V_{oc} [mV]	J_{sc} [mA cm^{-2}]	FF [%]	Absorber	Ref.
23	1.61	12.3	1082	17.1	66.6	$K_xCs_{0.05}(FA_{0.85}MA_{0.15})_{0.95}Pb(I_{0.85}Br_{0.15})_3$	[263]
23	1.62	11.3	1040	15.1	72.3	$MAPbI_3$	[265]
23	1.57	10.8	970	17.3	64.4	$MAPbI_{3-x}Cl_x$	[262]
24	1.87	9.4	1120	13.6	61.6	$MAPbI_{1.5}Br_{1.5}$	[260]
25	1.55	10.8	950	16.3	69.7	$MAPbI_3$	[266]
26	1.63	10.2	1070	12.2	78.1	$MAPbI_3$	[267]
27	1.60	12.1	1000	18.3	66.2	$MAPbI_3$	[260]
28	1.60	8.5	964	13.1	66.8	$MAPbI_{3-x}Cl_x$	[268]
28	1.57	8.1	1030	11.2	70.2	$MAPbI_{3-x}Cl_x$	[262]
30	1.62	12.8	1030	16.5	74.9	$MAPbI_{3-x}Cl_x$	[269]
30	1.65	7.4	1010	11.8	62.2	$Cs_{0.05}(FA_{0.85}MA_{0.15})_{0.95}Pb(I_{0.85}Br_{0.15})_3$	[261]
31	1.69	11.9	1050	16.3	69.4	$MAPbI_{2.5}Br_{0.5}$	[260]
33	1.55	7.3	1037	13.4	52.5	$MAPbI_3$	[270]
34	1.62	11.7	990	15.9	74.6	$MAPbI_{3-x}Cl_x$	[269]
36	1.79	10.3	1080	14.6	65.5	$MAPbI_2Br$	[260]
37	1.62	10.8	1010	14.7	73.1	$MAPbI_{3-x}Cl_x$	[269]
37	1.57	7.8	970	11.6	69.6	$MAPbI_{3-x}Cl_x$	[262]
38	1.63	10.7	1060	13.0	77.6	$MAPbI_3$	[267]
41	1.90	8.8	1110	12.8	62.2	$MAPbI_{1.5}Br_{1.5}$	[260]
42	1.42	10.3	1000	13.6	75.6	$MAPbI_{3-x}Cl_x$	[269]
45	1.64	8.5	960	12.6	73.5	$MAPbI_{3-x}Cl_x$	[269]
46	1.57	3.6	1030	5.4	64.4	$MAPbI_{3-x}Cl_x$	[262]
47	1.63	4.5	880	8.2	63.0	$MAPbI_3$	[271]
66	2.62	1.1	1000	2.1	52.9	$Cs_2AgBiBr_6$	[272]
68	2.35	7.8	1550	6.7	72.0	$FAPbBr_{2.43}Cl_{0.57}$	[161]
72	2.62	1.5	960	2.1	74.3	$Cs_2AgBiBr_6$	[272]
72	3.03	0.2	1110	0.6	35.4	$MAPbCl_3$	[273]
73	2.62	1.6	970	2.2	73.1	$Cs_2AgBiBr_6$	[272]
73	2.84	0.5	1260	0.9	44.9	$MAPbCl_{2.4}Br_{0.6}$	[273]
74	2.62	1.5	970	2.2	71.1	$Cs_2AgBiBr_6$	[272]

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 [%]	Active material	Ref.
2	1.66	7.6	770	15.6	63.3	PBDTTT-C-T:$PC_{71}BM$	[274]
9	1.42	14.2	854	23.0	72.3	PM6:Y6	[275]
11	1.66	7.1	760	14.5	64.4	PBDTTT-C-T:$PC_{71}BM$	[274]
13	1.42	13.3	853	21.7	71.9	PM6:Y6	[275]
14	1.45	11.1	727	21.4	71.3	PTB7-Th:FNIC2	[276]
15	1.52	8.9	772	18.3	63.0	PTB7-Th:FNIC1	[276]
17	1.39	12.6	810	21.2	73.2	PBDB-T-2F:Y6	[277]
18	1.39	11.7	810	20.7	69.6	PBDB-T-2F:Y6	[277]
19	1.42	12.4	852	20.4	71.4	PM6:Y6	[275]
21	1.39	10.5	800	19.3	68.3	PBDB-T-2F:Y6	[277]
25	1.34	11.0	750	20.9	70.0	PCE-10:A078	[278]
25	1.40	10.2	736	20.3	68.3	PTB7-Th:FOIC	[279]

Table 12. Continued.

AVT [%]	E_g [eV]	PCE [%]	V_{oc} [mV]	J_{sc} [mA cm^{-2}]	FF [%]	Active material	Ref.
26	1.40	12.9	825	21.6	72.4	PBDB-T-2F:Y6	[280]
28	1.66	5.6	760	11.9	61.9	PBDTTT-C-T:$PC_{71}BM$	[274]
30	1.35	10.8	718	21.9	68.7	PTB7-Th:IEICO-4F	[281]
34	1.40	9.1	733	18.5	67.1	PTB7-Th:FOIC	[279]
36	1.37	8.8	680	18.0	71.9	PCE-10:BT-CIC:TT-FIC	[282]
36	1.86	6.9	890	11.6	66.5	PSEHTT:ICBA	[283]
37	1.86	6.1	890	10.2	66.8	PSEHTT:ICBA	[283]
39	1.86	4.9	880	8.3	67.9	PSEHTT:ICBA	[283]
43	1.34	8.1	730	16.3	68.1	PCE-10:A078	[278]
44	1.37	8.0	680	16.2	72.6	PCE-10:BT-CIC:TT-FIC	[282]
46	1.34	10.8	750	20.4	70.6	PCE-10:A078	[278]
47	1.34	7.1	730	14.3	68.0	PCE-10:A078	[278]
47	1.86	2.4	860	4.1	68.2	PSEHTT:ICBA	[283]
49	1.37	7.2	670	14.8	72.6	PCE-10:BT-CIC:TT-FIC	[282]
50	1.38	8.3	746	16.7	66.8	PTB7-Th:FOIC:$PC_{71}BM$	[56]
51	1.39	7.4	749	14.7	66.7	PTB7:FOIC:PC71BM	[56]
53	1.86	1.8	890	3.8	54.8	PSEHTT:ICBA	[283]
53	1.32	5.7	750	10.6	69.5	DPP2T:IEICO-4F	[284][a]
60	1.33	3.9	749	7.34	70.2	DPP2T:IEICO-4F	[284][b]
62	1.33	5.9	690	12.9	66.0	PTB7-Th:6TIC-4F	[161]
73	1.50	1.2	990	1.54	81.0	CO_i8DFIC	[57]
84	2.81	0.4	520	1.3	65.0	PBMMA:PEMA:$(TBA)_2Mo_6Cl_{14}$	[285]
86	1.52	0.4	500	1.2	66.0	Cy7	[286]

[a]Bottom illumination; [b]Top illumination.

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	[287]
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]
9	1.28	6.5	597	22.9	46.5	CIGS	[292]
16	1.83	7.5	810	14.2	65.3	a-Si:H	[293]
17	1.83	7.7	810	14.1	67.3	a-Si:H	[293]
18	2.05	5.9	720	14.1	58.3	a-SiGe:H	[294]
19	1.87	7.3	820	13.1	67.6	a-Si:H	[293]
19	1.34	6.5	580	17.5	63.5	CIGS	[291]
20	1.64	1.7	495	8.9	40.8	CIGS	[295]
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][a]
26	1.50	5.9	710	14.6	57.4	CIGS	[297][a]
43	1.53	0.4	101	14.7	27.2	CdTe	[298][b]

[a] E_g taken from absorption spectrum; [b] Average transmittance instead of AVT.

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	$Cs_{0.05}(FA_{0.92}MA_{0.08})_{0.95}Pb(I_{0.92}Br_{0.08})_3$	[36]	MPP, AM1.5G, N_2, 40 °C, UV-f
1.57	20.6	20.2	20.2	4.1	20.1	$FA_xCs_{1-x}PbI_3$	[299]	MPP, w-LED, Ar, 55–60 °C
1.58	19.2	19.3	18.4	3.9	19.0	$(FA_{0.83}MA_{0.17})_{0.95}Cs_{0.05}Pb(I_{0.9}Br_{0.1})_3$	[300]	OC, AM1.5G, encapsulation, 70–75 °C
1.59	17.1	11.6	9.5	2.8	11.1	$MA_{0.85}Gua_{0.15}PbI_3$	[301]	MPP, AM1.5G, Ar, 60 °C
1.60	19.2	19.5	17.6	4.1	19.1	$MAPbI_{3-x}Cl_x$	[109]	OC, AM1.5G
1.60	19.6	19.6	18.8	3.9	19.4	$Cs_{0.05}FA_{0.81}MA_{0.14}PbI_{2.55}Br_{0.45}$	[302]	MPP-R_L, AM1.5G, encapsulation, 50–70% RH, 65 °C
1.61	18.1	11.9	13.6	2.6	13.0	$MA_{0.75}Gua_{0.25}PbI_3$	[301]	MPP, AM1.5G, Ar, 60 °C
1.63	12.2	13.3	12.3	2.1	9.9	$(FA_{0.79}MA_{0.16}Cs_{0.05})_{0.97}Pb(I_{0.84}Br_{0.16})_{2.97}$	[303]	77 mW cm^{-2}, MPP-R_L, AM1.5G, RH<25%, 26 °C
1.64	20.1	17.8	–	3.7	–	$Cs_{0.1}(MA_{0.17}FA_{0.83})_{0.9}Pb(I_{0.83}Br_{0.17})_3$	[304]	MPP, w-LED, N_2, 25 °C
1.64	19.7	17.2	–	3.5	–	$Cs_{0.5}(FA_{0.83}MA_{0.17})_{0.95}Pb(I_{0.83}Br_{0.17})_3$	[305][a]	MPP, w-LED, N_2, 20 °C
1.66	13.0	14.7	13.0	2.8	14.1	$Cs_{0.17}FA_{0.83}Pb(Br_{0.17}I_{0.83})_3$	[306]	MPP, AM1.5G, 40% RH, 35 °C
1.69	6.8	6.7	–	1.3	–	$CsSn_{0.5}Ge_{0.5}I_3$	[117]	MPP[b], AM1.5G, N_2, 45 °C
1.74	12.9	13.4	–	2.7	–	$CsPbI_3$	[307]	OC, AM1.5G, N_2, 25 °C, UV-f

[a] E_g taken from PL peak; [b] MA: methylammonium; 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	P3HT:o-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.

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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.

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