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Revisiting the Definition of Solar Cell Generations

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The classification of photovoltaic technologies into generations aims at facilitating the overview and equally can support the identification of future trends. The initial definition by Martin Green follows the historical development, which however does not necessarily need to imply that a certain technology is old or outdated. To find an update of that early graph without immediately refusing the initial classification, first, the representation is filled with up-to-date numbers. Despite several new definitions of generations being introduced, these merely stay on a general level without quantitative justification. Here, in contrast, classification is further strengthened by numbers of the latest efficiency records and module prices. By becoming specific, it is possible to draw the current picture, compare it to the initial idea and reveal novel trends and potential. Showing different representations of the quantitative values further allows setting a focus of investigation and looking at the situation from various perspectives. In this way, it is expected to support the discussion not just of classification but rather of future technology potential, which becomes apparent from parallel trends. In addition, the importance of advanced optical designs for future competitive efficiency enhancement will be presented.

1. Introduction

The categorization of different types of solar cells enables keeping an overview as well as identifying potential links and future trends. In this regard, in the early 2000s, Martin Green coined the initial definition of solar cells of the first, the second, and the third generation: Si-based wafer technology was the early start of photovoltaics (PV) and therefore constituted the first generation of solar cells with at that time high cost for good efficiency.[1] Since the material cost was assumed to become the limiting factor, the second generation of thin-film solar cells emerged at expected lower costs due to reduced material consumption along with slightly lower efficiencies. The third generation, of a "high performance, low-cost photovoltaic product"[1] furthermore enables efficiencies beyond the single-junction Shockley-Queisser limit.[2] In Green's original publication, this generation also reaches into the area of lower efficiencies, yet it is stated to make use of advanced concepts such as multi-junction and concentrator PV or other novel approaches like quantum dot, intermediate band gap, or hot-carrier solar cells, which are essentially designed for boosting the performance.

In recent years, this early categorization was questioned or replaced as it was found not to be up to date. For example, Wim Sinke depicted that this picture might give a false impression of which technology would persist or be mature.[3] As we know nowadays, crystalline silicon is dominating the market and has become the cheapest technology at efficiencies close to the single-junction limit. Thin films, on the other hand, come close in efficiency but could so far not keep up with cost reduction and hence large-scale deployment. Structures surpassing the Shockley–Queisser limit now rely on the combination of, e.g., silicon with thin-film technologies as the recent record of a perovskite/c-Si tandem has shown. Therefore, Sinke proposes an intermixing of the generations, mutually enriching each other. Various other recent literature categorizes dye-sensitized, organic but also perovskite solar cells as the third generation speaking about emerging technologies even if they will stay below 30% efficiency. Yet, this attribution is neither consistent nor is it well-defined where to draw the separation line between second and third generation photovoltaic technologies. Why would perovskite solar cells belong to the third generation despite showing comparable absorber thicknesses and efficiencies as chalcogenide-based devices? Our aim thus is to provide a clear definition of the first, the second, and the third generation of solar cells. In this way, the efficiency potential on the one hand (clear attribution of devices possibly surpassing Shockley–Queisser's single-junction limit to the third generation) and the application opportunities on the other hand (requiring, e.g., flexibility and semitransparency inherently feasible for second generation thin-film devices) are emphasized.

Given the recent development of viewpoints, revisiting the definition of solar cell generations is of relevance, since a clear view of the photovoltaic landscape shall provide an overview and orientation. Therefore, we revert to the early graph of Green and update it with recent numbers of solar cell efficiencies and module prices that have not been considered in the last years. The resulting picture differs from the original one when it comes to

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cost relations between the different technologies: crystalline silicon has made a big step toward lower prices, whereas thin films – in the vast view from CdTe, over CIGSe to organic and perovskite – span a wide cost range. Equally, the third generations technologies, including the combination of multiple absorber materials as well as light concentration, come at higher costs but with the potential for significant efficiency increase. For the latter aspect, the room for improvement becomes visible and trends for future research may be identified as is the purpose of the solar cell generation chart.

2. Technical

The work aims to update the picture of the solar cell generations first drawn by Green[1] and lately modified in many different ways. Therefore, we revert to the initial graph and fill it with recent numbers of solar cell efficiencies and module prices. A comparison reveals the latest development and provides an orientation where future research may head to.

For filling the graph with data, efficiency values from Green's latest efficiency table are taken.[4] It shall be noted, that sometimes different values were found in Green's table compared to the cited literature. For example, 26.7% are tabulated by Green et al. for c-Si but 26.3% are found in the original paper by Yoshikawa et al.,[5] and 29.1% are given in Green's table but 27.6% in the according reference for GaAs.[6] New records like 25.5% certified for perovskite by Min et al.[7] are classified as notable exceptions but do not occur in the main table of ref.[4] As the recognized listing of Green's paper shall not be questioned, we just point the interested reader to these observations but stick to the tabulated certified efficiencies in.[4] We only added the 15.2% efficiency for an ultrathin CIGSe solar cell by Mansfield et al., as this will be relevant for further analysis.[8] Generally, the single-cell record efficiencies were used in the plots to show the current uppermost limit. Naturally, there remains a certain discrepancy when plotting versus the prices estimated for full modules, which however we accept for the sake of showing the current potential. For an alternative representation, instead of these total efficiencies, the efficiencies per thickness or volume were taken. Therefore, absorber thicknesses were extracted from the respective publications or were estimated from comparable publications in the fields if no numbers were found in the original paper. In the case of multi-junction devices, the absorber thicknesses were added up. The efficiency values per thickness or rather volume were calculated as efficiency per thickness times concentration, the latter factor accounting for required smaller material consumption when operated under light concentration. All the values for efficiency, thickness, and efficiency/thickness • concentration are listed in **Table 1**.

As to costs, which are further included in Table 1, minimum sustainable prices for the main single-junction modules originate from a recent publication by NREL.[9] Specifically, we set 0.25 \$ W^{-1} for c-Si, 0.3 \$ W^{-1} for CdTe, 0.5 \$ W^{-1} for CIGSe, 0.4 \$ W^{-1} for perovskite, and 77 \$ W^{-1} for III–Vs. From these numbers, we estimate 0.4 \$ W^{-1} for CZTSe with a fabrication process similar to CIGSe but with cheaper materials and 0.3 \$ W^{-1} for a-Si. For both, organic and dye-sensitized solar cells, 0.2 \$ W^{-1} is assumed as a cheaper starting point despite there exists literature predicting even one order of magnitude lower prices for organic.[10–12] The split-ups in NREL's publication furthermore allowed estimating the costs, related to layers needed in addition to the bottom cell, for forming multi-junction devices. In detail, we assume a plus of 0.1 \$ W^{-1} for the perovskite top layers and 15 \$ W^{-1} for the MOVPE process of adding a III–V absorber. These estimations result in 92 \$ W^{-1} for a tandem up to 137 \$ W^{-1} for a five-junction III–V cell. For perovskite tandems, the costs are straightforward calculated to 0.35 \$ W^{-1} for perovskite/c-Si, 0.5 \$ W^{-1} for perovskite/perovskite, and 0.6 \$ W^{-1} for perovskite/CIGSe. The costs for the ultrathin CIGSe absorber were assumed to reduce according to the reduction of absorber thickness times 0.1 \$ W^{-1} absorber fabrication costs, i.e., for 500 nm absorber thickness a final price of 0.42 \$ W^{-1} resulted. For light concentration, the unconcentrated modules' prices were doubled, accounting for higher costs of potential large-scale and high-precision optics and tracking systems used with already expensive III–V solar cells, whereas more compact and low-cost concentrator designs are anticipated and feasible with cheaper thin-film technologies. Certainly, these are very rough estimations, which however shall provide us with a starting point for evaluating efficiency trends and potentials. The costs in \$ W^{-1} were converted to \$ m^{-2} by considering the solar irradiation of 1000 W m^{-2} and the efficiency values. In this way, a direct comparison to the initial figure by M. Green is possible.

3. Results and Discussion

Figure 1 shows the representation of the PV technology landscape according to the initial graph of Green by plotting efficiency versus price in \$ m^{-2}. The major difference in our plot is that we use specific numbers (efficiencies from Green's 2022 table and module prices as assembled by NREL, see Table 1) and therefore choose a logarithmic representation of the prices, which are exponentially increasing for III–V technologies.

The separation of solar cell generations along with corresponding technologies is precised as follows:

First generation: silicon-wafer-based technology,
i.e., c-Si

Second generation: thin-film technologies,
including all solar cells with absorbers of a few μm thickness, e.g. CdTe, CIGSe, CZTSe, perovskite, a-Si, dye-sensitized, organic; III–V solar cells are also attributed due to fitting absorber thickness

Third generation: technologies capable to surpass Shockley–Queisser's limit,
multi-junction and concentrator devices as shown in the figure, yet a multitude of other concepts like quantum dot or intermediate bandgap solar cells fall into this category as well

The graph confirms the classification since we can clearly group the generations as marked by the ellipses. Crystalline silicon in red constitutes the first generation and starting point with 26.7% record efficiency[4,13] and costs of 66.8 \$ m^{-2} resulting from an estimated module price of 0.25 \$ W^{-1}.[9] Compared to Green's initial figure from 2001, we find c-Si obviously shifted to lower prices and higher efficiencies, reflecting the development over the last years. The large group of second generation thin-film devices, marked in green, still reaches prices one order of magnitude lower, yet surpasses those of c-Si as the efficiencies get close.

Table 1. Overview of numbers used for the charts: Record efficiencies Eff and concentration values C from [3], (sum of) absorber thickness(es) d from original publications or descriptions of similar processes, prices from [8], and estimations based hereupon.

Technology	Eff [%]	d [µm]	C [suns]	Eff/d • C [% µm^{-1}]	Price [$ W^{-1}]	Price [$ m^{-2}]
Single junction						
c-Si	26.7	165	1	0.16	0.25	66.8
CdTe	21.0	3	1	7.00	0.3	63.0
CIGS	23.35	2.5	1	9.34	0.5	117
ultrathin CIGS	15.2	0.49	1	31.0	0.42	63.8
CZTS	11.3	2.5	1	4.52	0.4	45.2
perovskite	23.7	1	1	23.7	0.4	94.8
a-Si	10.2	0.235	1	43.4	0.3	30.6
dye-sensitized	11.2	3	1	3.73	0.2	22.4
organic	15.24	0.095	1	160	0.2	30.5
GaAs	29.1	4	1	7.28	77	22.4e3
InP	24.2	4	1	6.05	77	18.6e3
Multi junction						
perovskite/Si	29.8	166	1	0.18	0.35	104
perovskite/CIGS	24.2	3.5	1	6.91	0.6	145
perovskite/pero	26.4	2	1	13.2	0.5	132
GaInP/GaInAsP/Si	35.9	173	1	0.21	92.2	33.1e3
GaInP/GaAs	32.8	8	1	4.10	92	30.2e3
InGaP/GaAs/InGaAs	37.9	12	1	3.16	107	40.6e3
five jct III–V	38.8	20	1	1.94	137	53.2e3
Concentration						
conc Si	27.6	165	92	15.4	0.5	138
conc CIGSe	23.3	2.5	15	140	1	233
conc GaAs	30.8	4	61	470	154	47.4e3
conc four jct III–V	46.0	20	508	1.17e3	244	112e3
conc six jct III–V	47.1	24	143	281e3	304	143e3

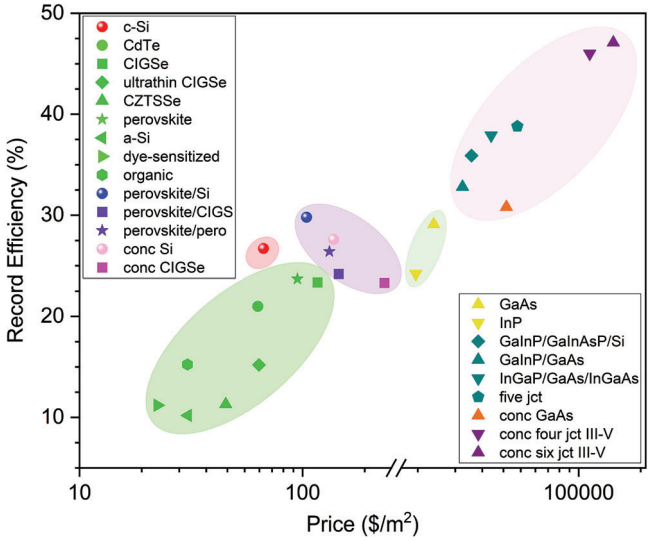

Figure 1. PV technology landscape plotting efficiency versus price in $ m^{-2}.

In detail, the technologies dye-sensitized, organic, a-Si, CZTS, CdTe, CIGSe, and perovskite span prices from 22.4 $ m^{-2} (dye-sensitized, calculated from an estimated 0.2 $ W^{-1}) to 117 $ m^{-2} (CIGSe, derived from 0.5 $ W^{-1}[9]). The corresponding efficiencies range from 10% (a-Si: 10.2%[4,14]) over 15% for organic[4,15] up to >23% (CIGSe 23.35%[4,5] and perovskite 23.7%[4,16]). Thus, all these second generation devices stay below c-Si in terms of efficiency and surpass it in price as the efficiencies increase. We will however see that this trend may change when looking from different perspectives. For all the detailed numbers, please refer to Table 1.

Here, we move on to the third generation technologies based on first generation Si and second generation thin films, thus interlinking the technologies as also the discussion by Sinke suggested.[3] In our classification of generations, however, these solar cells of the third generation do need to have the potential of surpassing Shockley Queisser's single-junction efficiency limit. Figure 1 depicts tandem and multi-junction devices as well as those operated under light concentration in purple. Tandem solar cells based on perovskites, either within the material system or in a combination with CIGS and c-Si, slightly surpass the efficiency of the respective single-junction bottom cell. Thus, only the perovskite/c-Si tandem achieves with 29.8% an efficiency beyond the single-junction c-Si record.[4,17] This device furthermore included nano-optical structures for efficient light collection and distribution, highlighting the benefit of a sophisticated

optical design. The costs are expected to increase moderately to 104 \$ m^{-2}, estimated from a plus of 0.1 \$ W^{-1} for basically the perovskite absorber[9] on top of the c-Si module price (i.e., 0.35 \$ W^{-1} total tandem cost). This calculation is on the cheaper side as additional costs for multi-junction devices can become relevant. Light concentration shows promise for c-Si, delivering 27.6% efficiency,[4,18] and also appears beneficial for CIGSe with proven 23.3%.[4,19] The increase in prices of these concentrator devices based on c-Si or CIGSe is currently however predominating the efficiency benefit, so further research and development are required. The same applies to perovskite concentrator devices, which have not been the focus of research so far, yet may hold significant potential when stable devices will have become standard.

In this context, it is interesting to look at the III–V materials, which were not included in our discussion so far, since they appear separated by 2–3 orders of magnitude higher costs (note the interruption in the x-scale). Prices start from 22.4 k€ m^{-2} for GaAs, i.e., >300 times the area price of c-Si, and increase accordingly for multi-junction and concentrator devices reaching another order of magnitude higher values. However, these devices reveal excellently, how the single-junction efficiencies (shown in yellow in the light green ellipse) with a record of 29.1% for GaAs[4,6]) can realistically be surpassed. When combining several absorbers to multi-junction devices (presented in dark cyan), a maximum efficiency of 38.8% was demonstrated for five junctions.[4] By applying light concentration (orange and dark pink symbols, all in the pinkish ellipse), 47.1% ultimate efficiency record was proven for a six junction device under 143 suns.[4,20] The four-junction device operated under 508 suns comes close with a record of 46.0%.[4,21] It is highly illustrative to see that the theoretical expectation of efficiencies beyond the single-junction limit may well be realized with high material quality and adequate device design. Interestingly, the third generation devices emerging from c-Si and thin films other than III–Vs stay restricted in significantly surpassing the respective single-cell efficiency but still come at higher prices. Drawing the parallel to the III–V technology, we clearly see that there is significant potential for these cheaper third generation devices when challenges of material and interface quality, as well as optimized device design, will be resolved.

Looking from a different perspective, namely giving prices in \$ W^{-1} rather than in \$ m^{-2}, the picture slightly changes. In **Figure 2**, the same efficiencies are presented just with the price axis modified and the III–V technologies shown as an inset. The clear trend of efficiency enhancement for multi-junction and concentrator devices for the III–V material system is equally revealed in this representation. The absolute numbers of up to 304 \$ W^{-1} as estimated for the six-junction concentrator module, clarify that their application will be restricted to very specific cases. The cost for the perovskite/c-Si tandem, on the other hand, is estimated to be 0.35 \$ W^{-1}, which then would be cheaper than the Perovskite device alone (0.4 \$ W^{-1}) while bringing a 3% higher efficiency. NREL's cost estimation even goes one step further and expects the price to drop to 0.31 \$ W^{-1}.[9] Therefore, tandems based on cheap, yet efficient devices appear to hold high promise.

Light concentration provides another pathway with proven potential to enhance efficiency. As the III–V system reveals, light concentration on a single-junction device can only moderately

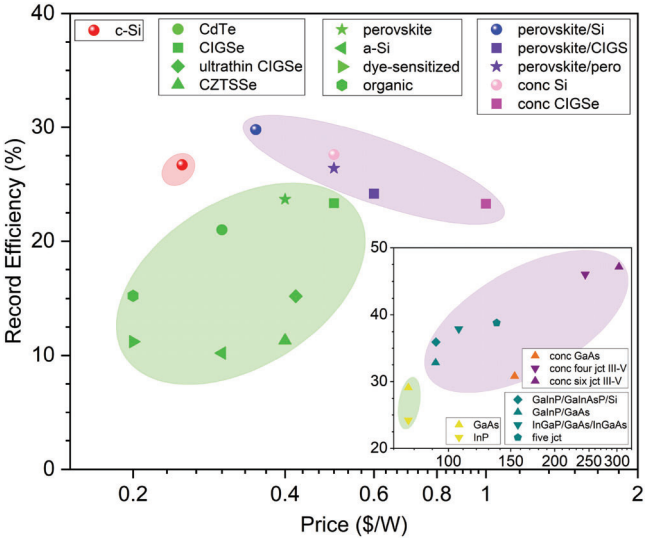

Figure 2. PV technology landscape plotting efficiency versus price in \$ W^{-1}.

enhance the efficiency (1.7% points for GaAs[4]), whereas application to multi-junction devices leads to a plus of almost 10% absolute. Here, it is very intriguing to draw the parallel to third generation devices based on c-Si and thin-films other than III–Vs. According to the current status, we can equally observe a slight increase in efficiency of ≈1% point when concentrating light on single-junction c-Si or CIGSe. Tandem devices, on the other hand, have also shown the potential for efficiency increase. Thus, extrapolating from the III–V technology, concentrator multi-junction devices based on c-Si, CIGSe, perovskite, or CdTe are predicted to become strong future game players. Due to the feasibility of compact module designs like micro concentrator solar cells,[22] the price is expected to stay moderate even when the efficiency will follow the trend indicated by the III–V devices. In the picture drawn here, the technologies including c-Si have the best records; in the following, we will also take a look from another perspective. Price-wise, only dye-sensitized and organic solar cells can beat c-Si when looking at costs per power.

For further investigation, **Figure 3** shows an alternative representation of the PV technology landscape. The prices are still given in \$ W^{-1}, but the efficiency per absorber volume is plotted. This is an important aspect from the perspective of material efficiency, as valuable raw materials may be saved. The focus on the amount of active/absorber material addresses this point, as well as the reduced consumption of toxic materials used for many absorbers. Almost every solar cell technology is touched by these aspects for which specifically the rare elements In and Ga contained in CIGSe, the toxic elements Pb in pervoskites or Cd in CdTe, and the consumption of toxic silane gas during c-Si fabrication shall be mentioned. To represent the material efficiency, the record efficiency of the respective device is divided by the absorber thickness and multiplied by the concentration factor (1 if no concentration is applied) to account for the material saving potential when operating under increased light intensity. Note the resulting unit of % μm^{-1}, despite talking about volume efficiency. In this picture, c-Si marks the bottom line with

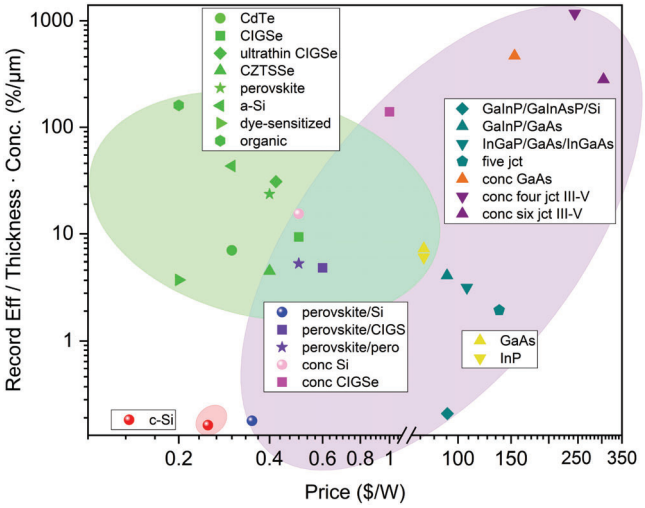

Figure 3. PV technology landscape plotting efficiency/thickness • concentration versus price in \$ W^{-1}.

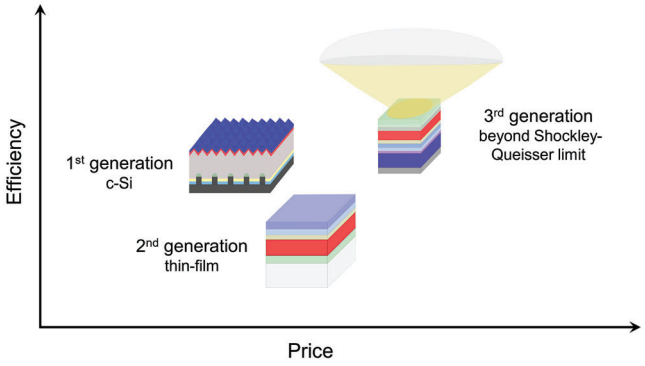

Figure 4. Schematic of solar cell generations in PV landscape.

0.16% μm^{-1} due to its wafer thickness, and also the perovskite/c-Si device can only make it to 0.18% μm^{-1}. The second generation thin-film technologies clearly stick out in efficiency per volume and overlap with the third generation devices. Most interestingly, the organic devices show the best performance with 160% μm^{-1} at an estimated price of 0.2 \$ W^{-1}. Amorphous silicon follows with 43.4% μm^{-1} at costs of 0.3 \$ W^{-1}. The potential of material saving is revealed by the ultrathin CIGSe device: when reducing the absorber layer thickness by a factor of ≈5, the volume efficiency enhances from 9.34 to 31.0% μm^{-1} at a cost reduction from 0.5 to 0.42 \$ W^{-1}. Furthermore, the CIGSe concentrator device reaches 140% μm^{-1} for an estimated 1 \$ W^{-1}. Due to the nature of added absorber thicknesses, multi-junction devices based only on thin films stay behind their single-junction reference when it comes to efficiency per volume. The low material efficiency at relatively higher costs is observed for combinations with perovskite as well as for the III–Vs. Concentrating devices, however, keep the potential of high efficiency per volume and therefore may be a promising future technology also for thin-film materials other than III–Vs. The aim of staying cheap while maximizing efficiency persists and our representation of PV landscapes may support identifying promising directions. In particular, when looking into the reduction of absorber material, semitransparency, and related applications are opened up.

In addition, it is important to consider that the cheapest or even most efficient technology does not necessarily come with the best long-term stability. While the lifetime has been rated high to very high for CIGSe/CdTe and c-Si (25 and 30 years, respectively), it is notably lower for organic and perovskite-based solar cells. Ref. [23] mentions ≈10 years for the latter two, while many current research papers discuss stability still on the level of thousands of hours. The relevance of stability will however also depend on the application: while large-scale PV power plants require high lifetimes due to cost-intensive installations, solar cells integrated into products with short lifetimes themselves can easily come with lower long-term stability. In these cases, flexibility both in the immediate mechanical sense as well as in terms of production, together with cheap and environmental-friendly fabrication methods may outweigh lifetime benefits. For a further discussion balancing these factors of influence, the reader is referred to the publication of Heinrich et al.[23] Additional attention may be paid to energy requirements of the fabrication processes, which will come, e.g., with a higher demand for crystalline silicon growth than for vacuum-free solution-based processes. A consideration of these and other factors of influence will be highly interesting for future redrawing of the PV landscape when comprehensive and comparative datasets are available.

4. Conclusion and Outlook

In sum, the picture of solar cell generations was revisited and renewed with specific and up-to-date numbers for efficiencies and prices. By doing so, the current PV technology landscape is revealed and the following attribution of technologies to generations confirmed and manifested:

First generation: silicon-wafer-based technology
(c-Si)
Second generation: thin-film technologies
(incl. a-Si, dye-sensitized, organic, perovskite, CZTSe, CIGSe, CdTe, III–Vs)
Third generation: technologies capable to surpass Shockley–Queisser's efficiency limit
(e.g., multi-junction, concentrator, quantum dot, or intermediate band gap solar cells, up and down conversion)

Figure 4 depicts the schematic summary of identified status and trends. First generation c-Si has without any doubt become the technology with the highest absolute efficiency at low cost: 26.7% record efficiency for 0.25 \$ W^{-1}. While currently just c-Si is included in the first generation, future development may give rise to other technologies with thick absorbers showing high-efficiency potential but limited flexibility and semitransparency. The capability of potentially flexible and semitransparent devices is however inherently assumed for the second generation of thin-film devices. They span wide ranges of both efficiency and cost: dye-sensitized and organic solar cells start with efficiencies from 10–15% at prices of 0.2–0.3 \$ W^{-1}, CdTe, CIGSe, and perovskite deliver 21–23% for 0.3–0.5 \$ W^{-1} and GaAs 29% for 77 \$ W^{-1}. Despite the vast span, all these technologies are grouped into the

second generation since they have a common structure based on thin films with absorber thicknesses of a few μm.

Importantly, it is possible to draw parallels from the development of one material system to another when moving toward third-generation devices. The III–V technologies have excellently shown, that material combination to tandem and multi-junction solar cells can continuously increase the efficiency, here to 38.8% for the five-junction device. Light concentration is most promising atop of these rather than on the single-junction solar cell: 30.8% when applied to GaAs alone, but 47.1% on the six-junction device. For materials other than III–Vs, efficiency enhancement by tandems and light concentration was proven with a plus of 1–2%, showing the feasibility while still leaving room for improvement. Therefore, a future trend is seen for tandem concentrator devices based on perovskite, CIGSe, and potentially CdTe, which are expected to enhance efficiency at moderate costs. A combination with the base-technology c-Si appears promising for a stable high-efficiency low-cost starting point. In this way, third generation devices with costs in the low \$ W^{-1} range and efficiencies well beyond 30% are expected, emerging from first and second-generation solar cells. Novel concepts like quantum dot or intermediate band gap solar cells, up and down conversion, etc. may provide further potential to boost efficiency. They were not considered in the discussion here because of their lacking entries in Green's efficiency table.

Light management schemes play an important additional option for the efficiency enhancement of all and in particular the third generation solar cells as they support light incoupling, trapping inside the absorber layer as well as localization of light where it can most effectively be converted. A multitude of nanostructures has been investigated in literature ranging from metallic nanoparticles over dielectric ones to regular and irregular nanopatterns. They can be related to various optical effects like plasmonic field enhancement, large angle scattering, evolvement of whispering gallery modes, or coupling into waveguide modes, which may also be mixed depending on the respective structure.[24,25] The purpose of exploiting these optical modes emerging from the nanostructures is the reduction of reflection and the enhancement of absorption inside the active layer, even if this one comes with a minimum thickness. Nanostructure can furthermore support interface passivation and contribute to electrical benefits.

Another very fundamental way for enhanced exploitation of solar radiation is bifacial operation, i.e., collection of light from various directions of incidence, in particular front and back side. This improved usage of, e.g., diffuse or unabsorbed light constitutes a simple means of efficiency enhancement without high additional costs. Whereas bifacial modules are already governing the market,[26] there is currently only one entry in the efficiency tables (a four-junction/bifacial c-Si hybrid module with 34.2% efficiency[4,27]), which however did not reach the performance record of the corresponding multi-junction device and was thus not included in our chart. Yet, it is very interesting to note that the concept of bifaciality is applicable to any generation of solar cells: Obviously, thin films solar cells are touched, which were defined here in relation to potential semitransparency,[28] but actually it is again c-Si that is dominating the market also in the bifacial form.[26] Furthermore, a bifacial operation is equally an option for tandem solar cells (see, e.g., the perovskite/Si bifacial tandem in Ref. [29]) and intrinsically for concentrator devices in order to also exploit diffuse radiation (see, e.g., the early publication by Edmonds [30]). Thus, bifacial concepts constitute a viable and promising approach across all solar cell generations for increasing the energy yield by a factor of >30%.[31]

In the end, the respective application will decide about the most suitable technology. Whereas highly expensive but efficient III–V devices can find usage for specific applications like in space, the major market stays dominated by cheap and efficient c-Si technology. As we are electrifying more and more areas of daily life and renewable energies are the future, suitable material systems for various applications need to be identified. Asides from large-scale power plants, PV finds its way of integration into buildings, vehicles, or agriculture. The fields of building-integrated photovoltaics (BIPV), vehicle-integrated photovoltaics (VIPV), device-integrated photovoltaics (DIPV), agrivoltaics, and others will play a non-negligible role in the future, where efficiency and cost need to be relativized by aspects like flexibility (also regarding the substrate), semitransparency or esthetics. In regard of these characteristics, the second generation of thin-film devices stands out before the first generation and the heading toward third generation designs plays an important role. Both, technologies at the low-efficiency/low-cost end as well as those with high-efficiency potential at moderate costs will be of interest. In particular, when it comes to a twofold purpose, i.e., electricity generation and, e.g., semitransparency, the consideration of optical aspects becomes of additional relevance. Then, highly efficient and at the same time low-cost concepts for efficient light management need to be considered on top. Cheap and compact devices with integrated sophisticated optics for full light exploitation at high resource efficiency are seen to be the future. The direction of tandem concentrator devices based on cheap thin-film materials opens up a promising direction here, for which the potential was also derived from the updated PV landscape. Finally, for optimum exploitation of solar radiation, bifacial designs and custom-designed light collectors may constitute the future ahead.

All in all, the definition of the originally proposed three generations of solar cells was revisited and a clear separation line drawn between the recently blurring second and third generations by referring back to Shockley–Queisser's single-junction limit. The naming "generations" was maintained here, which however may find an alternative wording in the future. In this regard, the just-mentioned diversity of applications may play a role and provide the basis for an alternative naming and classification. It will be gratifying to see this perspective triggering discussions about viewpoints on solar cell technologies together with their future development and deployment.

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Conflict of Interest

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Keywords

c-Si, light concentration, multi-junction, next-generation photovoltaics, photovoltaic technology landscape, solar cell generations, thin-film

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[1] M. A. Green, *Prog. Photovolt.: Res. Appl.* **2001**, *9*, 123.
[2] W. Shockley, H. J. Queisser, *J. Appl. Phys.* **1961**, *32*, 510.
[3] W. C. Sinke, *Renew. Energy* **2019**, *138*, 911.
[4] M. A. Green, E. D. Dunlop, J. Hohl-Ebinger, M. Yoshita, N. Kopidakis, K. Bothe, D. Hinken, M. Rauer, X. Hao, *Prog. Photovolt.: Res. Appl.* **2022**, *30*, 687.
[5] K. Yoshikawa, H. Kawasaki, W. Yoshida, T. Irie, K. Konishi, K. Nakano, T. Uto, D. Adachi, M. Kanematsu, H. Uzu, K. Yamamoto, *Nat. Energy* **2017**, *2*, 17032.
[6] B. Kayes, H. Nie, R. Twist, S. Spruytte, F. Reinhardt, I. Kizilyalli, G. Higashi, in *Proc. 37th IEEE Photovoltaic Specialists Conf. (PVSC)*, Seattle, WA, USA, June **2011**.
[7] H. Min, D. Y. Lee, J. Kim, G. Kim, K. S. Lee, J. Kim, M. J. Paik, Y. K. Kim, K. S. Kim, M. G. Kim, T. J. Shin, S. Il Seok, *Nature* **2021**, *598*, 444.
[8] L. M. Mansfield, A. Kanevce, S. P. Harvey, K. Bowers, C. Beall, S. Glynn, I. L. Repins, *Prog. Photovolt.: Res. Appl.* **2018**, *26*, 949.
[9] B. L. Smith, M. Woodhouse, K. A. W. Horowitz, T. J. Silverman, J. Zuboy, R. M. Margolis, *Photovoltaic (PV) Module Technologies: 2020 Benchmark Costs and Technology Evolution Framework Results*, National Renewable Energy Laboratory, Golden, CO, USA **2021**.
[10] T. H. Syed, W. Wei, *Inorganics* **2022**, *10*, 191.
[11] J. Guo, J. Min, *Adv. Energy Mat.* **2019**, *9*, 1802521.
[12] F. Machui, M. Hosel, N. Li, G. D. Spyropoulos, T. Ameri, R. R. Sondergaard, M. Jorgensen, A. Scheel, D. Gaiser, K. Kreul, D. Lenssen, M. Legros, N. Lemaitre, M. Vilkman, M. Valimaki, S. Nordman, C. J. Brabec, F. C. Krebs, *Energy Environ. Sci.* **2014**, *7*, 2792.
[13] M. Nakamura, K. Yamaguchi, Y. Kimoto, Y. Yasaki, T. Kato, H. Sugimoto, *IEEE J. Photovolt.* **2019**, *9*, 1863.
[14] T. Matsui, A. Bidiville, K. Maejima, H. Sai, T. Koida, T. Suezaki, M. Matsumoto, K. Saito, I. Yoshida, M. Kondo, *APL* **2015**, *106*, 053901.
[15] U. Würfel, J. Herterich, M. List, J. Faisst, M. F. M. Bhuyian, H.-F. Schleiermacher, K. T. Knupfer, B. Zimmermann, *Sol. RRL* **2021**, *5*, 2000802.
[16] J. Xu, C. Boyd, Z. Yu, A. Palmstrom, D. Witter, B. Larson, R. France, J. Werner, S. Harvey, E. Wolf, W. Weigand, S. Manzoor, M. F. A. M. Hest, J. Berry, J. Luther, Z. Holman, M. McGehee, *Science* **2020**, *367*, 1097.
[17] P. Tockhorn, J. Sutter, A. Cruz, P. Wagner, K. Jäger, D. Yoo, F. Lang, M. Grischek, B. Li, J. Li, O. Shargaieva, E. Unger, A. Al-Ashouri, E. Köhnen, M. Stolterfoht, D. Neher, R. Schlatmann, B. Rech, B. Stannowski, S. Albrecht, C. Becker, *Nat. Nanotechnol.* **2022**, *17*, 1214.
[18] A. Slade, V. Garboushian, in Technical Digest 15th Int. Photovoltaic Science and Engineering Conf., Shanghai, October **2005**.
[19] J. S. Ward, K. Ramanathan, F. S. Hasoon, T. J. Coutts, J. Keane, M. A. Contreras, T. Moriarty, R. Noufi, *Prog. Photovolt.: Res. Appl.* **2002**, *10*, 41.
[20] J. Geisz, M. Steiner, N. Jain, K. Schulte, R. France, W. McMahon, E. E. Perl, D. Friedman, *IEEE J. Photovolt.* **2018**, *8*,626.
[21] F. Dimroth, T. N. D. Tibbits, M. Bach, F. Predan, P. Beutel, C. Karcher, E. Oliva, G. Siefer, D. Lackner, P. Fus-Kailuweit, A. Bett, R. Krause, C. Drazek, E. Guiot, J. Wasselin, A. Tauzin, T. Signamarcheix, *IEEE J. Photovolt.* **2015**, *6*, 1.
[22] M. Schmid, G. Yin, M. Song, S. Duan, B. Heidmann, D. Sancho-Martinez, S. Kämmer, T. Köhler, P. Manley, M. Ch. Lux-Steiner, *J. Photonics Energy* **2017**, *7*, 018001.
[23] M. Heinrich, T. E. Kuhn, F. Dimroth, U. Würfel, J. C. Goldschmidt, M. Powalla, S. Glunz, D. H. Neuhaus, in *Proc. 37th European Photovoltaic Solar Energy Conf. and Exhibition*, Lisbon, September **2020**.
[24] I. Massiot, A. Cattoni, S. Collin, *Nat. Energy* **2020**, *5*, 959.
[25] M. Schmid, *Semicond. Sci. Technol.* **2017**, *32*, 043003.
[26] International Technology Roadmap for PV online available at https://www.vdma.org/international-technology-roadmap-photovoltaic (accessed: June 2023).
[27] J. F. Martinez, M. Steiner, M. Wiesenfarth, G. Siefer, S. W. Glunz, F. Dimroth, *Prog. Photovolt.: Res. Appl.* **2021**, *29*, 614.
[28] Y. Li, G. Yin, M. Schmid, *Sol. Energy Mater.* **2022**, *234*, 111431.
[29] M. De Bastiani, A. S. Subbiah, M. Babics, E. Ugur, L. Xu, J. Liu, T. G. Allen, E. Aydin, S. De Wolf, *Joule* **2022**, *6*, 1431.
[30] I. R. Edmonds, *Sol. Energy Mater.* **1990**, *21*, 173.
[31] R. Kopecek, J. Libal, *Energies* **2021**, *14*, 2076.

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