Future industrial solar PV technologies: Record cell efficiency announcements versus industrial reality

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Abstract

Record cell efficiency announcements have a history that is as old as the PV industry. Whereas up until around 2015 such announcements were mostly published by PV institutes processing small solar cells 2×2cm² in area, during the last five years industrial cell and module manufacturers have begun to publish record cell and module efficiency announcements more and more frequently for so-called *large-area industrial devices*. These efficiency announcements are somewhat heterogeneous in terms of device structures (not always corresponding to the commonly used nomenclature) as well as in terms of measurement conditions. The values range from the recently published 26.3% efficiency for a silicon heterojunction technology (HJT) solar cell from LONGi, with measured fill factor (*FF*) close to the theoretical limit (exceeding 86%), to 21.1% for actual, currently available, modules in mass production from Trina Solar. Accordingly, this paper discusses what is actually behind these announcements and how an evolutionary industry sector such as PV is becoming, it seems, decidedly revolutionary with large jumps in efficiency. In reality, these announcements give the wrong impression: the PV industry still needs to be conservative, as PV modules must be low cost and long-term stable at the same time. This is why the transfer of innovations to mass production will now (and also in the future) always require a certain amount of time, and PV technology development will continue to proceed in an evolutionary way through a step-by-step introduction of innovative concepts.

Introduction

By 2020, solar PV – with its bifacial passivated emitter and rear cell (PERC) technologies – had been crowned the new king of the energy markets [1], sporting extremely low offers in tenders in the Middle East and North African (MENA) states, such as Saudi Arabia, drawing prices as low as 1USct/kWh [2] in 2021. As PERC is currently on the verge of reaching its efficiency limits, the question now is: what is next? And which cell technology will take the thrown as the new 'emperor'? Moreover, is there going to be a rapid shift from p-type Si-based PERC to n-type Si cell technologies, as was the case about five years ago when the PV industry switched very quickly from Al-BSF to PERC? As shown in Fig. 1, PV-Tech Research [3], as well as a significant part of the PV community, believes so.

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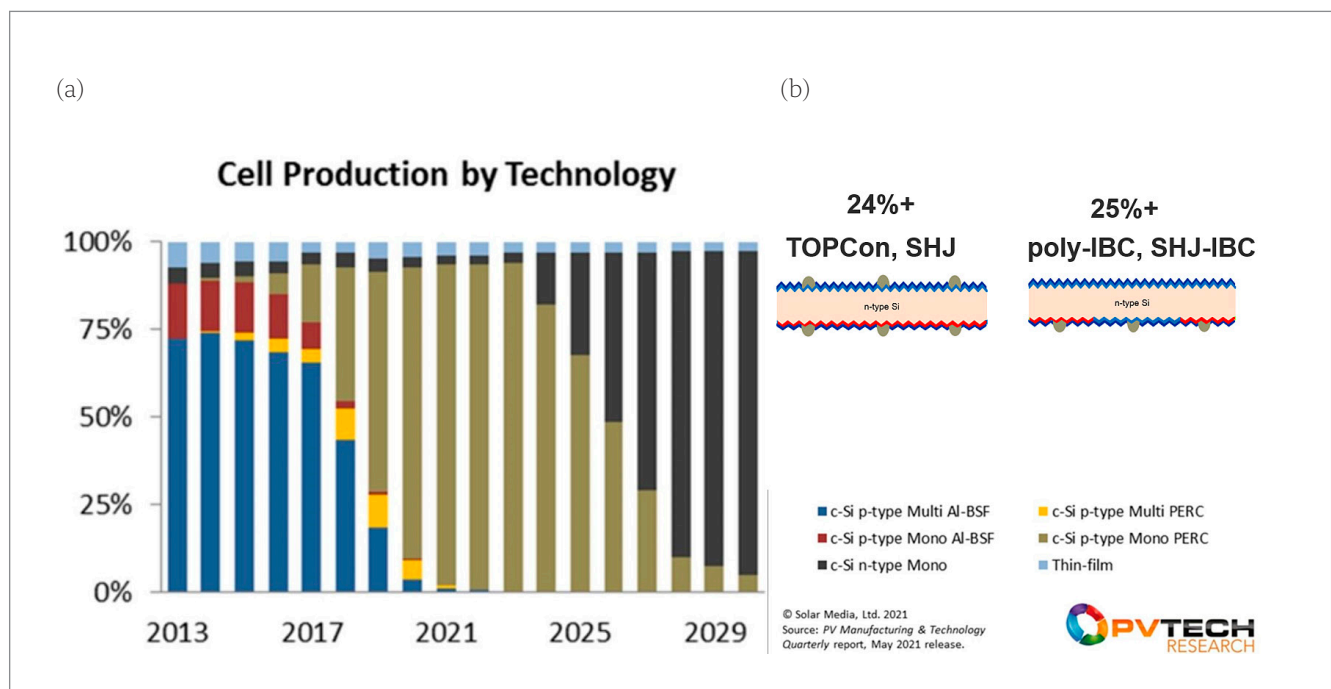

Figure 1. (a) Historical data showing the switch from Al-BSF technology (blue and red bars) to PERC (light brown bars) and forecast of a switch to n-type technology (grey bars) in coming years [3]. (b) Schematic cross sections for TOPCon, HJT and poly-IBC, HJT-IBC.

But what will be the next mainstream technology? Silicon heterojunction technology (HJT)? Tunnel oxide passivated contact (TOPCon)? A combination of both in an interdigitated back contact (IBC) structure? Tandem cells? The race is on and the record cell efficiency announcements are now being published at a steadily increasing frequency. PERC record efficiencies at the cell and module levels are announced by Tier 1 manufacturers with the aim of supporting the claim that this technology still has the potential for significant efficiency increases. The various announcements regarding n-type Si cell technology, on the other hand, are intended to show which of the different options will be the most promising one to choose in the future.

Solar cell improvements in industry

In a very clear and simple representation, Fig. 2(a) depicts a linear yearly growth of cell efficiency in the industry of about $0.6\%_{abs}$, as reported by Martin Hermle [4]. The switch from Al-BSF to PERC was set in motion in 2016, when Al-BSF technology reached its efficiency limit; this was mainly the result of the limited surface passivation of the rear side by the homogeneous Al-BSF, as shown in the cross section in Fig. 2(b).

With a dielectric stack (AlO_x/SiN_x) below the Al paste and Al-BSF point contacts, a better rear-side passivation can be realized, leading to an average

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open-circuit voltage (V_{oc}) of 680mV and a maximum of 690mV. Now, to go beyond 700mV, passivating contacts with poly-Si in TOPCon must be used. To surpass 720mV, passivating contacts need to be used on both polarities, or a-Si layers in HJT technology have to be employed. Then, in the next step, in order to overcome the Auger limit or even the Shockley–Queisser limit, tandem structures are necessary. Accordingly, this linear curve is based on first-order incremental improvements of the voltage by a better passivation with advanced cell structures.

A comparison can be made of these technologies with the various mobile networks and their speeds: 3G (Al-BSF at 665mV) is nowadays virtually obsolete, and the working horse is currently 4G (PERC at 685mV), with 5G (passivating contacts at 700mV) already in place. For most applications (e.g. ground-mounted utility-scale PV systems), however, 4G is still sufficient and the – up until now – more expensive 5G is only required for certain applications. Nevertheless, in a few years' time 5G will be the norm for all applications, and we will even be preparing the ground for 6G (tandem).
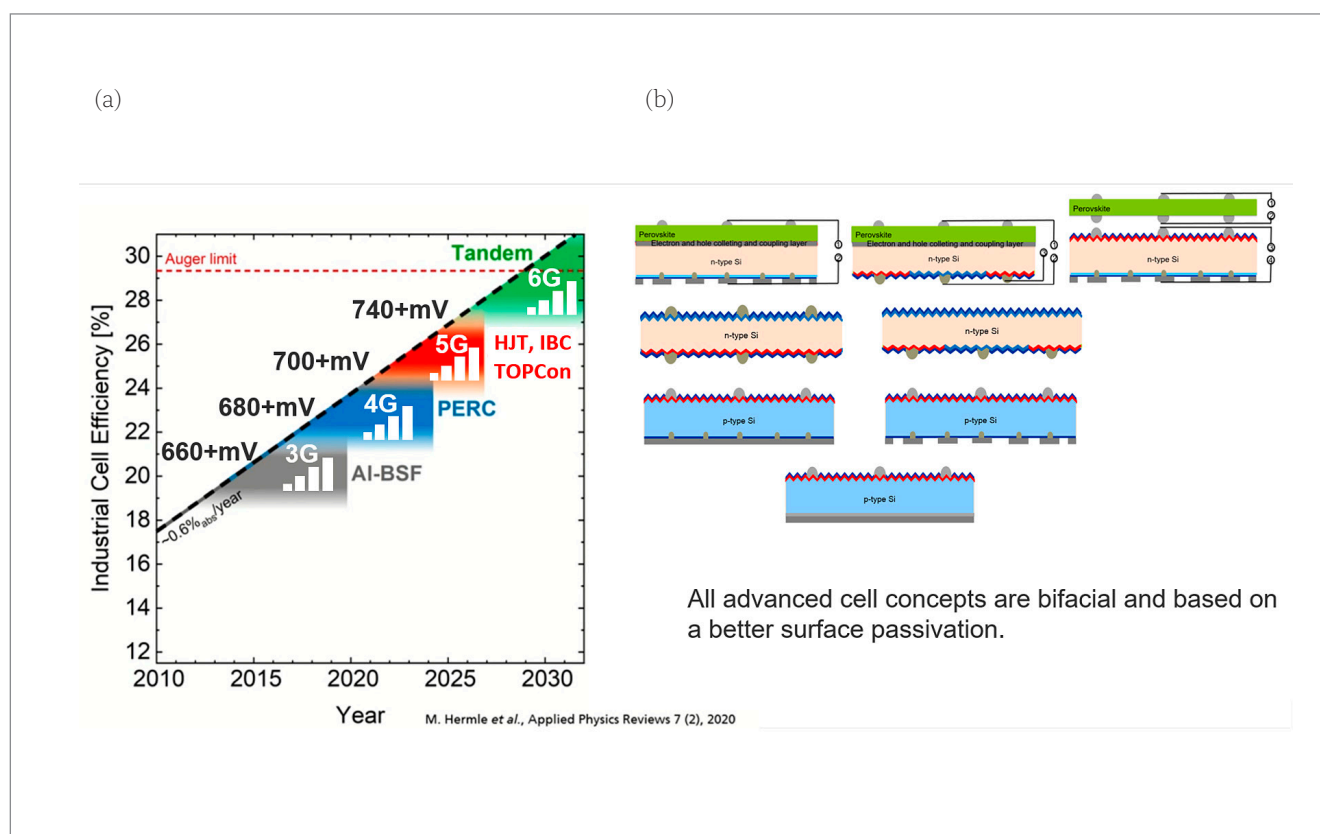

Figure 2. (a) Efficiency (open-circuit voltage) improvements and limits of c-Si technologies in the past, along with future predictions, with an analogy to the 3G–6G mobile networks (graph adapted from Hermle et al. [4]). (b) Schematic cross sections for Al-BSF, mono and bifacial PERC, TOPCon, HJT, IBC and two-, three- and four-terminal tandem configurations.

Considering the various technologies that have been implemented during the last few decades in the PV industry, and which have achieved a mainstream market share, one can reasonably conclude that the PV industry has always followed an evolutionary technology roadmap. On the other hand, the efforts of various players to promote their respective roadmaps (some evolutionary, others rather disruptive) has led in the past to an increasing number of 'industrial' record cell and module efficiency announcements, mostly from Tier 1 manufacturers.

In the following sections, an attempt will be made to further dissect the practices and peculiarities related to the various record efficiency announcements.

"The active area module efficiency is not relevant in the appraisal of the benefits of high module efficiency in terms of savings for area-related balance of system cost."

High-efficiency cell announcements

Most of the time, high-efficiency announcements reveal nothing more than the practical limit of each technology, as depicted in the graph in Fig. 2(a). However, more often than not there is a gap in efficiency of at least $1\%_{abs}$ between what is possible – using additional process steps or non-industrial process steps as well as specific, R&D-like measurement conditions – and what can be implemented in mass production in a cost-effective way. Consequently, there are several elements of such announcements that tend to cause a certain amount of confusion with the public (investors, CEOs, scientists and other stakeholders):

- The nomenclature used for the cell concepts is different from that for the cells actually being announced. For example, the 24.06% PERC cell announced from LONGi in 2019 already had a selective poly-Si on the front side in order to deliver 694mV, while the 25.4% TOPCon from JinkoSolar in 2021 most likely also has poly-Si passivating contacts not only on the rear side but also on the front, leading to a V_{oc} of 720mV.

- Sometimes, even when the announcement of an 'industrial solar cell' makes the headlines, laboratory-type processes, such as double anti-reflective coating (ARC) including MgF_2 deposition by thermal evaporation, have been used in the fabrication of such cells. Many of these processes have been known for decades and used in R&D in order to demonstrate the potential of certain materials or cell concepts; however, they are just too complex and too expensive to be implemented for mass production.

- Even though a reported efficiency has been measured by an independent calibration laboratory or certification body, the I–V measurement will have been performed under conditions that – until recently – have only been used in the field of R&D:
  - ○ Active area efficiency is measured instead of aperture area efficiency (at the cell level as well as at the module level).
  - ○ Cell efficiency measurements are taken with multiwire contacting, and efficiency values reported without taking into account the shading by the metal grid (or at least by the busbars).
  - ○ Contacting methods are used that result in the metal grid series resistance (front or rear side, or both sides) to be neglected, leading to measured fill factors (FFs) that are very close to the pseudo-fill factor (i.e. theoretical limit of FF for zero series resistance and infinite shunt resistance).
  - ○ Such 'R&D-like' efficiency measurement conditions are not suited to properly characterizing industrial solar cells, as they are not representative for the efficiency that can be reached at the module level: at the module level, the shading of the metal grid(s) as well as their series resistance will contribute to reducing the module efficiency, thus increasing the cell-to-module power loss.

- In the case of the reported efficiency values being based on in-house measurements, there is the risk of an overly optimistic calibration, leading to an overestimation of the efficiency.

Very often, in the related press releases, the above-listed peculiarities associated with efficiency measurements are only stated in the fine print and require careful reading in order to allow a correct appraisal of the reported efficiency value.

One recent example of misleading efficiency reporting is the 23.03% record module efficiency, which was – as reported by Trina [5] – an 'aperture efficiency'. While the standard module efficiency is the *total area* efficiency, which is the electrical power output (P_{mpp} at standard test conditions – STC) divided by the irradiance on the total area

divided by the total area of the module (module length multiplied by the module width), the *aperture area* module efficiency excludes the area occupied by bussing ribbons and junction boxes, as well as the mandatory gaps between the outer solar cells and the edge of the laminate in addition to the frame. In consequence, the aperture area efficiency reaches higher values (approaching the cell efficiency) than the total area module efficiency. Accordingly, the active area module efficiency is not relevant in the appraisal of the benefits of high module efficiency in terms of savings for area-related balance of system cost.

A fairly recent example of the R&D-like measurement conditions mentioned above is the surprisingly high FFs measured at certain calibration laboratories. If one reads the fine print, for instance, inserted below the I–V curve measured at ISFH CalTec shown in Fig. 3 [6], the reasons for the extremely high FF (close to the theoretical limit) and the high short-circuit current measured on LONGi's 26.3%-efficient HJT record cell become apparent: while the current benefits from back reflection of light by the gold-coated chuck, the FF is enhanced as a result of a large fraction of the total series resistance of the cell being neglected. In the case of an industrial cell line, however, pins are used to contact the busbars on the front and rear sides of the cells, thereby mimicking the way the cells are interconnected by ribbons within the PV module and without providing any back reflection of light into the rear of the cell.

Table 1 summarizes the record announcements versus reported average efficiencies in production (including a potential overestimation by in-house measurements) and available module efficiencies
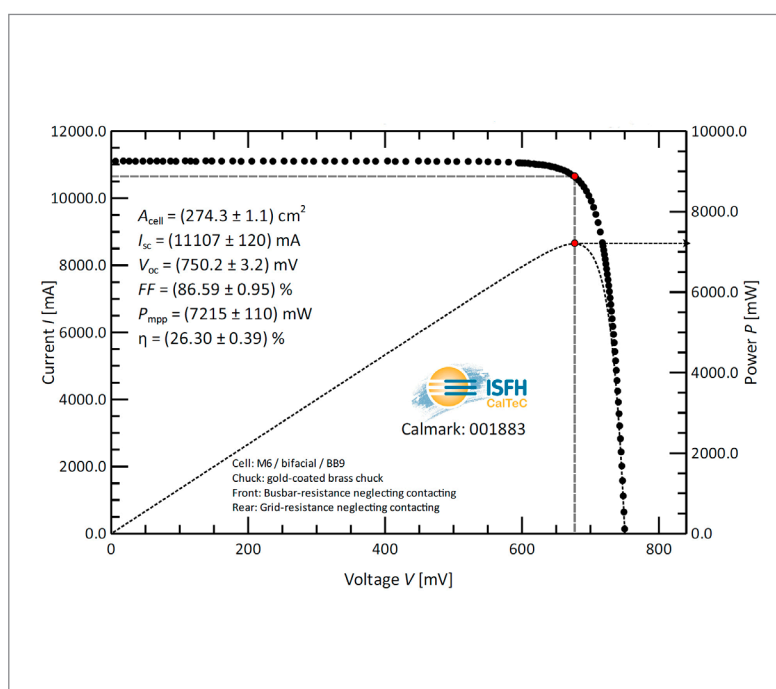

Figure 3. Calibrated I–V measurement at ISFH of the 26.3% highest efficiency HJT cell from LONGi [6].

on the market, as well as the potential voltage and efficiency of the various technologies.

The PV market is witnessing a fade-out of *Al-BSF (3G)*, as it is also monofacial. The average cell efficiencies in production reach up to 20%, with a V_{oc} of around 665mV. A few years back, one of the record efficiencies announced was 20.29% [9], but the module efficiencies on the market are well below 20%.

The king of the energy markets, *bifacial PERC (4G)*, yields average solar cell efficiencies of around 23% in production. PERC module efficiencies on the market are mostly below 21%, but can reach up to 21.1% (e.g Trina [9]). For the 24.06% record PERC cell efficiency already achieved by LONGi in 2019 [10], a selective poly-Si was used on the front; the cell also has other features that have not yet been implemented in industrial production, and which will require in any case additional process steps coming in at a higher cost.

PERC-based technologies – such as TOPCon and PERC-based IBC – benefit from reduced cost as a result of the technological progress in PERC technology as well as the economy of scale for equipment and material thanks to PERC mass production. The major challenge, as in almost all n-type technologies, is to reduce the Ag consumption for the metal contacts, which is currently a very important R&D topic.

TOPCon (5G) cells reach in production an average efficiency of about 23.5%, whereas a record cell efficiency of 25.4% [11] has been recently demonstrated by JinkoSolar. In this case, neither the exact process flow and cell architecture nor the single I–V parameters (I_{sc}, V_{oc}, FF) have been published by Jinko. However, considering that a very high V_{oc} is required in order to reach an efficiency above 25%, it can be assumed that – in addition to other non-industrial features –a selective poly-Si(B) was most likely used, which is more complex than the current industrial TOPCon process and not yet ready for industrial mass production. Depending on the current silver price, the COO (cost of ownership) for a standard TOPCon cell is currently about 15–30% higher than that for PERC (e.g. [17]). But, the higher efficiency, higher bifaciality, lower degradation and lower temperature coefficient for P_{mpp} make these modules already attractive not only for rooftop applications but also for ground-mounted utility-scale solar, as well as for hot regions and on systems with high ground albedo too.

PERC-based IBC (5G) (Jolywood, SPIC, Trina, ValoeCell), with a 25.04% efficiency demonstrated by Trina [12], is commercially produced at average efficiencies of around 24%, having a potential of 25%. At the moment, such cells are mostly suited to rooftop PV applications. With the ongoing reduction of Ag metallization, the bifacial version could also be used on a utility scale in the future.

In the case of *low-cost HJT (5G)* (REC, Meyer Burger, Maxwell), an efficiency of 25.26% was demonstrated by Maxwell [13], whereas *complex HJT (5G)* (Panasonic, Kaneka, LONGi) has reached record efficiencies of 26.3%, as very recently shown by LONGi [17]. *Complex IBC (5G)* devices are produced by SunPower and LG. At the laboratory level, an efficiency of 26.1% has been demonstrated by ISFH on a poly-Si on oxide (POLO) structure [15], and 26.6% by Kaneka using an HJT-IBC structure [16].

Non-industrial cell processes and R&D-type measurements used for 'industrial' record efficiency announcements

Table 2 summarizes a list of ways to modify an industrial solar cell process, or how to measure differently from the standard technique, in order to achieve significantly higher cell efficiencies, but at the expense of industrial feasibility and cost effectiveness.

Summary and outlook

In summary, there are many record cell announcements making the news – even

Technology	Equipment	Record cell efficiency announcements [%]	Reported average cell efficiency in production [%]	Available module efficiency [%]	V_{oc} potential in production [mV]	Efficiency potential in production [%]
Al-BSF	Standard	20.29 [8]	19.5–20.0	<20%	670	20.5
PERC		24.06 [10]	22.5–23.5	20.2–21.1 [9]	685	23.5
TOPCon	Standard PERC based	25.40 [11]	23.0–24.5	21.4 [9]	725	24.5
Low-cost IBC		25.04 [12]	23.5–24.5	21.3 [9]	725	24.5
Low-cost HJT	Thin-film based	25.26 [13]	23.5–24.5	21.9 [9]	735	25.0
Complex HJT	Thin-film and electronic industry based	26.3 [14]	24.5–25.0	21.7 [9]	740	25.5
Complex IBC	Thin-film and electronic industry based	26.1 [15] 26.6 [16]	25.0–25.5	22.0–22.8 [9]	740	26.0

Table 1. High-efficiency announcements (red column) versus the available module efficiency reality (green column) of all relevant c-Si technologies on the PV market (adapted from PV-Tech [6]).

from industrial cell manufacturers – that demonstrate the capabilities of the respective R&D divisions when using their laboratories and advanced pilot lines but which do not allow an apple-to-apple comparison with the respective technologies currently (or close to being) up and running in industry. Accordingly, it is difficult to deduce from such announcements when (and if ever), and at what production cost, the related technologies will be implemented with similar efficiencies in industrial production.

'Trick', 'uncertainty' or gain that cannot be transferred to the module	Absolute efficiency gain [%] compared to mainstream industrial process sequence	Comments
WAFERS		
Use of hand-picked premium material (FZ-Si or very good Cz-Si)	Up to 0.5%	It is possible to use p-type wafers with >5ms (and n-type >10ms) lifetimes, but these are not yet available as commercial material (i.e. they are significantly more expensive).
Pre-gettering or extra hydrogenation of material	Up to 0.5%	Pre-treatment (takes place before the actual cell process) of the as-cut wafers that consists of performing, for example, a $POCl_3$-diffusion with subsequent wet-chemical removal of the P-doped layer containing gettered impurities from the bulk of the wafers.
Use of small-area wafers	Up to 1%	Overcoming inhomogeneities in non-standard processes and/or wafer material quality, reduction of series resistance losses (shorter finger length).
SOLAR CELL PROCESSES		
Very good, laboratory-type cleaning (e.g. RCA)	Up to 0.5%	Extensive (and expensive) cleaning methods not used in the PV industry can be used prior to critical high-temperature processes.
Advanced texture (masking + etching)	Up to 0.5%	Very good and complex texture can be applied to the surface with, for example, masking and wet-chemical treatment.
Long diffusions	Up to 0.3%	Long diffusions not used in production can lead to, for example, better selectivity of the emitter.
High-quality, thick thermal SiO_2 layers for surface passivation or as masking steps	Dependent on cell architecture	Thick thermal SiO_2 layers allow more flexibility regarding the cell architecture when used as a masking layer, and provide perfect surface passivation. Process cost, however, is too high for industrial PV manufacturing (duration and pre-cleaning).
Light blue ARC	Up to 0.4%	The ARC can be adapted to the sun simulator, for example with an increased minimum amount of reflection in UV (in a wavelength range where glass and encapsulants are strongly absorbant, i.e. advantage is lost at the module level).
Double ARC	Up to 0.4%	For example, using laboratory processes, such as thermal evaporation of MgF_2.
No edge isolation	Up to 0.4%	Omitting the edge isolation results in cells that feature a higher efficiency but which cannot be used in commercial modules.
Additional printing steps	Up to 0.4%	Additional printing steps and the use of more metal paste for improving the finger aspect ratio can result in an extremely high *FF*.
Plating, evaporated contacts or other nonstandard techniques	Up to 1%	Alternative complex metallization methods can lead to a boost in all cell *I–V* parameters.
MEASUREMENTS		
'Active area efficiency'	Up to 1%	Calculated efficiency with no grid (fingers and busbars) shading on the front.
'Implied efficiency'	Up to 1.5%	Calculated efficiency with the assumption of no voltage losses and no series resistance losses after metallization (using implied voltage and pseudo-*FF*).
Erroneous in-house measurements	Up to 1.5%	Using incorrect calibration can have an impact on measurement accuracy.
Zero-busbar measurement (*I–V* at STC obtained using GridTouch contacting method)	Up to 0.7%	Only the fingers are printed, reducing the shadowing and V_{oc} losses from absent busbars. Gain compared to five-BB scheme can be up to 0.7%, but even assuming a multiwire interconnection at the module level, only a part of the efficiency gain can be transferred to the module.
Non-standard contacting of cells that neglects series resistance	0.5% to 1.5%	Even measurements within CalLabs can differ, mainly because of the contacting scheme used.

Table 2. Overview of non-industrial process steps and R&D-type efficiency measurements that can be used in order to fabricate record cells (updated version of the list included in the PV-Tech blog [7].

"There are many record cell announcements which do not allow an apple-to-apple comparison with the respective technologies currently up and running in industry."

That said, record cell efficiencies allow a glimpse of what the mid-term future might bring. Ultimately, if one has the scope for determining for a given cell technology the highest cell efficiency currently available in commercial production, the most practical and reliable way is to look for the respective module with the highest P_{mpp} at STC (for a given module area) that is commercially available, and – taking account of the total cell area as well as a realistic cell-to-module P_{mpp} ratio – to ascertain the related cell efficiencies.

The c-Si PV industry has always had, and will have in the future, an evolutionary development, with year-on-year increases in efficiency of 0.3–0.6%$_{abs}$. This will still be the case in the next ten years, until the practical efficiency limit of 26–27% is reached. What will happen after that is still unclear. The success of tandem solar cell devices will very much depend on the successful development of perovskites and corresponding tandem architectures with regard to stability, reverse behaviour, etc.

The average efficiencies of industrial PERC solar cells will remain between 22.5% and 23.5%, whereas the average efficiencies of industrial n-type devices will be well above 24% in one to two years, and surpass 25% in three to five years. Available PERC modules will yield efficiencies of around 21%, whereas n-type module efficiencies will exceed 22% from 2022 onwards, and most likely 23% from 2025 onwards. What will happen after c-Si hits its practical efficiency limit of 26–27% remains uncertain.

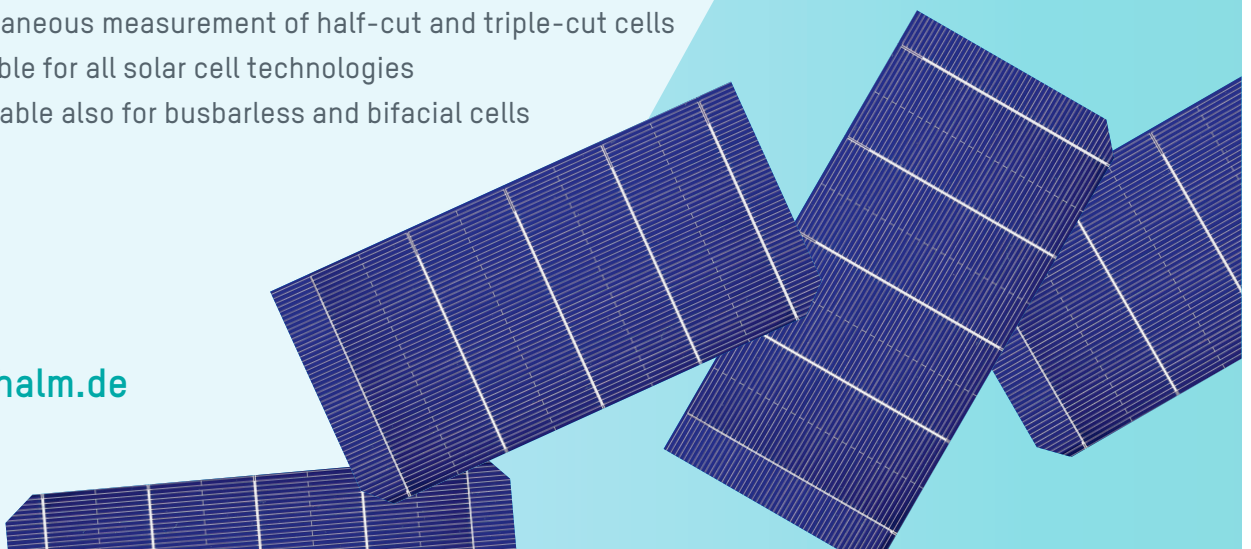..

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