State-of-the-art bifacial module technology

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Abstract

Bifacial PV promises a significant reduction in the levelized cost of electricity (LCOE) for PV systems, which, compared with efficiency improvements at the cell level, is still achievable with comparatively moderate effort. Almost all major PV module suppliers have bifacial modules in their product portfolios or have announced production. This paper gives an overview of the currently available bifacial modules and cell technologies and the performance of these modules. Special attention is given to the cells and the layout of the modules, including light trapping and interconnection technologies, the encapsulation materials and the adapted mounting solutions. Finally, an outlook is given on the basis of the compiled information.

Introduction

Bifacial solar cells go as far back as the 60s [1–3] and were first used in satellites [4–6] and for niche applications, such as sound barriers [7], and for shading elements [8]. The production volume remained low at the semi-industrial fabrication level [4,9], but has increased with the introduction of the Sanyo HIT Double and later the Panda [10] and EarthOn [11] modules from Yingli and PVGS. Since about 2012, interest in bifacial PV has been constantly increasing, which is reflected by the installed capacity [12], the number of available products [13] and the number of publications. As a result of technical progress, such as improved bifacial cell concepts and the availability of thin solar glass, this technology has become increasingly attractive. Furthermore, some of the new solar cell technologies, which are currently being implemented in industrial production, allow a comparatively simple adaptation to a bifacial layout. The general trend towards glass/glass modules with superior reliability, as well as the interest in 'peak shaving' and customized solutions for specific applications, further supports the development path towards bifacial technology.

In spite of the advantages, the installed capacity of bifacial systems is still small compared with monofacial mainstream systems. A major issue is the uncertainty regarding the additional 'bifacial' yield, which is due to the more complicated irradiation conditions and the power rating of bifacial modules.

It is still common to regard bifaciality as an add-on and to base the power rating/pricing on the front-side measurement under standard test conditions (STC). The effect of this is that embedding bifacial solar cells in a monofacial module structure with a reflective backsheet may allow a higher price on the market than if they were embedded in a real bifacial module version [14,15]. This is also a reasonable procedure if the cell type used is bifacial, but the modules are mounted in locations with unattractive albedos, such as shingled roofs. Panasonic offers specific modules [16] to exploit the advantages of their bifacial HIT cell technology in 'non-bifacial' modules.

While it is comparatively simple to define standardized indoor measurement conditions for a monofacial module, the measurement of a bifacial module must also include the power generated by the rear side. Standardized measurement conditions for bifacial modules are still under discussion but close to finalization [17,18].

Even if a standardized indoor measurement procedure for bifacial modules is defined, the actual yield of a bifacial PV field will always be extremely dependent on the installation conditions. For free-standing bifacial modules, the optimum orientation is a trade-off between the front- and rear-side outputs, and the efficiency is dependent on factors such as the ground reflectance, tilt angle and installation height. In extended arrays, additional factors, such as direct shading and reduced ground albedo due to adjacent rows, have to be considered. Because of the sensitivity to multiple additional factors, compared with monofacial standard installations, an accurate prediction of the yield of a bifacial PV array is, by far, more complicated. At present there are still only limited simulation tools available for bifacial arrays; however, the number of software suppliers is increasing [19–21], and there is considerable effort being devoted to improving the models and to appraising the prediction reliability [22,23].

While the improvements with regard to the simulation and measurement are important, the increasing installed capacity [12] will in itself promote the future growth of this technology. The estimates concerning the bifacial market share for the coming years vary but are most promising (Fig.

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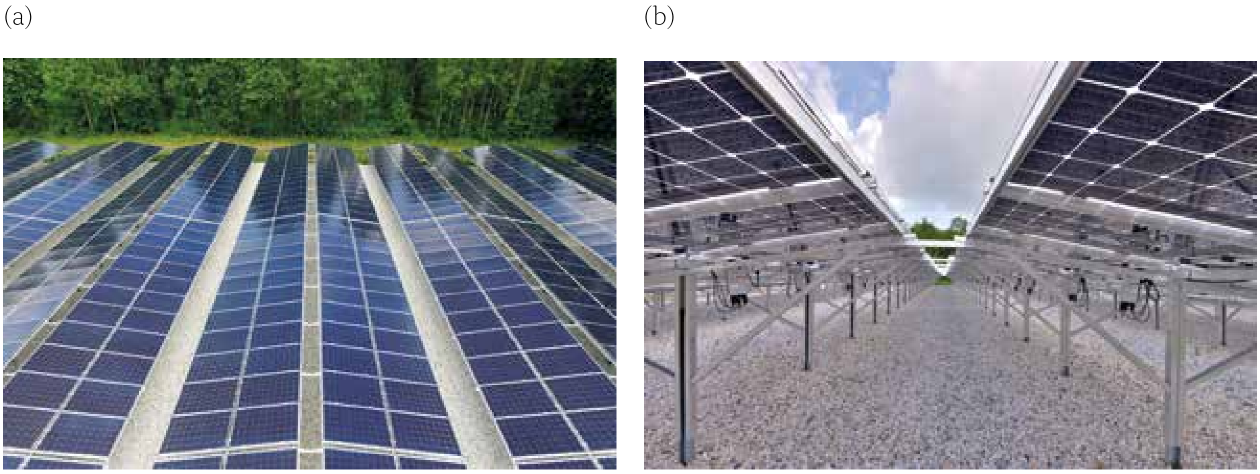

Figure 1. A bifacial 400kWp system from Tempress with an east–west orientation [26], which is indicative of the expected significant rise in the market share of bifacial PV: (a) view from above, and (b) view of the rear of the bifacial modules. The white gravel results in an albedo of 40%. (Source: Tempress, Amtech Group.)

1); indeed, starting from today's 3% bifacial market share the ITRPV roadmap 2017 predicts an increase to around 30% by 2027 [24], while Bloomberg even anticipates 40% by as early as 2025 [25]. Accordingly, more and more adapted components for bifacial technology will become available. In addition, the bifacial module design, which is still very similar to the standard monofacial one, may reflect specific conditions, such as increased currents or more inhomogeneous irradiation uniformity. This paper presents a comprehensive overview of the state-of-the-art technology for bifacial PV modules and of the potential trends concerning future developments.

Solar cells

Bifacial solar cells were first proposed in the 1960s [1]. Even though cells of various types were produced on a very limited scale to cover the demand (e.g. for satellite applications [6,9]), such cells were not produced in large volumes. The industrial production of bifacial cells began in 2007 with Sanyo implementing an open Ag grid for their proprietary HIT cell technology [27]. Yingli Green Energy was the first company to launch an n-PERT (passivated emitter, rear totally diffused) cell [28] in 2010; this was followed about four years later by announcements of the industrial production of bifacial p-PERC (passivated emitter and rear cell) cells and modules [29,30] by companies such as SolarWorld and NSP/ET Solar. Since then the interest in bifacial systems has been on the increase, with reports of many different technical solutions; these differ in detail but can be assigned to a limited number of technologies, which will be discussed below (HJT, PERC, PERT, IBC). More detailed comparative information concerning the technologies can be found elsewhere in the literature [2,31–33]. The technologies in question are predominantly linked to a preferred type of wafer doping: PERC is mostly related to p-type wafers, while heterojunction technology (HJT) and the PERT concept are typically linked to n-type wafer material.

Cells based on HJT were the first commercially produced bifacial solar cells. On the front and rear sides of such cells, a material other than c-Si (amorphous silicon) is deposited in order to passivate the surface and to form a second p-n junction. After Sanyo's patent on this technology expired in 2010, several module manufacturers and equipment suppliers offered comparable products based on HJT, with some differences in the processes, often using their own naming conventions, such as HCT technology from Sunpreme [34].

Today, among other companies, Panasonic, Hevel [35], 3Sun [36], Hanergy and Jinergy [37] are producing, or ramping up their production of, silicon heterojunction cells. Manufacturers, institutes (such as CSEM [38] and CEA INES [39]) and equipment providers (such as Meyer Burger [40]) are constantly working on improvements to increase efficiency and obtain more cost-effective processes. HJT cells achieve superior efficiencies of up to 23.4% on a pilot scale [39], with high bifaciality (> 0.95) as well. While the technology is attractive in many regards, cell fabrication is very different from that of homojunction c-Si cells. Existing cell manufacturers cannot therefore simply adapt the technology in an evolutionary process, like an upgrade. Nevertheless, some companies, such as Jinergy, which are already producing PERC cells have also announced the fabrication of HJT cells [37]. It is also an option for some companies to start up production, such as Sunpreme [34,41], and in particular it offers opportunities for companies which have a background in thin-film deposition, such as Hanergy [42] and 3Sun [36].

In contrast to HJT technology, the well-known

PERC concept has been (or currently is being) implemented by many mainstream p-type c-Si cell producers (p-PERC) in terms of an upgrade. Basically, the former standard Al-BSF (back surface field) type of cell is changed in such a way that the full-area rear-side aluminium layer is replaced by a passivating layer and the rear-side metallization process is correspondingly adapted. To obtain a bifacial PERC cell, which is often termed *PERC+* [43], the rear-side metallization is realized by a grid, as on the front side. SolarWorld started to produce bifacial modules in 2015 [44]. Today, the PERC+ concept is mainly implemented by Chinese and Taiwanese tier one manufacturers, such as Longi [45,46], Trina [47,48], JA Solar [49,50], NSP [51,52], EGing [53] and Jinko [54]. Because of degradation issues on multicrystalline (mc) material [55], however, all the above-mentioned PERC+ concepts are realized on p-type Cz wafers. At the PV Cell Tech conference, Canadian Solar announced it was switching all its P4 mc PERC cell production to PERC+ in 2018 [47].

A disadvantage of bifacial PERC is the comparatively low bifaciality, although Longi recently announced a significant improvement [46], with a bifaciality factor of 0.82% (at the R&D level) and reports of front efficiencies of 21.2% and higher in production. Because of the large PERC production capacity installed worldwide, the growing interest in bifacial technology, and the comparatively easy implementation of PERC+ in an existing PERC line, it is not surprising that bifacial PERC modules are increasingly becoming available.

A higher bifaciality factor is made possible by PERT technology [4], which is in principle quite similar to PERC technology. The 'T' in PERT stands for 'totally diffused' and indicates that the doping and passivation layers on both sides of the wafers are applied by diffusion. PERT is suitable for p- and n-type wafers (p-PERT; n-PERT) and also applicable to mc wafer material, as demonstrated by RCT Solutions and Shanxi Lu'An [56]. The technology has the potential for higher efficiencies than those possible with PERC, but is more complex and based on more expensive components (boron deposition, n-type wafers, silver paste consumption, etc.). In the case of p-type wafers, the rear side is exposed to boron diffusion instead of the deposition of an aluminium oxide layer in the PERC process. It should be pointed out that p-PERT has a very low market share. It has to be mentioned, though, that p-PERT was already used in the first bifacial cells for the Russian space programme; additionally, PERT is also still subject to recent research [4]. Examples of technology providers for p-PERT are RCT Solutions [57] and Schmid [58].

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The implementation of n-PERT technology is more common than p-PERT, with PERT being the standard technology on n-type wafers. Since both n-type and bifacial technology have increasingly attracted interest in the PV community, it is not surprising that numerous bifacial n-PERT processes and module types are on offer today [32], aiming at cost-effective solutions. A description of all the different processes would be beyond the scope of this paper, but suffice it to say that the aim of several processes is to introduce simplifications in order to make them more cost-effective.

All of the major suppliers of diffusion furnaces – centrotherm, Tempress, Schmid and others – offer process technology and adapted equipment. Some processes also use quite different process equipment: the diffusion process, for example, can be replaced by ion implantation [32] (Yingli [59], Jolywood [60]).

Bifacial n-PERT modules are offered, for instance, by Yingli [61–63], Jolywood [60,64], LG [65,66], Prism Solar [67], HT-SAAE [68], Linyang [69], Trina [70], Adani [71], REC [72], Jinko [73,74] and Valoe [75], with some of those mentioned being in the launch phase.

Table 1. Bifacial solar cells, main parameters and manufacturers (some products in the launch phase).

Cell concept	Bifaciality factor	Si base material	Junction and BSF doping method	Contacts	(Front) Efficiency potential	Industry
Heterojunction	>0.95	n-mono	a-Si:H p- and n-type doped	TCO / Ag TCO / Cu plated	22–25%	3Sun, Hanergy, Hevel, Jinergy, Panasonic, Sunpreme, etc.
PERT	>0.90	n-mono p-mono p-multi	B and P tube diffusion n-doped poly-Si rear side possible	Ag and Ag/ Al printed	21–23%	Adani, Jinko, Jolywood, LG, Linyang, REC, Trina, Yingli, etc.
PERC+	>70%	p-mono p- multi n-mono	B and P tube diffusion, local Al BSF	Ag and Al printed	21–23%	Eging, JA Solar, Jinko, Longi, NSP, SolarWorld, Trina, etc.
IBC	>70%	n-mono	B and P tube diffusion APCVD doped oxides	Ag and Ag/ Al printed	22–25%	Valoe

The highest lab efficiency reported so far is 22.8%, achieved by imec [38] and featuring a bifacial factor of 97% [39]. In future, the introduction of passivated contacts [60] with high-temperature firing through metallization might increase the efficiency level of industrial n-type-based solar cells to a value of 23% or higher [76].

Bifacial IBC cells are another promising option to obtain high-efficiency solar cells. 'IBC' stands for *interdigitated back contact*, which means that the contacts are solely on the rear side of the solar cell; this approach requires other fabrication procedures, while the core process equipment of n-PERT may also be used for IBC [77]. Bifacial IBC is still in its infancy, but corresponding modules have already been fabricated [78] and are even on the verge of entering industrial production [75].

Table 1 lists the most common bifacial cell architectures, including the main technological features.

Cell interconnection

The key requirement for interconnecting bifacial solar cells in terms of an optimized power output is the application of a module interconnection technique with the lowest ohmic losses. This is essential because bifacial modules experience far higher current generation because of the rear-side contribution which is added directly to the front generation. The above requirement becomes even more important in locations with increased albedo, for cells with higher bifaciality factor or for larger output currents in general (e.g. tracked modules). While most commercial PV modules based on commercially available bifacial solar cells currently utilize all the same 'standard' soldering interconnection technology, alternative technologies exist with greater benefits in terms of quality and reduced ohmic losses. Nowadays, the interconnection standard still relies mainly on an H-pattern metal grid on the front and rear sides of the cells, as applied to the very first cells decades ago. So-called *conductive fingers* collect the silicon-bulk-generated photocurrent and transfer the current to busbars (BBs), thereby creating the H pattern of the metallization. Coated (usually containing Sn and Pb) Cu ribbons are soldered to the busbars; this way a serial interconnection between the front of one solar cell and the rear of the adjacent cell is formed and so on, typically creating a string of up to 10 or 12 series-connected cells. Soldering is a mainstream interconnection technique in electronics but not necessarily the favoured process for novel high-efficiency solar cells. The applied temperature of up to 250°C jeopardizes the cells' mechanical integrity and is not suitable for all metallization schemes and materials. In addition, the resistive losses in the cell–cell interconnections usually dominate all other resistive losses in a solar panel compared with a bare solar cell.

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Solar module concepts are rare and only a few have been developed over the last 12 years to specifically pass the required IEC and UL certification standards to enter the mass-production process. Several hurdles have to be overcome for any new technology in order to finally prove its superiority over soldering, which is such a simple technology that has remained virtually unchanged over the years. The easiest way to reduce ohmic losses is to instead make modifications at the cell level, specifically by increasing the number of busbars. For more than 10 years, the standard number of busbars has been three, but there are now solar cells available with four, five or six busbars. By adding more busbars, the effective transfer length for charge carriers in the emitter is significantly reduced, with the additional benefit of redundancy in case of cracks or similar flaws. The interconnection still typically relies on soldering but causes less damage to the mechanical integrity because of the much-reduced ribbon thickness. Beside this, the modifications required for mass-production equipment, such as stringers and cell flashers, are relatively minor. Ohmic losses are reduced for each busbar added, but the positive effect in terms of series resistance reduction gradually gets smaller and smaller. An optimum is typically reached somewhere between five and six busbars in terms of technological, process and financial aspects, also for bifacial cells, with 10–30% higher output current. A logical continuation of this approach would be to further reduce the diameter of the ribbon, now referred to as *connecting wire*, as the number of wires increases significantly, to far more than 10. Two mass-production techniques based on this principle are the multi-busbar technique from Schmid [79], employing typically 12 wires with a core diameter of 360μm, and the Day4Energy [80] interconnection scheme, in which 36 wires of 150μm diameter are used. The latter method was purchased and further developed by Meyer Burger and is now called *SmartWire Technology* [81]. Both technologies allow the omission of cell busbars completely, thereby significantly reducing the number of cell metallizations, emitter recombination and direct light shading. Because of the very small nature of the series resistance in both technologies, the merits for interconnecting bifacial cells are evident. In addition, because of the unique solder coating in the Day4Energy concept, the cell aluminium layer can be contacted directly, paving the way for interconnecting cells with modified metallization layouts and materials.

Cell concept	5BB	5BB HC	Conductive BS	Multi-busbar	Day4Energy / SmartWire	NICE	Shingled
PERC, PERT	+	++	In comb. with MWT	++	++	Combined with 5BB /HC ++	++
HJT	o	o	In comb. with MWT or IBC	o	++	++	++
IBC (Zebra, Mercury,...)	(√)	(√)	++ (bifacial?)	(√)	(√)	(√)	-

o = suitable, + good fit, ++ special advantages, (√) suitable, but adaptations necessary (isolating layers...)

Table 2. Ratings of interconnection technologies suited to bifacial modules.

Ohmic losses can be attributed to two sources: the series resistance, as established by the above-mentioned three technologies, and the cell current. Reduction of the latter is addressed by a module concept based on half cells [82] or by the so-called *shingling technology* [83]. Both of these concepts are very well suited to interconnecting bifacial solar cells: the standard soldering technique is used for half cells, whereas typically electrically conductive adhesive (ECA) or solder paste is applied for shingling. Half cells require only minor modifications to the cell and module process; however, shingling technology can really be regarded as a different (though not necessarily novel) approach, which is based on a different module process with significant modifications at the cell level. Although the origin of the shingling approach goes back decades, it had never been used in mass production until just recently, when its implementation was driven mainly by the need to interconnect cells with the highest output currents and the lowest ohmic losses. In fact, fill factor values at the module level exceeding 80% can be achieved, demonstrating the benefits of shingling technology [84]. Besides this, the necessity of applying an ECA also allows cell interconnection concepts which are not suitable for soldering, for example because they cannot withstand the high soldering temperatures. Currently, bifacial modules with shingled cells are also being tested at the R&D level [84,85], and the first bifacial products have even already been launched [45]. The use of conductive adhesives in combination with a structured ribbon for HJT cells was announced by Teamtechnik [86].

A technology for simplifying the interconnection and for reducing the mechanical load at the cell edges is the *flip-flop* design of bifacial solar cells [87], in which the p and n sides are respectively alternated for adjacent cells in a string. This is only possible with reasonable mismatch losses if the cells with p and n sides have a very similar power rating, which means a high bifaciality factor.

An alternative solar cell interconnection approach is the *conductive backsheet* method, invented by Eurotron and ECN [88]; this concept is based on a PCB (printed circuit board) design, typically used in electronics. All the contacts are formed inside the copper layer, which itself is integrated into the backsheet; the solar cells are interconnected on the conductive backsheet layer by either ECAs or soldering pastes. The conductive backsheet technology overcomes cell bowing issues and is therefore a perfect match for interconnecting rear-contact solar cells. The electrical polarities of the solar cell are separated by isolating trenches which form continuous circuit tracks to establish the current transport. Usually this technology results in monofacial modules; however, if a large part of the conductive backsheet layer is removed, thereby creating conductive circuit tracks with a well-defined aspect ratio, a ribbon-like interconnection can be created, allowing bifacial operation.

Finally, the NICE module concept from Apollon [89] can be mentioned as one technology that is very well suited to the interconnection of bifacial solar cells for several technological reasons. Cell interconnection is based on a pressure contact rather than soldering, allowing the use of a greater amount of ribbon to interconnect the solar cells without the detrimental effects of the soldering process. Furthermore, NICE technology is by nature a glass/glass technology, which makes it perfectly suited to bifacial application. Table 2 shows a rating for the discussed module technologies, and indicates how well the specific module technology is matched with the various bifacial solar cell types available on the market.

The light-trapping properties of the cell interconnection are discussed in a later section dedicated to optical confinement and light management.

Encapsulants

A state-of-the-art solar module contains various components, all designed and developed with specific functions for increasing longevity and for optimizing the potential to harness sunlight and convert it into electricity. The key to longevity of solar modules is the selection of the right material, which is indeed even more important for bifacial products. One of the key materials is the

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encapsulation film, which protects the solar cell and guarantees reliability and performance by protecting it against water vapour and aggressive chemical substances, as well as partly against mechanical shock and other disturbances. Its role is to provide the highest possible optical transmissivity, hinder moisture from entering the module interior, deliver a very high and durable adhesion to the adjacent materials, and guarantee a capacity to withstand high voltage.

The material of choice for many decades has been ethylene vinyl acetate (EVA), which now comes with a long track record of almost 40 years in terms of field experience and successive developments. Even today, EVA is still the most commonly used solar module encapsulation material, and dozens of experienced suppliers exist worldwide. On the negative side, three disadvantages can be listed for EVA: 1) the relatively high UV cut-off wavelength; 2) the high moisture vapour transmission rate; and 3) the materials added to improve EVA's crosslinking and adhesion properties, which generate free radicals (such as acetic acid), contributing to physical deterioration and degradation of the material properties [90]. Typical field failures here can be corrosion, yellowing or discoloration.

With all its advantages for bifacial solar modules, glass is currently the best choice for the front- and rear-side superstrates [91]. No other material delivers the same mechanical stability, transmission rate and water transmission rate of practically zero. The last of these properties also means that free radicals stemming from the encapsulation material are trapped inside the module interior, and can only be released in the limited regions of the module edges [92]. Acetic acid – in combination with photons of higher energy (meaning those in the lower visible light spectrum), heat and the time factor – acts in a deteriorative way on the module materials and can significantly reduce the module lifetime. This is particularly true for bifacial modules, given the higher operating temperature because of the significantly increased irradiation levels to which the materials are exposed. Alternatively, transparent backsheet materials can be combined with front glass, thus eliminating the above-mentioned risks but also resulting in a much-reduced mechanical strength compared with glass.

Decreasing the module temperature to a minimum is key to reducing the chemical reaction rate inside the encapsulation film [93]. For a typical glass/glass bifacial solar panel, the main chemical reaction is related to a degradation of the chemical stability of the encapsulation film, which will result in delamination or discoloration over time. Besides degradation, corrosion is aggravated by increased temperatures: the coated copper ribbon and the solar cell metallization can both suffer corrosion. The water ingress rate is significantly reduced in the case of glass/glass bifacial modules, and is therefore one of the promoting factors for degradation and corrosion that is taken out of the equation. As long as chemical by-products exist inside the encapsulation film, however, any degradation will inevitably occur over time. Therefore, there has been (and still is) an urgent need to develop new encapsulation materials.

Nowadays, various encapsulation materials – besides standard EVA – are available on the market: new EVA material developments with a lower UV cut-off (320nm), polyolefin (POE), thermoplastic polyurethane (TPU), polyvinyl butyral (PVB) and silicone-based products. Each of these materials has its advantages, and in all cases unfortunately also inevitable disadvantages, even if these (in some cases) are only related to the pricing. In terms of energy production, most of the various encapsulation materials with UV cut-off wavelengths of approximately 320nm will perform alike. Since the degradation effects of the encapsulation material are more pronounced and accelerated in bifacial modules, leading to an early material degeneration and hence a loss in transmissivity, the choice of the best materials is key to longevity. This means that module manufacturers must carefully evaluate the encapsulation material for overall long-term durability.

Junction box

The junction box electrically connects the embedded solar cells within the module with the outside world; it houses the bypass diodes and protects them, as well as the sensitive interconnections, from the environment. Overheating of bypass diodes or increased contact resistances of the clamped or soldered interconnections, caused (for example) by corrosion or faulty clamping, may lead to hazardous situations. Such defects pose a real threat and, as repeatedly reported, have caused considerable economic damage to manufacturers [94–96] and are a long-term burden [97,98]. The junction box is therefore a crucial part of the module with regard to reliability and safety.

On monofacial modules, the junction box can be placed on the module rear side without causing a detrimental shading effect. Accordingly, the size of the box is not a relevant factor, allowing sufficient volume for a thorough interconnection and enabling options which permit sufficient heat transfer, such as potting. For bifacial solar modules, however, this is obviously not the case, since any shading of the light-sensitive sections on the rear side should be avoided. Because an increase in the module dimension is also undesirable, the junction box has to be reduced in size and should preferably be placed on the rim of the module. At the same time, smaller junction boxes need to handle high currents because of the extra current generated by the module rear side; moreover, the heat generated by the bypass current has to be taken into consideration.

Because of the risks described above, it is not surprising that, in spite of the considerable rear-side shading, numerous manufacturers of bifacial modules have relied, or still rely, on conventional junction box types. Another factor favouring the use of conventional junction box types is the lower cost associated with standard components.

There are, however, also junction boxes available (or in development) which are explicitly designated for use on bifacial modules by TE Connectivity [99], Stäubli/multicontact [100,101], Leoni [102], Changzhou Almaden [103] and Amphenol [104]. These junction boxes are far smaller and are placed at the edge of the laminate [100] or at the rim of the laminate rear surface [102–104]; some are appropriate for both placements [99]. Typically, these boxes also address the market of glass/glass modules in general, which is not limited to bifacial devices, because a low visibility of the junction box is desirable for this module type.

Positioning the junction box at the edge of the module is an attractive option, because the laborious handling of the cross-connectors and the related opening of the rear-side cover are avoided and the non-productive glass area is minimized. On the other hand, this type of fixture may be more vulnerable to mechanical damage or to moisture ingress as a result of the more irregularly formed and smaller contact surface.

Another option for bifacial modules is the use of multiple junction boxes, which are generally smaller in size than the typical standard devices. While two of the already mentioned boxes for bifacial modules are of this type [99,103], there are numerous other examples which may also be suitable for bifacial modules, provided that the electrical parameters are within the specified range [105,106]. The decentralized design enables a simpler layout of the cross-connectors and attracts related material savings; it should also result in lower series resistance and improved heat transfer. Triple-pole junction boxes are used in several bifacial modules from, for example, Yingli [107], Ningbo [108], Trina [109], JA Solar [49], Jolywood [110] and Meyer Burger [111], among others. It must be mentioned, however, that the rear-side glass needs to have additional feedthroughs.

Multiple-pole junction boxes are also found on bifacial modules which are based on the half-cell approach and on the innovative interconnection scheme as presented by REC [112] in the form of a split module concept. In these cases, the splitting of the junction box into several units is adapted to the new layout; the same concept is also realized in similar modules incorporating monofacial solar cells. The half-cell approach is interesting for bifacial modules [62,113] because the impact of the increased additional current from the rear side is reduced. Such new module architectures with combined parallel and serial electrical layouts may also be a means of addressing inhomogeneous irradiation effects. With regard to the irradiation inhomogeneity, the use of integrated optimizers is also of interest for bifacial applications and has reportedly been implemented [114]. Furthermore, other developments – such as the replacement of bypass diodes by active elements [101] – may be particularly useful for bifacial modules in coping with the higher current rating of these types of module.

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Optical confinement/light management

In monofacial modules, an optimized absorption of light in the cell is typically realized by using a front glass, covered with an anti-reflection coating (ARC), an encapsulant with a refractive index close to that of glass, and a highly reflective backsheet.

In the case of a bifacial module structure, the rear side needs to be transparent in order to utilize the irradiation which is usually reflected from the ground (albedo). It should be mentioned, however, that white, full-area backsheets are also used in modules with bifacial solar cells. This can be advantageous when the pricing is based on STC measurement results alone, or if the modules are intended for use in locations with low albedo. For these measurement conditions, the contribution of the bifacial module rear side due to the albedo in real installations is not taken into account. With a white, full-area backsheet, light passing through the bifacial cells or the spacing between the cells is reflected by the backsheet, and also utilized to a certain extent [14,15,115]. The specific gains and losses are dependent on the cell spacing, the spectral properties of the solar cell, and the reflectivity of the backsheet. Panasonic [16] offers modules which utilize this effect, and Dunmore [116] promotes a highly reflective backsheet particularly for this purpose. Related concepts are the structuring of the backsheet or the application of IR-reflecting coatings on the rear side [14]. Even though these measures are applied to transparent module structures to utilize the albedo, they also aim to use the reflected light from the rear side.

Light passing through the spaces between the cells of the module area contributes, after reflection from the ground, to the rear-side illumination only to a small extent. Several approaches have been proposed for reducing these power losses. One way that is effective is the use of white reflecting foil stripes in the areas between the cells [115,117]; this has now been rolled out as a commercial product (or it has been announced that it will be marketed), for example by SolarWorld [118] and Trina. These highly reflective stripes are advantageous compared with the transmission of light through the cell spacing and subsequent reflection on the ground described earlier, while leaving the electrically active rear side of the bifacial solar cells open.

Another approach aims at increasing the portion of collected light on the rear side by using a specially designed light-trapping foil (LTF) on the back of the module [119]. This specific light-trapping layer for bifacial modules was designed by the manufacturer DSM to fulfil two functions: 1) to enhance the back reflection of light coming from the front side towards the cells; and 2) to reduce the reflection of diffuse reflected light from the ground. The LTF has not yet been launched as a commercial product.

Other efforts to increase the light management are the use of structured ribbons or light-directing films which are positioned on top of the soldered ribbons, as offered, for example, by Ulbrich [120,121] and 3M [122]. The use of conductive adhesives in combination with a structured ribbon for HJT cells was announced by Teamtechnik [86]. In addition, multiwire approaches, such as the SWCT smart-wire technology from Meyer Burger, promote light-trapping properties [123].

Several years ago, the company Prism Solar developed an interesting module concept [124,125]. In this layout, a wide spacing between the cells results in a module area coverage by solar cells of around 50%. An optical film called *holographic planar concentrator (HPC)* is embedded between the solar cells; this layer guides the incoming light via total internal reflection at the glass–air interface to the strings of solar cells, resulting in a concentration of energy per unit area of PV material. This low-concentration design is especially suited to a bifacial module structure. Other low-concentration concepts have been proposed but have not yet been integrated into the module structure [126–130].

Modules

As with monofacial modules, a common attribute of bifacial modules is the cell technology used; often the module names do not directly refer to the underlying technology, such as n-PERT, HJT or p-PERC+, but are instead chosen by the manufacturer for their specific process. As shown in the solar cell section of this paper, there is a wide range of different technologies that allow a differentiation of cell types. Apart from the cell technology, the layout of bifacial modules is still quite homogeneous.

Aside from some products which use bifacial cells in a monofacial module with a white reflective backsheet (as offered, for example, by Panasonic [16]), the rear side of a bifacial module has to be transparent in at least in one direction. In addition, modules which partly utilize internal reflection, by covering the cell spacing with a white reflective material [115], have a transparent rear side, as implemented in some commercial modules (e.g. SolarWorld [118], Trina or Linyang). For details of both of these approaches, see also the internal reflection section of this paper.

To obtain a transparent rear side, there are two options available on the market: laminates with a transparent backsheet or a glass/glass layout. By far, most of the suppliers choose a double glass design, which promises better reliability and is also being increasingly used for monofacial modules; on the other hand, some very large bifacial manufacturers, such as LG and Jolywood (which is also a leading producer of backsheets), offer transparent backsheet modules. (Jolywood offers bifacial modules with glass/glass and glass/transparent backsheet structures [110].) Interestingly, in the authors' market screening, modules with the highest STC efficiency (Jolywood: 20% [110]) and the highest overall front power (LG: 395W [66]) were found to be those assembled using a transparent backsheet. DuPont recently announced its release of a transparent Tedlar backsheet [131], whereas manufacturers such as Krempel [132], Dunmore [116], Coveme [133] and Isovoltaic among others offer a transparent backsheet or are currently working on its development. SolarWorld changed the module layout and replaced the version with a transparent backsheet [134] by a glass/glass version [135].

The advantages and disadvantages of both layouts are widely discussed in the PV community. Glass/glass has obvious advantages concerning the mechanical stability and shielding capability of the inner components. In a symmetrical structure, the cell matrix is also located along the neutral fibre, which means that any bending of the laminate does not result in tensile or compressive stresses to the cells. On the other hand, a backsheet allows undesirable chemicals, such as acetic acid (which is a result of EVA degradation), to diffuse out of the laminate [92], as described earlier in more detail in the encapsulant section. A backsheet also promises a lower cell operating temperature, may result in a lighter module and allows a faster lamination process.

While glass/backsheet modules almost always have a circumferential frame, with glass/glass modules (dependent on glass thickness, size and the intended mechanical load resistance) frameless configurations are also standard. In the case of monofacial modules, most are currently 156mm × 156mm in size and incorporate 60 cells, but the share of 72-cell modules is increasing. The number of cells also defines the module size and is therefore often dependent on the application.

Other trends, such as half cells and shingle cells, are relevant to bifacial modules as well as to monofacial ones. With regard to half cells, the lower current is particularly interesting; because of the additional rear-side contribution, bifacial modules

> "Interestingly, in the authors' market screening, modules with the highest STC efficiency and the highest overall front power were found to be those assembled using a transparent backsheet."

have higher currents and consequently greater ohmic losses than monofacial modules. Accordingly, the highest promoted module efficiency has also been demonstrated with a half-cell module [110]. Innovative layouts for half-cell modules [72,136,137] with non-standard interconnection schemes may be advantageous for bifacial modules in other respects too, because the performance in shaded conditions could be improved.

Measures, particularly the multi-busbar approach, to reduce the series resistance affect bifacial modules even more than monofacial ones because of the higher currents. Currently, bifacial modules with shingled cells are also undergoing testing at the R&D level [84,85], and the first bifacial products have even already been launched [45].

Another trend, which is also implemented in monofacial devices, is the use of optimizers [138]; because of the more inhomogeneous irradiation conditions, the technique might even be more relevant to bifacial installations or at the bifacial module level, as implemented by Sunpreme [114].

Today, bifacial state-of-the-art modules are framed glass/glass modules with 2.5mm sheet thickness, POE encapsulation, 60 or 72 full-size n-SHJ, n-PERT or p-PERC+ five-busbar ribbon-connected cells, three separate junction boxes and an Al frame. The most common module variations are a transparent backsheet, cells with three or four busbars, half-cut cells, interconnections based on round wires (multi-busbar, SWCT or similar), single junction boxes or single module power optimizers, and a frameless structure. Efficiencies range between 17 and 20% at STC for front illumination. Not all companies state the bifacial factor of their products, nor is it yet common practice to give a quantitative statement on the bifacial energy gain under specific irradiation conditions. For double-glass modules, the thickness of the glass could be reduced to 2mm or below, from a technical point of view. There is no real cost-reduction potential, however, since a thickness reduction of hardened solar glass to under 2mm is complicated and at present only feasible using expensive techniques, such as chemical treatment. In addition, the module layout would need a redesign, with supporting structures located on the rear [139], since the mechanical stiffness of such thin laminates would not be adequate.

Table 3 is an attempt to summarize bifacial modules of different types, without claiming to be complete. It also has to be mentioned that manufacturers usually promote several types with different properties; in the list, however, typically only one product has been arbitrarily chosen as an example, except where there are striking differences, such as half-cell and full-cell versions, which are interesting for comparison. Generally, the version with the highest power output has been selected. Note also that the products are subject to change,

Table 3. A selection of bifacial modules implementing different technologies.

	STC front [W]	Eta front [%]	Cell	No. of busbars	No. of cells	Cover	Frame	Junction box	Remarks
JA	370	18.6	p-PERC	5	72 full	GG	yes	3 edge	short frame optional
Jinko	310	18.7	n-PERT	5	60 full	GG 2x2.5mm	no	edge	
Jolywood	325	19.8	n-PERT	4	60 full	GG 2x2.5mm	no	3 edge	
Jolywood	330	20	n-PERT	4	120 half	G/BS 3.2mm	yes	edge	high voltage
LG	395	18.7	n-PERT	12 round wires	72 full	G/BS 3.2mm	yes	edge	large cell size
Longi	310	18.7	p-PERC	5	60 full	GG	yes	3 edge	
Megacell	280	16.9	n-PERT	3	60	GG 2x2mm	yes	rear	~2015
Ningbo	340	17.1	n-PERT	4	72 full	GG 2x2.5mm	yes	3 edge	
NSP	310	18.5	p-PERC	5	60 full	GG 2x2.5mm	yes	3 edge	POE
Prism	295	17.7	n-PERT	3	60 full	GG 2x3.2mm	no	edge	
Panasonic	225	15.7	HJT	3	72 full	GG	yes	edge	~2014 small cell size
SolarWorld	290	17.3	p-PERC	5	60 full	GG	yes	edge	white cell spacing
Sunpreme	410	19.5	HCT (HJT)	5	150 half	GG 2x2.8mm	yes	2 edge	
Sunpreme	380	19.5	HCT (HJT)	3	72 full	GG 2x2.9mm	no	edge	Tigo optimizer
Trina	310	18.6	p-PERC	5 (12)	60 full	GG 2x2.5mm	no & yes	3 edge	POE
Yingli	295	17.8	n-PERT	5	60 full	GG 2x2.5mm	no	3 edge	
Yingli	360	17.8	n-PERT	5	144 half	GG 2x2.5mm	no	3 edge	

and the data shown may differ from information found on the manufacturers' websites.

A bifacial module which matches the typical description above is the DUOMAX Twin from Trina, as shown in Fig. 2. This is a frameless glass/glass module with 60 monocrystalline cells (5BB) and p-type PERC technology, with a bifaciality factor of greater than 70%. It is constructed with split junction boxes on the edge with three bypass diodes. The standard glass thickness is 2.5mm on both sides. The module efficiency ranges from 17.6 to 18.9% under STC conditions.

Modules with various modifications may be acquired from other manufacturers. According to Trina, their bifacial modules are also available with white reflective covering in the spaces between the cells, with an alternative glass thickness of 2mm, and also in a framed version. Trina also offers modules with 12 busbars. On the Trina website, a 72-cell DUOMAX Twin version is promoted [140].

Another non-standard feature is the use of POE instead of EVA as the encapsulant for bifacial modules.

Module mounts and single-axis trackers

In contrast to standard monofacial PV modules, the output performance of bifacial module installations is much more dependent on the mounting and on the condition of the ground. Four installation configurations exist, namely fixed-tilt and vertical, along with one-axis and two-axis tracking. In all cases, the rear-side irradiation reaching the bifacial cells needs to be maximized, the rear-side light has to be uniformity optimized, and the portion of rear-side shading must be prevented. All the parameters mentioned earlier have an impact on the energy yield of bifacial module plants; they therefore have to be taken into account and if relevant will need to be optimized. This also applies to the cable guiding and the junction box, which must be installed outside the active area of the cells.

Since bifacial solar modules are categorized either as *framed* (typically glass on the front and transparent backsheet foil on the rear) or as *frameless* (typically glass on the front and rear) products, depending on the mounting structure, it is essential that the right module type be carefully chosen. For framed bifacial modules, the solar cells adjacent to the frame parts (i.e. the cells located directly beside the frame) are specifically subject to excessive shading under certain light conditions (usually in the early morning and late afternoon) [141]. Consequently, frameless bifacial modules are favoured over framed ones. Nevertheless, this is only a valid assumption if the mounting structure itself is arranged in such a way as to prevent any additional shading on the rear side. In other words, the uniformity of the indirect irradiation (the diffuse and reflected portion) over the entire module rear side is a key parameter to be optimized. The rear-side light uniformity is significantly improved with increasing module height above ground, affecting the rear-side irradiance level as well [142]. SolarWorld, for example, recommends an installation height of at least 1m for their current fixed-tilt-installed bifacial products [143]. This parameter, in combination with the ground reflectivity (typically called the *ground albedo value*), defines the amount of light reaching the rear side of the bifacial solar module. These two parameters play no significant role in monofacial PV plants but require a careful pre-evaluation to be performed by the installers/planners in order to squeeze the maximum energy yield out of a bifacial installation.

Solar trackers are a highly efficient way to mount PV modules: the sun's position in the sky is tracked, which maximizes the energy yield throughout the day, and indeed throughout the year. Since the sun's position constantly changes, it is impossible to achieve optimal energy production with fixed-tilt or vertical PV installations. The use of tracking systems entails higher installation and maintenance costs than for fixed systems but ensures a higher energy output during the whole year. Single-axis trackers have only one axis of

Figure 2. The DUOMAX Twin bifacial module from Trina, featuring a frameless glass/glass configuration with 60 monocrystalline cells (5BB) and p-type PERC cell technology; the reported bifaciality factor is greater than 70%. The module incorporates split junction boxes at the edge with three bypass diodes. The standard glass thickness is 2.5mm on both sides. The module efficiency ranges from 17.6 to 18.9% under STC conditions. (Source: Trina Solar.)

> "The output performance of bifacial module installations is much more dependent on the mounting and on the condition of the ground."

movement, allowing the installed panels to move from east to west, thereby tracking the sun as it rises, moves across the sky and finally sets. On the other hand, dual-axis trackers possess two axes of movement, allowing the tracking to also take into account the change in seasons. The major advantages of dual-axis tracking are evident during the winter months.

The yield gain for tracked PV installations finally depends on the geographic location, the type of module tracker used and the module temperature coefficients, since the module operating temperature increases with the light level and exposure time.

According to new data from GTM Research, global solar tracker shipments hit a record of 14.5GW in 2017 [144]. With the significant benefits associated with tracked solar modules, the tracker market is now also adapting to bifacial module technology. The necessary adaptations, however, mean a redesign of existing trackers. The mounting structure must not cause shading of the rear side of the module; this argument is also valid for any driving and actuator units, and the cabling needs to be arranged accordingly. With such specifically designed tracking devices, suppliers such as Arctech Solar promise energy yield gains ranging from 15 to 50%; if the tracker system using bifacial modules is installed over a water surface, the achieved increase in yield can approach 60%, compared with a fixed-tilt system utilizing monofacial modules, as reported by Big Sun Energy.

Fig. 3 shows a specifically designed single-axis tracking system for PV systems which avoids shading of the rear side of the modules.

Figure 3. Independent horizontal single-axis tracker from Arctech Solar, designed for bifacial modules [145]. The modules are fixed using aluminium elements at the module edges, overlapping with the long purlins to avoid covering the back of the bifacial modules. Junction boxes at the module edges in such a system, as shown, can be integrated without shading caused by cables. (Source: Arctech Solar.)

Outlook

At the moment, it is impossible to predict which cell technology will be superior for bifacial applications. HJT and IBC, both with more complex processes and more expensive n-type wafers, promise the highest efficiencies in bifacial systems, although HJT is superior with regard to the bifaciality factor. Bifacial IBC is the most complex but least investigated technology. The most common bifacial cell types today are n-PERT and PERC+, with n-PERT yielding a higher bifaciality and higher efficiency potential, but at a higher cost. There are a large number of n-type manufacturers, but there are also a steadily growing number of p-type PERC+ competitors.

PERC+ has the advantage that the current switch from Al-BSF as a mainstream cell technology to PERC, combined with the growing interest in bifacial and the comparatively simple implementation of the bifacial PERC+ layout, will lead to increased efforts in this direction. Considering the historical development and the focus on mainstream technology in the PV industry that has repeatedly been demonstrated, this is an impressive argument. On the basis of these observations, it may be reasonable to assume that PERC+ will increasingly dominate in the short to mid term, while the improvements in n-type processing will make this technology superior in the mid to long term.

Besides cell selection, the module layout is of great interest. While there is a lot of activity in backsheet manufacturing, there is a general trend towards glass/glass modules (also true for monofacial modules) in order to improve durability and reliability. Since glass/glass is adaptable to bifacial demands, it is also very likely that this approach will dominate in the future. Glass thicknesses below 2mm will not be standard in the mid term. If modules are available as a framed or unframed product, the choice will mostly depend on the size and the application. Some developments which are innovative today show a lot of promise concerning their application to bifacial systems. In particular, the more inhomogeneous irradiation conditions over the module area make corresponding techniques that have been developed for monofacial modules (such as innovative interconnection schemes or optimizers at the module level) even more attractive for bifacial modules. The use of innovative interconnection schemes, especially the split module type, is often linked to half cells, which, because of the lower current, are an obvious alternative for bifacial devices anyway. Ultimately, the price–performance ratio and the observed reliability will, as always, be the decisive factor for the success of all innovative approaches.

“HJT and IBC promise the highest efficiencies in bifacial systems, although HJT is superior with regard to the bifaciality factor.”

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