PV systems with lowest LCOE using bifacial modules: State-of-the-art systems and components

System integration | Bifacial technology is proving to be an effective means of reducing the levelised energy costs of PV systems, offering substantially improved energy yield for only a minor additional cost. Hartmut Nussbaumer, Markus Klenk, Joris Libal and Radovan Kopecek report on the state-of-the-art in bifacial PV systems, giving an overview of components such as modules, sub-constructions, tracking systems and inverters, and presenting comparative simulation and measurement results from bifacial and monofacial systems

The major motivation to build photovoltaic systems is the economic generation of electric energy. Obviously, the cost of the produced energy is dependent on the specific system layout, its yield and several other factors, such as the system durability. The levelised cost of energy (LCOE) concept is a standard measure to compare different types of energy sources economically [1]. Since the early stages of PV production the LCOE of photovoltaics has been continuously reduced, mainly by lowering the specific US$/Wp cost of the PV modules. This could be obtained by increasing the efficiency, but even more important by reduced material and manufacturing costs. However, over time, the respective possibilities for decreasing costs were increasingly exhausted. Today, with a cost share of solar modules in a PV system below 50%, and with limited options concerning the "balance of system" (BOS) components, there is little room for further improvements in this regard. Other aspects, such as lifetime durability, are increasingly important.

Due to the additional yield from the rear, bifacial PV turned out to be a very effective setscrew to improve the LCOE. Bifacial PV technology has been known about for a long time, but there was no real breakthrough in the early stages, with still quite expensive cells and modules. This changed however due to technical progress, such as improved bifacial cell concepts or the availability of thin solar glass. Some of the advanced solar cell technologies, which are currently implemented in industrial production, enable a comparatively simple adaption to a bifacial layout. This allows a harvesting of the additional yield with little or no additional cost. The general trend towards glass/glass-modules with superior reliability, as well as the interest in "peak shaving" and customised solutions for specific applications, further supports the development towards bifacial technology. Based on that, since about 2014, bifacial PV systems have grown from being a niche application to a larger market, showing an improved energy yield in various types of applications and orientations [2-6]. In parallel with the increasing market share, remaining issues, such as the definition of a meaningful power rating procedure or the development of simulation tools, which consider the more complicated irradiation conditions [7], are currently being addressed by numerous companies and institutions.

Modules

The LCOE of a bifacial PV system is obviously dependent on the price and the output of the used solar modules. All module manufacturers have to deal with the continuing price decay and try to optimise the specific cost (per Wp or kWh) of their products. For an optimization, the technologies of cells and other components are as well important as the module layout and the used materials.

For bifacial as for monofacial modules, a common attribute is the used cell technology, which is often not directly referring to the underlying technology, such as n-PERT, IBC, HJT or p-PERC, but to the name chosen by the manufacturer for their specific process. There is a wide field of technologies, which allow a differentiation. A detailed discussion of the respective cell concepts, their advantages and drawbacks, would be beyond the scope of this article, but comprehensive information can be found elsewhere [8-11].

Figure 1. Bifacial IBC (interdigitated back contact) cell with bifacial character (ISC Konstanz, "ZEBRA" cell; bifacial factor in module >0.75)

HJT and IBC, both with more complex processes and more expensive n-type wafers, promise the highest efficiencies and HJT is superior with regard to the bifaciality. Bifacial IBC is the most complex but least investigated technology. N-PERT and also PERC+ are the most common bifacial cell types today, with n-PERT showing a higher bifaciality and higher efficiency potential, but at higher cost. There is a large number of n-type manufacturers, but there is also a steadily growing amount of p-type PERC+ competitors. Bifacial PERC+ has the advantage that the cell process can be comparatively easily upgraded from monofacial PERC and PERC is currently replacing Al-BSF as mainstream cell technology. Considering the historical development and the repeatedly shown focus on the mainstream technology in the PV industry, it may be reasonable to guess that in the short to mid term PERC+ will increasingly dominate, while the improvements in n-type processing will in the mid to long term make this technology superior.

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 white reflective backsheet, as offered e.g. by Panasonic [12], the rear side of a bifacial module has to be transparent. Also modules which partly utilise internal reflection, by covering the cell spacing with white reflective material [13], have a transparent rear side, as implemented in some commercial modules, e.g. from Solarworld [14], Trina or Linyang.

To obtain a transparent rear side there are two options available on the market: laminates with transparent backsheet or glass/glass layout. By far most of the suppliers choose a double glass design, which promises better reliability and is also increasingly used for monofacial modules, while some very large bifacial manufacturers as LG and Jolywood (Jolywood is also a leading producer of backsheets) offer transparent backsheet modules. (Jolywood offers bifacial modules with glass/glass and glass/transparent backsheet structure [15]). DuPont recently announced that it had released a transparent Tedlar backsheet [16]; manufacturers such as Krempel [17], Dunmore [18], Coveme [19], Isovoltaic and others offer a transparent backsheet or are working on its development. Solarworld changed the module layout and replaced the variant with transparent backsheet [20] against a glass/glass version [21].

The advantages and disadvantages of both layouts are widely discussed in the 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 a bending of the laminate does not result in tensile or compressive stress in the cells. On the other hand, a backsheet allows undesired chemicals, such as acetic acid, which is a result of degrading EVA, to diffuse out of the laminate [22]. It also promises a lower operating temperature of the cells, may result in a more lightweight module and allows a faster lamination process.

For double glass modules, glass thickness could be reduced to 2mm or below, from a technical point of view. There is however no real cost reduction potential since a thickness reduction of hardened solar glass below 2mm is complicated and at present only feasible with expensive techniques such as chemical strengthening. In addition, the module layout would need a redesign with supporting structures at the rear side, since the mechanical stiffness of such thin laminates would not be sufficient.

Glass/backsheet modules usually have a circumferential frame, while for glass/glass modules, dependent on the glass thickness, size and the aimed mechanical load resistance, frameless modules are possible. As for monofacial modules, presently most modules are with 60 cells, 156mm x 156mm side length, 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.

In addition, other trends, such as half-cells and shingle cells, are relevant for bifacial as well as for monofacial modules. With regard to half-cells the lower current is particularly interesting for bifacial modules, which, due to the additional rear side contribution, have higher currents and consequently increased ohmic losses, compared to monofacial ones. Innovative module layouts for half-cell modules [23-25] with non-standard interconnection scheme may be advantageous for bifacial modules also in other regard, because it could improve the performance at partly shaded conditions.

Measures to reduce the series resistance, particularly the multi-busbar approach, affect, due to the higher currents, bifacial modules even more than monofacial ones. Currently, also bifacial modules with shingled cells are being tested at R&D level [26, 27] and the first bifacial products have even been launched [28] already. Another trend, which is also implemented in monofacial devices, but which may, due to the more inhomogeneous irradiation conditions, be even more relevant for bifacial modules, is the use of optimisers [29] for bifacial installations or even at module level as implemented by Sunpreme [30].

A factor that heavily affects the competitiveness of bifacial modules is not directly related to the LCOE from the technical point of view, but to the power rating. It is still common to regard bifaciality as an add-on and to base the power rating/pricing on the front side STC-measurement. In addition, not all companies state the bifacial factor of their products; it is also not yet common practice to give a quantitative statement on the bifacial energy gain at specific irradiation conditions. While it is comparatively simple to define standardised indoor measurement conditions for a monofacial module, the measurement of a bifacial module also has to include the power, which is generated by the rear side. Standardised measurement conditions for bifacial modules are still being discussed, but close to finalisation [31, 32]. In the future, different efficiencies for standardised rear side illumination levels and measurement will allow a better comparability.

Systems

Bifacial systems have been constructed continuously at larger volumes starting with a ~1MWp installation with PVGS modules in Japan in 2013 [33], ~10MWp by

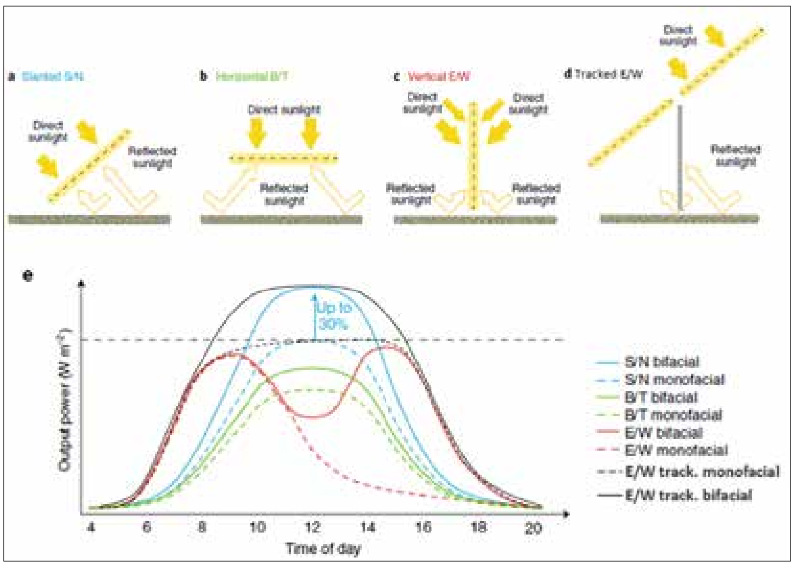

Figure 2. (a-d) Possibilities of installations for bifacial modules and (e) power generation curves for monofacial in comparison with bifacial modules [38]

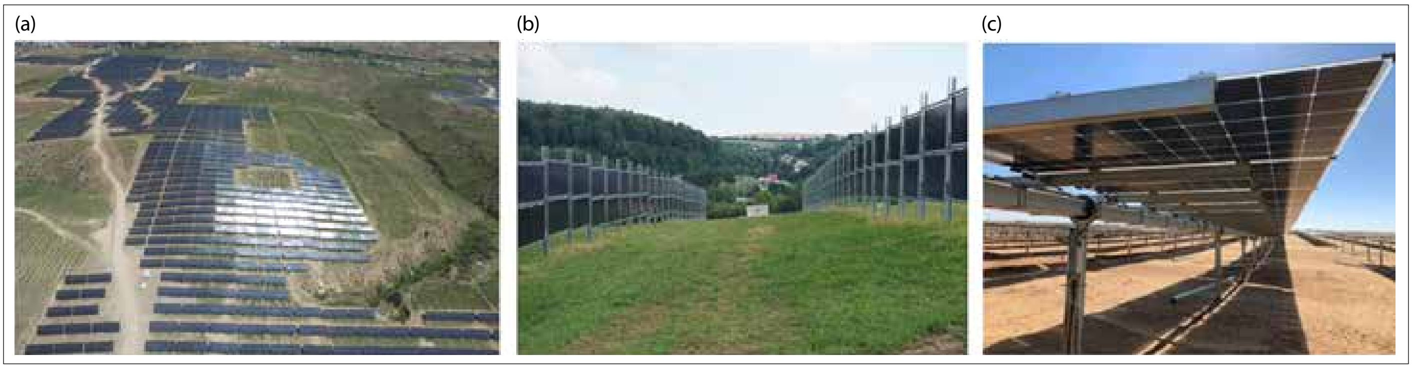

Figure 3. (a) Bifacial 50MWp fixed tilt PV system by Yingli (China), (b) bifacial vertical 2MWp installation by Next2sun (Germany) and (c) bifacial HSAT 400MW by Scatec Solar (Egypt)

Sunpreme in 2016 in the US [34], ~100MWp by Yingli and NSP in Asia [35, 36] in 2018 and the currently largest one in construction by Scatec with 400MWp in Egypt [37]. Now, at the end of 2018, the total installed capacity of bifacial systems amounts to about 3GWp, which corresponds to a market share of about 0.7% (bifaciality is becoming "visible") but is expected to grow to a total share of close to 20% in the coming five years in the 1TW-scale market.

When using bifacial modules the possible geometries for installations are getting more complex, depending on the application, as the rear-side irradiance of the modules also have to be considered. Figure 2 depicts the variety of possibilities (a-d) and corresponding schematical power generations curves in (e).

The systems can be installed classically with (a) a slanted tilt facing towards the sun receiving additional albedo from the ground reflection. When the bifacial modules are used in a carport and installed (b) horizontally then the power generation is decreasing – however still showing a bifacial gain. Vertical E/W installations (c) need bifacial modules with a high bifacial coefficient (n-PERT, HJT) to achieve a symmetrical power generation curve as depicted as a solid red curve in (e). The most common applications these days with the highest yield potential are bifacial horizontal single-axis tracking (HSAT)systems (d) which were discussed in detail at the 5th bifacial workshop, bifiPV2018, in Denver. Such systems can reach up to 50% more power (black solid curve) in comparison with classical fixed-tilt monofacial equivalent systems (dashed blue), which, depending on location, albedo, installation height etc, can lead to the lowest LCOEs possible as already proposed by EDF/Masdar in the lowest bid of all times of 1.78 US cents per kWh [39].

Utility scale

Figure 3 shows the largest bifacial utility-scale PV systems for (a) bifacial fixed tilt, (b) bifacial vertical E/W oriented application and (c) bifacial HSAT.

The annual yield gains due to bifaciality, compared to a standard fixed-tilt monofacial PV system, are reaching from about 10% (Yingli) [40], above 10% (Next2Sun) [40] to 13% (enel) [41]. For Scatec´s installation in Egypt, no numbers are available yet, as the system is still under construction.

The largest system so far, set up by Scatec Solar in Egypt, uses the natural albedo of the desert in combination with bifacial PERC modules with an expected bifacial gain of about 10% (compared to monofacial HSAT) - slightly lower to the La Silla installation by enel in Chile [41] where nPERT (BiSoN) modules with a higher bifaciality were used.

As bifaciality is becoming increasingly bankable and the yield simulations more and more precise, bifaciality will presumably dominate the utility -scale market in desert regions in combination with HSAT very quickly. At the bifacial workshop in Denver last September, several presenters from the US were convinced that, similar to trackers three years ago, bifacial HSAT systems will become standard in the US in the next two years.

Rooftop and building integration

HSAT is not a technology that can be simply used on flat roofs because of several reasons. On the one hand the trackers will add too much weight and on the other the wind loads of such high installations could not be anchored easily to the roof. However, there are companies working on lightweight trackers for roofs as well.

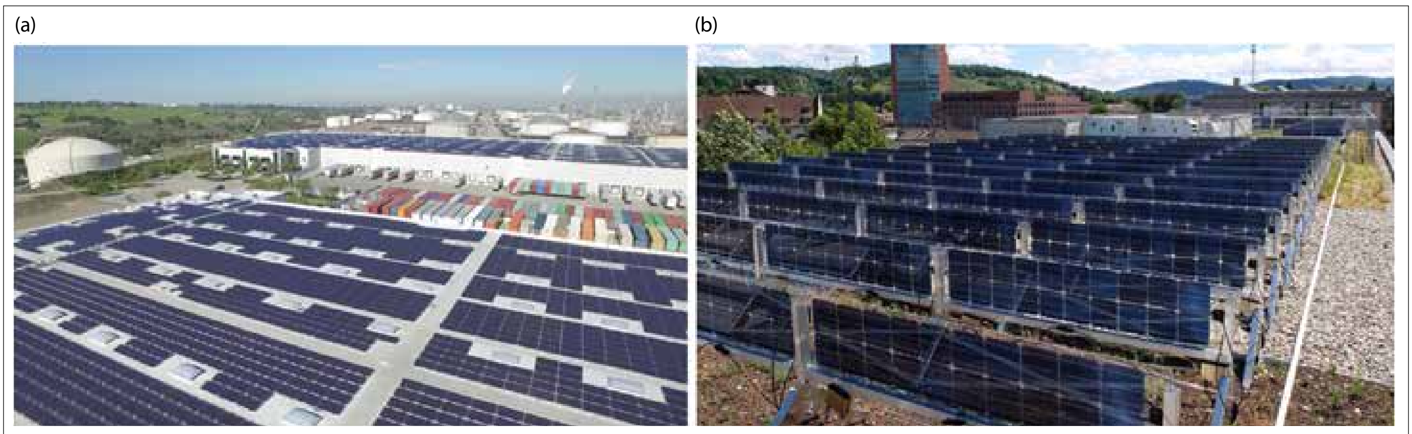

Figure 4. (a) 10 MWp bifacial fixed tilt installation by sunpreme (USA) [42] and (b) bifacial vertical installation by Solarspar (Switzerland) [43]

Installation	Monofacial comparison	Bifacial gain [%]	Comment
Fixed tilt bifi	Fixed tilt mono	15+-3 [40]	MegaCell in La Hormiga (without white quartz)
Vertical bifi	Fixed tilt mono	10+-3 [40]	Next2sun in Germany
HSAT bifi	HSAT mono	10+-3 [40]	Enel in La Silla in Chile

Table 1. Typical bifacial gains (albedo 30%, module bifacial factor of 0.9 and module edge distance from the ground of 60cm) in comparison with standard monofacial systems

The main installation mode for bifacial modules on flat roofs is fixed-tilt mounting, as e.g. realised by Sunpreme (Fig. 4 (a)). However, there are also more unconventional approaches, such as vertically installed mini modules (Fig. 4 (b)) as installed by Solarspar.

As the distance of the modules from the roof is quite low, in the most common installation mode bifacial gains are limited. However, the albedo of many roofs can be considerably enhanced by using reflecting paint or roofing foil and bifacial gains can exceed 10% as well.

Floating PV is, similar to bifacial PV, a growing market. A combination of floating PV and bifacial PV is a logical consequence even if water is not the best reflector. Depending on the type of installation, bifacial double-glass modules above water may result in higher yearly energy yields, because of better cooling compared to installations above ground [40].

Table 1 reports bifacial gains for typical utility scale installations. In order to achieve the highest possible bifacial gains, appropriate mounting structures are necessary; a topic that is discussed in the next paragraph.

Sub-constructions

The first large >1MWp bifacial PV power plant used PVGS n-PERT modules [33]. Fig. 5 depicts the historical PV plant with a non-optimal sub-construction for the bifacial modules, as shown in Fig. 5 (b).

You can clearly see the shadowed rear side of the modules by the stabilisation bars that are nearly touching the rear side of each module. Even with this very un-optimised feature, PVGS was reporting very high yearly bifacial gains of close to 20%. The reason for this was partly that the system was built in a snowy region where seasonal high albedo values of snow enhance the bifacial gain.

From this system we also learned that such a severe shadowing on the rear side does not cause any hot spot and consequent shunting problematics of the modules which was not observed by PVGS and is explained in the next section.

Shadowing of the rear

During the bifacial workshop bifiPV2018 in Denver, Hanwha Q CELLS showed various systematic experiments and measurements of how a shadow on a rear side affects the module performance and reduces the bifacial gain [44]. Similar studies were done e.g. by ISC Konstanz and ECN [45] before. Figure 6 (a) shows very demonstratively how the current distribution looks and that only a little fraction of that comes from the rear side. Therefore, hotspot problematics, which are often discussed by the bifacial community, simply do not exist for shadows from sub-constructions.

The experimental graph in Fig. 6 (b) then also shows how such a loss depends on the distance of a certain object (here 6cm wide and 10cm deep) as shown in Fig. 6 (a) that is shadowing the rear side. For a minimum distance of 30cm the losses are almost zero.

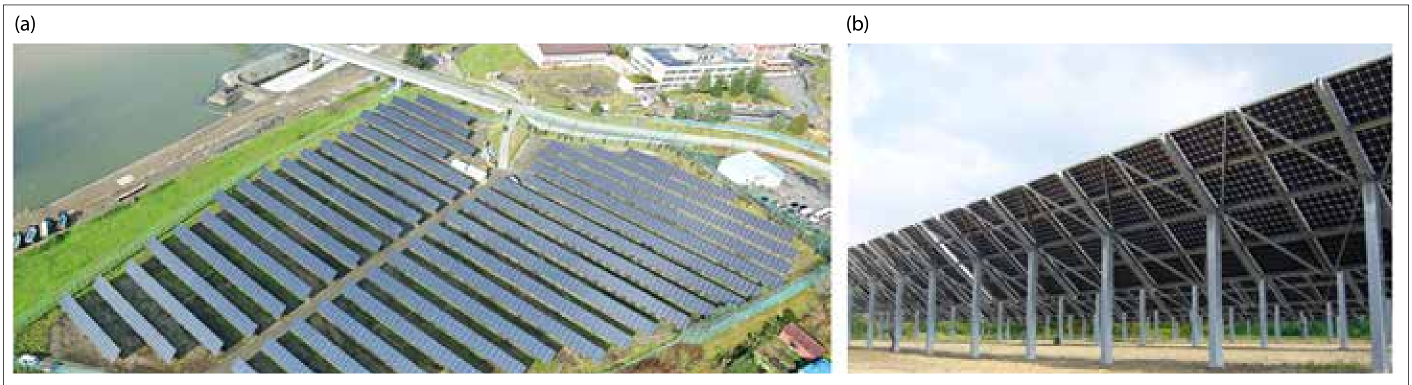

Figure 5. (a) Top view and (b) detailed view on the first large bifacial installation by PVGS in Japan [33]

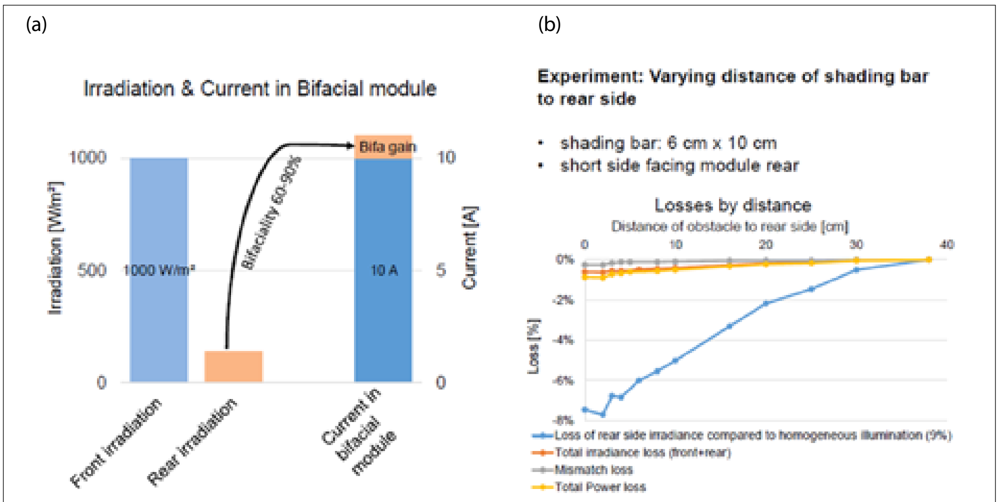

Figure 6. Hanwha Q CELLS' explanations at bifiPV2018: (a) why shading on the rear side does not cause hot spot problems; and (b) when the shading object is a certain distance from the cell then the shading effect is negligible [44].

With such a non-optimal sub-construction Hanwha Q CELLS reached still very good yearly bifacial gains as summarised in Figure 7 (b).

Fixed-tilt systems

We have seen in the previous paragraphs that even in the non-optimal cases high bifacial gains can still be obtained. However, in order to reach the highest possible energy yield the sub-constructions need to be optimised for bifacial use. Figure 8 shows two very nice examples where specially designed sub-constructions were used for bifacial applications. There are already a couple of large companies that are offering adapted products standardly – such as Arctech Solar [46].

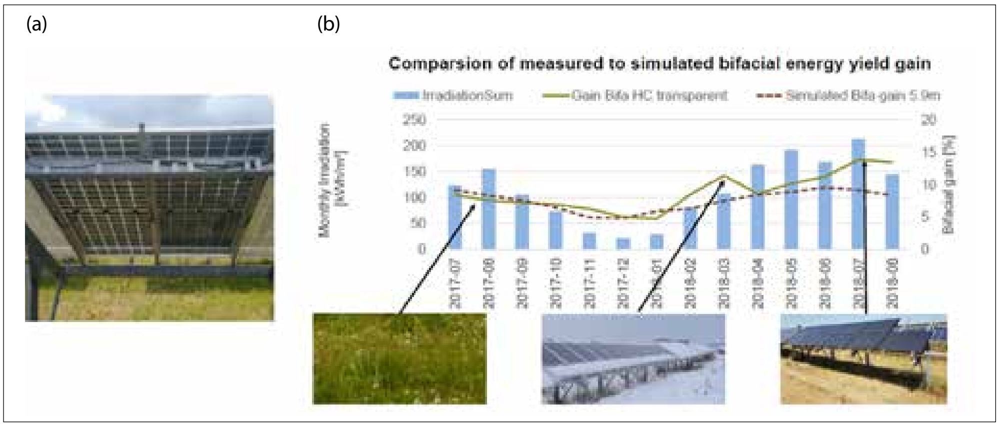

Fig. 7: Hanwha Q-cell's (a) sub-construction and (b) a graph of monthly bifacial gains in that bifacial PV system [44]. Note: this non-optimal standard sub construction was used on purpose to demonstrate that even in this case bifacial gains of 9% in average were obtained.

Tracking systems

In the meantime there are many bifacial tracking systems out there that are optimised for bifacial use. The reason is that many large electrical companies such as EDF, TOTAL, Engie, SPIC and many others realised that in order to reach lowest LCOEs in desert regions bifacial HSAT is the best solution. On the other hand it is very simple to design an optimal solution in the case of trackers.

Standard single module trackers [47] are not particularly optimal for bifacial applications when the bar is covering the rear side close to the module (but acceptable for lower bifacial gain). But many tracker manufacturers such as Soltec [48], Arctech Solar [46] and NEXTracker [49] are putting two modules right and left in a distance from the rotating axis - in landscape or in portrait. In January 2019 NEXTracker revealed that it is currently setting up more than 750MWp bifacial 1V HSAT systems in the US. In some of these systems, advanced half-cut-cell modules are used where the junction boxes are in the middle of the module. This clever configuration helps to reduce the bifacial losses and maximises the power output of the system.

Landscape or portrait have both their advantages and disadvantages but it seems that the portrait technology is going to win due to an easier clamping technology as well as a higher mounting density for the modules. The distances and dimensions as shown in Figure 8 and 9 are important to be optimised in order to achieve maximum energy yield by also considering the material consumption. As said, the most popular installation for bifacial HSAT is the portrait geometry, which is also seen in the picture of Figure 9 (a). However, these systems have to be more robust, as for example 1V systems, due to possible wind loads. Typical numbers in that case are d_{1min} =60cm, d_2=200cm, d_3=10-30cm and d_4=0-30cm. In order to minimise all the losses and to get a deeper understanding of all effects including soiling of bifacial systems many test sites have been launched lately. For example Soltec has established an evaluation centre in the US. In addition Chile is granting a bifacial module and system institute for desert PV

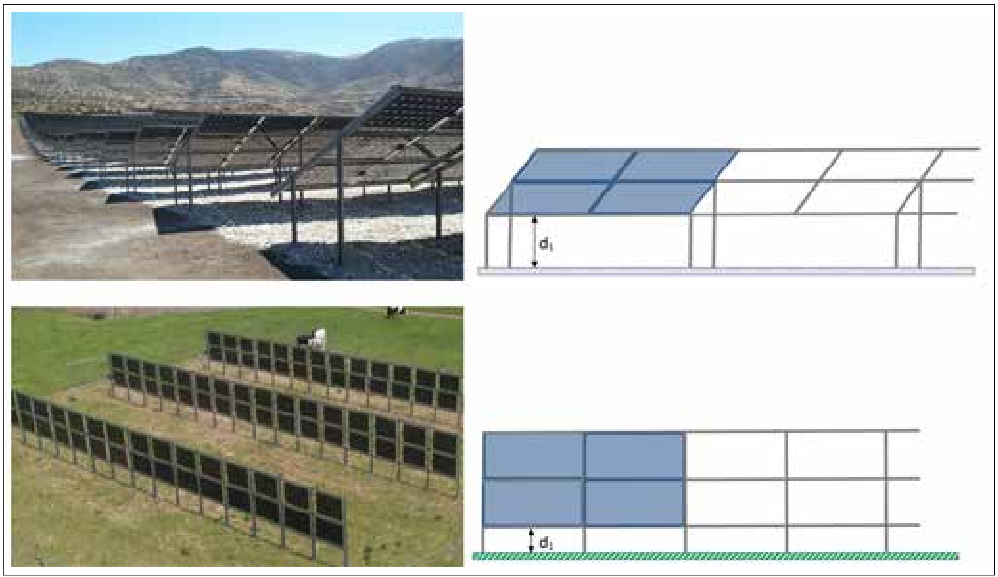

Figure 8. (top) La Hormiga close to San Felipe in Chile and (bottom) vertical bifacial PV system testing site in Losheim am See in Germany

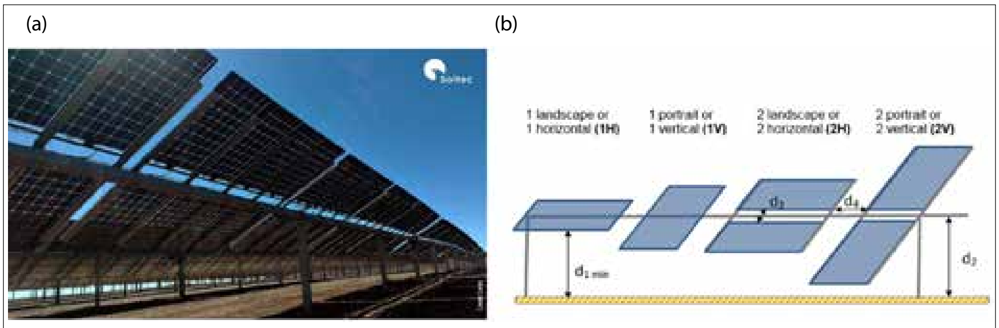

Figure 9. (a) Tracking system from Soltec in La Silla in Chile and (b) and possible configuration of modules on horizontal single-axis trackers

applications – AtaMoS-TeC [50].

In order to reach bifacial gains between 20% and 30% the reflectance of the ground has in most cases to be conditioned as described in the following section.

Energy yield enhancement by improving the ground surface properties

The ground reflectance is described by a factor called albedo, which is defined as the ratio between the power of the reflected and the total incoming light. The albedo of the ground underneath the modules of a PV system is of upmost importance with regard to the ground reflected rear irradiance, which can be calculated by:

$$E_{ref,rear} = \rho \times GHI \times F_{ns} + \rho \times DHI \times F_s \quad (1)$$

with ρ being the albedo of the ground surface, GHI, the global horizontal irradiance, DHI, the diffuse horizontal irradiance and F_{ns} the view factor from non-shaded, F_s from shaded areas respectively [51]. The rear irradiance of a bifacial module over time is, in turn, decisive for the energy yield of the bifacial PV system and the bifacial gain defined by

$$BG(\%) = \frac{eb - em}{em} \cdot 100 \quad (2)$$

With e_b and e_m being the normalized energy yield in kWh/kWp (nominal operating hours) of a bifacial and monofacial PV system respectively.

The higher the albedo and the rear side efficiency of the bifacial module, the higher is the potential bifacial gain of a PV system. However, it has to be noticed, that the energy yield of bifacial systems is also dependent on a variety of additional factors, such as ground cover ratio, installation height of the modules and tilt angle. The factors also show interdependencies, so there may be different optimum tilt angles for different installation heights. Nevertheless, it is clear, that the albedo has a decisive role for the bifacial gain of a PV system.

The albedo is strongly dependent on the ground surface properties. Green grass for example exhibits an albedo of about 0.2, whereas the albedo of snow ranges between 0.6 and 0.9. In order to enhance the ground reflectivity, material with high albedo, for instance white stones, sand or special reflecting plants can be chosen.

Summarising reflectance properties in a single, constant factor is of course a simplification. The reflectance of the ground depends on the angle of vision [52], except for a perfectly diffuse reflector. In addition, the reflection is dependent on the wavelength [53, 54, 55]. Both effects have an influence on the rear side irradiance of bifacial modules in PV systems. There may also be varying albedo factors due to seasonal changes, for instance from soil to snow, or ageing effects.

Numerous approaches to improve the rear side irradiance artificially have been realised. At the PV power plant "La Hormiga", for instance, white quartz sand was used in order to improve the albedo of the ground (see Figure 8 top). Tempress in the Netherlands (Figure 10) chose the same approach [56].

Another way of improving the rear side irradiance of bifacial modules is to mount them on flat roofs covered with highly reflecting foil or paint. Special reflecting roof sealing foils are available for instance from the companies Sika and Kemperol. An example of an installation with roofing foil is shown in Figure 4 (a).

The installation of bifacial systems on roof tops is a trade-off between maximum installed peak power and nominal operation hours of the system. In most of the cases, rooftops were covered with modules at a low tilt angle in the range of 5 to 15 degrees, resulting in a ground cover ratio (GCR) of 80-95% depending on the specific design of the PV system. Low tilt angles and high GCR values, however, are not favourable for achieving high bifacial gains because in that case the ground is self-shaded by the modules.

Combining green roofs using highly reflecting plants in combination with vertically installed PV modules is an option to combine an energy-generating roof and water retention in urban areas [43]. The vertical installation enables a considerably improved accessibility, reduced maintenance effort and the realization of real green roofs instead of largely covered areas, as shown in figures 4b and 11. Choosing plants with reflective, silvery leaves may enhance the ground reflectivity (Figure 11); these types of plants are also more resilient to extreme sun exposure as typically found on flat roofs.

In future bifacial PV systems also specifically formed cheap reflectors could be realised, leading to a further enhancement of the light concentration on the collector [52, 57].

Inverters

The most obvious factor concerning the inverter of bifacial systems compared to standard, monofacial ones, is the increased current and power of bifacial modules. This affects the availability of suitable inverters and causes an uncertainty in the system design. While there will soon be a new IEC-norm for measurement of bifacial modules [58], the actual increase of the current is still dependent on the albedo and the installation conditions (height, row distance and row width, tilt, shading by structure, latitude).

According to an estimation of the expected bifacial gain, the electrical components of the system (inverters, cables, protection devices, etc.) have to be dimensioned and selected. It is important to note that not only the maximum DC input tolerances need to be considered, but also less obvious factors such as the fuses which are implemented in the string inverters or DC combiner boxes. A too large fuse will leave the module unprotected while a prolonged small overload may result in heat generation and potential damage.

When the DC power produced by the PV array exceeds the maximum input level of the inverter, the inverter adjusts the direct current to reduce the DC power. This process is also referred to as clipping. Designers of bifacial systems will tend to select an inverter with a larger DC input current, based on the expected gain. Concerning the LCOE this can be detrimental if a more expensive inverter is chosen. Also manufacturers of inverters state in their system design guides [59, 60] that the typical annual clipping loss is in the range of a few percent, even if an inverter is chosen according to the STC-rated power, which means without considering the bifacial gain. The reason for this is the comparatively rare occurrence of conditions that actually lead to clipping. In contrary, the inverter can be operated at higher efficiencies most of the time [60].

Another characteristic of bifacial modules and systems is the impact of the more inhomogeneous rear side illumination. This is unavoidable and enhanced for low installation heights, steeper tilt angles and all factors which increase the rear side shading. Due to the inhomogeneity there is a mismatch and reduced efficiency at both module and system levels. As a result of the increased mismatch it is considerably more difficult to define an optimum common MPP for a system. Measures which consider these effects are inverters or optimisers at module level or central distributed inverter systems with multi MPP inputs.

In the meantime there are several products which are adapted for use in bifacial systems. Sineng Electric launched a central distributed PV inverter for bifacial solar modules [61]. The inverter is equipped with a MPPT combination box designed especially for bifacial modules, capable of supporting an increase in the maximum operating current up to 12.5 A. Huawei promotes its "FusionSolar Smart Solution" and upcoming string inverter multiple MPPT units [62]. The system also adopted a fuseless security protection solution. Another manufacturer of different inverter types for bifacial applications is the company Senergy [63]. Options at module level (optimisers, module inverters) are now also implemented in modules from Sunpreme (Tigo) [64], Panasonic (Enphase) [65] or offered by Solaredge [66].

Bifacial yield simulations and LCOE

In the same way as for standard (monofacial) modules, predicting with a good level of accuracy the expected yearly energy yield for a planned bifacial PV system is of paramount importance in order to determine the LCOE and therewith its profitability.

The prediction of the yearly energy yield of a bifacial PV system requires the calculation of the power output of each module of the PV array at each moment of the year. In order to perform this task it is necessary to model –

for each time stamp – based on meteorological data (global horizontal irradiance, diffuse irradiance data and ambient temperature) the front and rear side irradiance in the plane of array (POA) as well as the module temperature. In addition, it is necessary to establish an electrical model that allows the calculation of the electrical output of the module using the calculated POA irradiance and the module temperature as input values.

Compared to monofacial modules, the modelling of bifacial modules is more complex, mainly due to the fact that also the irradiance on the module rear side has to be calculated. The rear side irradiance is strongly influenced by the module installation height, the ground reflection coefficient (albedo), as well as by the distance between module rows. In addition, the diffuse irradiance fraction plays an important role, as most of the light incident on the module rear side is diffused light that is either reflected from the ground or scattered by the sky.

Early work showing the potential of bifacial PV [67] and dealing with the modelling of bifacial modules [68] has been performed in the late 20th century. In recent years, an increasing number of studies about the energy yield modelling of bifacial modules have been published [69–74]. The main challenge when modelling bifacial PV systems is the calculation of the rear POA irradiance. The main concepts used for this scope are view factors [75, 76] and ray tracing [77]. Regarding the modelling of module temperature, several approaches exist such as the so-called NOCT (normal operating conditions temperature) model [78, 79] used by ISC Konstanz bifacial simulation tool, MoBiDiG (modelling of distributed bifacial gain) [80], and the steady state mode as used e.g. by the commercial software PVSyst [81] and ECN's bifacial simulation tool [82] in its energy yield models.

In the following, an electrical model is needed in order to calculate for each time stamp of the considered time period (usually one year) the electrical output (Impp, Umpp) of a given bifacial module based on its I/V parameters measured at STC (under front as well as under rear side illumination) and based on the simulated module temperature and the modelled POA irradiance (front and rear) for the respective time stamp. Thereby one-diode models as well as two-diode models [72] are used by various authors (e.g. [72] and [83]). From this, the expected total energy yield can be easily calculated.

Source: Tempress, Amtech Group

Figure 10. Bifacial 400kWp system from Tempress with East/West orientation [26x]. The white gravel results in an albedo of 40%. Left picture: View from above; Right picture: View onto the back of the bifacial modules.

Figure 11: Silvery leaves (left) may enhance the ground reflectivity compared to standard plantings (right); this type of plants is also more resilient to extreme sun exposition as typically found on flat roofs [43]. Details from the Solarspar system shown in Figure 4 (b).

Source: T. Baumann

As for suitable applications and locations, this configuration has the potential to result in the lowest LCOE amongst all types of PV systems, in recent years, particular efforts have been made in modelling bifacial tracking systems – in particular horizontal single-axis tracking (see e.g. [84], [85], [86], [87])

Analysis of LCOE for bifacial systems

LCOE is a widely used metric that is obtained by dividing the complete cost for setting up and operating a PV system by the total electricity generated during the useful lifetime of the system:

$$LCOE = \frac{total\ life\ cycle\ cost\ [EURO]}{total\ lifetime\ electricity\ generation\ [kWh]}$$

Taking into account the fact that the present value of future payments (and revenues) has to be discounted (net present value) by a rate that is linked to the interest rates to be paid for bank loans and equity financing, and including the yearly expenses for operation and maintenance of the system, the LCOE can be expressed as (see details about the derivation e.g. in [88]):

$$LCOE = \sum_{t=1}^{N} \frac{(I_t + O_t)/(1+d)^t}{E_t/(1+d)^t}$$

With N being the system lifetime, It being the repayment for debt and equity in the year t, O_t the cost for operation and maintenance in the year t, E_t the energy produced by the system in year t and d being the discount rate.

Accordingly, as most of the input parameters, such as e.g. the solar irradiance as well as the financing conditions (discount rate), are subject to different levels of uncertainties, the result will be rather a range of possible LCOE values than one single value (a comprehensive study on this topic has been presented e.g.in [89]).

Figure 12 shows the summary of a set of LCOE calculations for a typical installation site in Southern Europe. These results show for example that assuming a price premium (based on total system cost) for the bifacial system of 10%, a bifacial gain of at least 10% is required in order to achieve the same LCOE as for the equivalent monofacial systems, while higher bifacial gains will lead to a lower LCOE for the bifacial system.

A very useful and publicly available

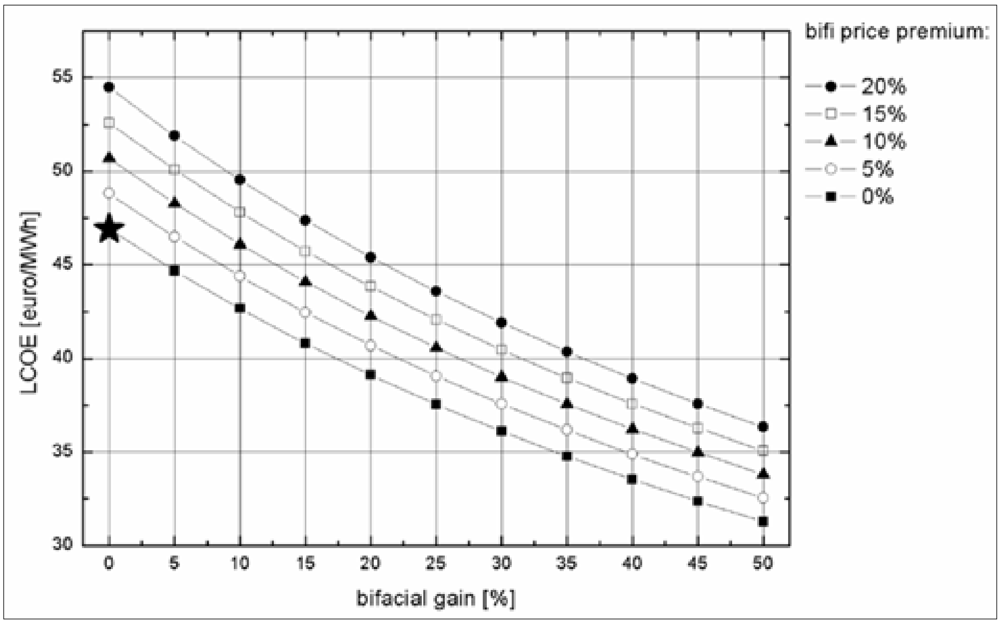

Figure 12. Results of LCOE calculations for a location where a monofacial fixed-tilt, utility-scale ground-mounted PV systems shows a yearly energy yield of 1,750kWh/kWp and the total system cost (including modules) of the monofacial system is €0.79/Wp. The resulting LCOE of the monofacial system is marked with a star. The percentage of the price premium for bifacial systems refers to the system cost and can be – at least partially – due to a higher module price. For all cases (monofacial and bifacial gain), a discount rate of 6% has been assumed. Figure from [82]

tool for LCOE calculations is included in the System Advisor Model (SAM), developed by National Renewable Energy Laboratory, Sandia National Laboratory and the US Department of Energy [90]. It allows for the implementation of the most important financial parameters

A detailed overview about modelling of bifacial PV modules can be found e.g. in [91] and in the related chapter of [40]. Many useful codes can be found in the library (PVlib) provided by the PV Performance Modelling Collaborative [92].

Summary

The LCOE of photovoltaics has been continuously reduced, mainly by lowering the specific cost of the PV modules. However, over time, these possibilities have been increasingly exhausted. Bifacial PV modules and systems are a means to overcome this limitation. Lowest LCOE values are obtained due to the additional energy yield from the module rear side.

Even though bifacial technology is not new, it has become increasingly attractive in the last couple of years. The early bifacial cell types were considerably more complex and expensive, compared to the monofacial industrial standard cell with Al-BSF. Currently however, more advanced cell types have transferred into industrial production; most of them enable a cost-effective realisation of a bifacial layout.

Other trends, such as the increasing share of glass/glass modules to improve durability are favourable for the implementation of bifacial systems as well.

While earlier bifacial modules and systems were quite similar to monofacial standard products, their design is increasingly adapted to bifacial technology. Corresponding module and system components, such as slender junction boxes, sub-constructions or inverters are available today. In addition, adapted installation concepts such as vertically mounted modules or horizontal single-axis tracking have turned out to be very effective, or enable innovative applications.

Even though the additional energy yield of bifacial compared to monofacial systems has been repeatedly demonstrated in numerous studies and projects, the still limited predictability of the energy yield is an obstacle for the bankability of bifacial PV systems. The more complex irradiation conditions at the rear side of the module do presently still not allow as reliable simulations and yield predictions as for monofacial modules. However, several groups are currently working on simulation tools for bifacial systems and studies that prove the prediction accuracy are increasingly published. Also another drawback – the lack of a clearly defined power rating procedure – has been successfully addressed; a corresponding norm was recently presented.

These measures will further promote the installed bifacial capacity and its market share that is constantly increasing. It can be expected that the yearly share of bifacial systems may reach 50% or 75GW in 2022. Lowest LCOE are possible with utility-scale, ground mounted bifacial systems, particularly when realised with horizontal single-axis tracking. Such systems can reach up to 50% more power compared to classical, fixed-tilt monofacial equivalents. This enables the lowest LCOEs that are possible today with PV, as proposed by EDF/Masdar in the lowest bid of all times with 1.78 US cents per kWh. Also, the size of realised systems is increasing, with a recently announced bifacial HSAT system, 400MW by Scatec Solar in Egypt, being the largest one in construction today. ■

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