Bifaciality: One small step for technology, one giant leap for kWh cost reduction

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ABSTRACT

The aim of this paper is to dispel the common belief that bifaciality is nonsense as it is not a mature technology, it is expensive and, because in large systems there is limited albedo from the rear side, it only serves the niche market. A complete picture of bifacial cell technologies and module concepts is presented, as well as levelized cost of electricity (LCOE) results for present and future bifacial systems.

Introduction

At a time when high-efficiency solar cell technologies are in any case moving towards bifaciality, and many module producers are changing to glass–glass, as well as the fact that high-power modules are necessary in order to minimize the balance of system (BOS) costs, the authors are very confident that bifaciality will become an extremely important technology in driving down costs per kWh for PV systems. When rooftops are the main market in a particular location (e.g. the Netherlands), bifaciality is, needless to say, not of great interest. However, for flat roofs and ground-mounted installations of large systems (e.g. in desert areas), bifaciality is extremely helpful for driving down the levelized cost of electricity (LCOE) and also for increasing the duration of electricity generation.

> "For flat roofs and ground-mounted installations of large systems bifaciality is extremely helpful for driving down the LCOE."

There are still several technological challenges which are not trivial: for example, how to design and where to place the junction boxes, how to build shadowless and stable mounting systems and, most importantly, how to standardize bifacial measurements and how to simulate the bifacial benefit of individual installations. However, all of these challenges have already been tackled individually for some time by a number of companies and institutes. This article summarizes some of these outcomes, which were presented and discussed at the Second BifiPV Workshop in Chambéry, revealing

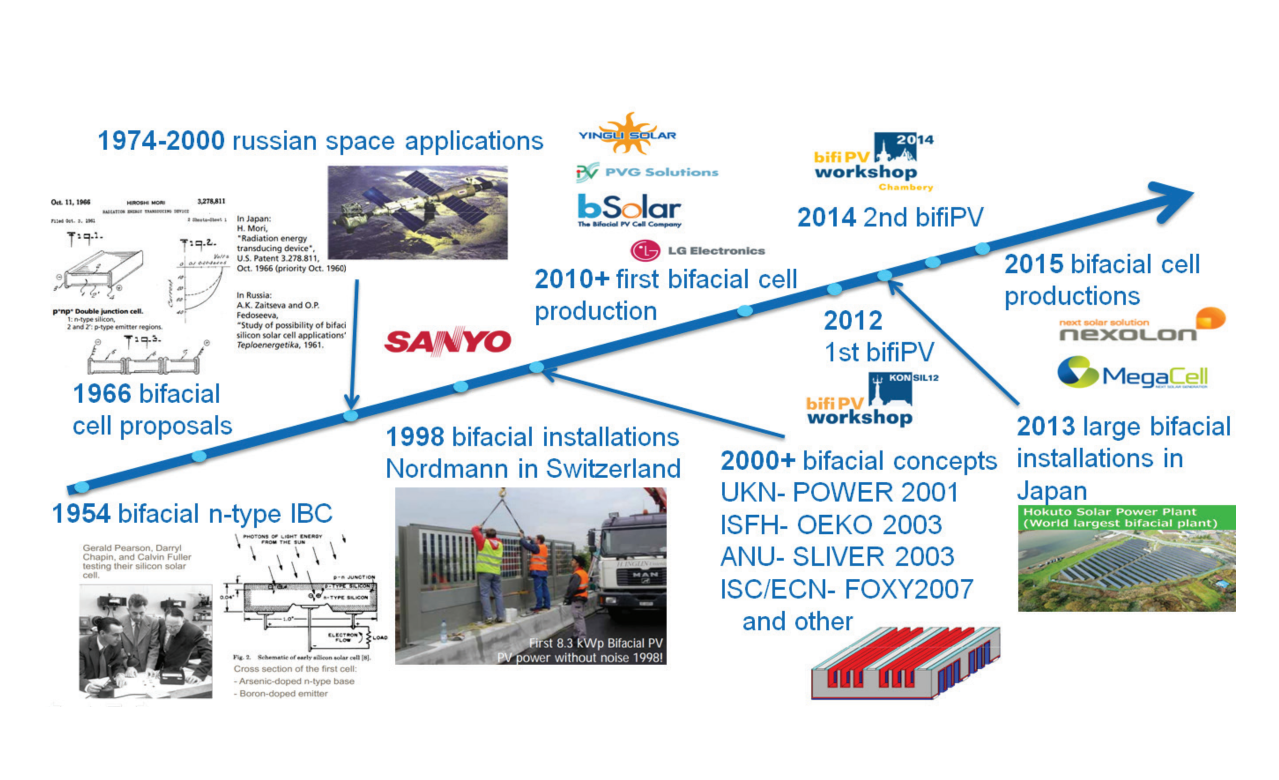

Figure 1. Brief history of bifacial cells, modules and systems.

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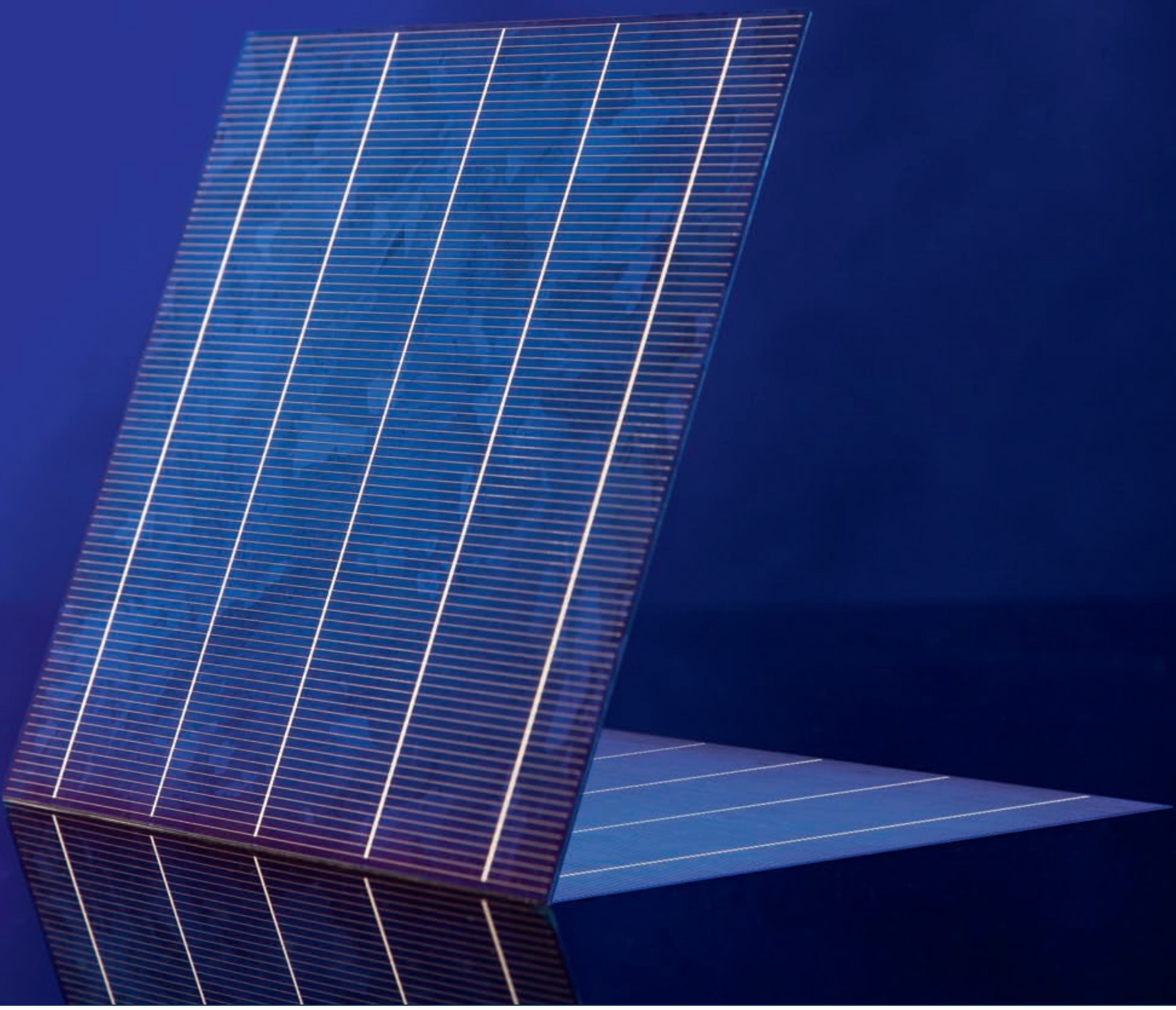


Expect Solutions. **GEMINUS.**

The SCHMID's GEMINUS bifacial cell technology enables low manufacturing costs of multi and mono bifacial cells featuring over 30% more energy yield (kWh/kWp)*. It combines outstanding manufacturing simplicity based on standard tools with highest efficiencies on all common p-type based material. The resulting multi crystalline based bifacial module operates at efficiency equivalents of over 18% and hence has a 7-10 USc BOS advantage as in comparison to current monofacial multi modules.

* Gain in energy depending on rear side illumination and module mounting.

the big picture of the status of bifacial technology. At that workshop several working groups were established, assigned to work on standards for bifacial measurements, qualification standards for bifacial modules and the development of dedicated simulations of bifacial systems.

Bifacial history and status, and estimations of LCOE

History and status

Bifacial solar cells have a very long history. The concept actually originated at Bell Labs in 1954 with the very first solar cell processed, which was an n-type bifacial interdigitated back contact (IBC) solar cell. The history is depicted in Fig. 1, as presented by Kopecek at the Second bifiPV Workshop [1]. Russian and Spanish groups made proposals in the 1960s on how bifaciality could be used, and bifacial cells have been employed in space applications in Russian satellites since the 1970s. Around 2000 bifacial modules have also been used in terrestrial applications, for example by Nordmann [2] on Swiss highways. However, all the cell and module concepts employed at that time were extremely expensive, so these systems were strictly niche applications, in which costs were not a concern (e.g. space applications), or they were used for demonstrations.

Since 2000, several groups have been picking up the idea of bifaciality again: with the development of, for example, cost-effective n-type solar cells, bifacial technology is being borne in mind in order to benefit from the active rear side. One of the first cost-effective bifacial mc-Si solar cells is described in the Ph.D. thesis of Kränzl [3]. The institutes ECN and ISC Konstanz were partners in the successful EU-funded FoXy project, running from 2006 to 2008 within the Sixth Framework Programme (FP6) [4]. The project dealt with low-cost silicon and cost-effective n-type cell and module processes for mass production.

Today, six years later, the n-type processes are being used in several industrial production lines, under such designations as n-PASHA (ECN) and BiSoN (ISC Konstanz) solar cells. ECN and European OEMs have successfully transferred their n-type technologies to cell and module manufacturers outside Europe (Yingli, Mission Solar Energy), while ISC Konstanz is currently transferring the BiSoN process to MegaCell in Italy. Mission Solar Energy and MegaCell are investing in the installation of additional solar cell capacity because of bifaciality.

Electricity costs with bifaciality

Photovoltaics' share in EU renewable electricity production could be substantially increased if its cost structure were to further improve. The cost of solar electricity can be reduced by increasing efficiency, implementing low-cost manufacturing technologies, and improving reliability and sustainability. A fourth powerful approach to reducing cost is to increase the energy yield, namely the kWh produced per Wp module power. The important metric for analysing cost is the LCOE, which takes into account the costs and the energy produced over the system lifetime.

In southern Germany the current value of LCOE for a state-of-the-art system is around €ct8/kWh. Although most of the cell and module manufacturing has moved to Asia,

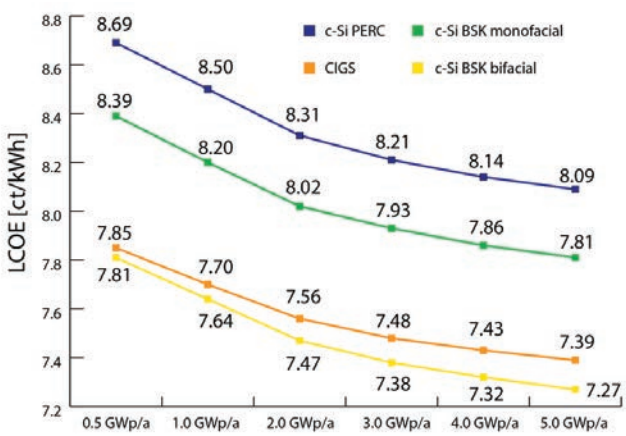


Figure 2. LCOEs of a PV system in southern Germany for different technologies as a function of the scale of production (GW study of FHG IPA/ISE). A range of €ct8.2–8.69/kWh is calculated for the production of standard c-Si technology on a 0.5–1GWp/a scale.

Today (2014)	Solar cells in 2020+	Bifaciality in 2020+
Cz-Si cell Efficiency: >20% Power: 5Wp Costs: €0.3/Wp	**Cz-Si cell** Efficiency: >24% Power: 5.7+Wp Costs: €0.2/Wp	**Bifaciality factor: 0.8** Effective power: up to 450Wp-e*
60-cell module Cell-to-module loss: 3% Power: >290Wp Costs: €0.55/Wp	**60-cell module** Cell-to-module gain: 2% Power: >350Wp Costs: €0.4/Wp	Yearly system power gain: 15–30% (depending on installation) A conventional 0.7GW factory when upgraded to this technology will produce 1GW
System in southern Germany Costs: €1.5/Wp Electricity production costs (running for 25 years): €ct8.5/kWh	**System in southern Germany** Costs: €1.1/Wp (reduction in module and system costs through decrease in area) Electricity production costs (running for 30 years): €ct6/kWh	**System in southern Germany** (running for 40 years/improved reliability with glass–glass): down to €ct3–4/kWh

* Wp-e is the real effective peak power that is generated by a module mounted in a system. For a module with a high BF, Wp-e can be more that 30% higher than the measured front-side power Wp.

Table 1. Cost of ownership (CoO) for cells and modules and the resulting LCOE for current and future monofacial and bifacial technologies. (The bifaciality factor – BF – is the ratio between rear- and front-side efficiency; for identical efficiencies the BF is 1.)

large-scale production is expected to become competitive in Europe. A recent study by Fraunhofer, with other similar studies coming to the same conclusion, predicted that multi-GWp production in Europe based on relatively conventional technology can be cost effective at this state-of-the-art LCOE (see Fig. 2). Moreover, if bifaciality is considered, solar cell production on an even smaller scale can be cost effective. Table 1 shows the results of the calculation of LCOE for today's systems with standard technology and future systems with higher efficiency and increased power output using bifaciality.

The cell and module concepts of many institutes and companies aim for higher cell efficiencies (>24%) and lower overall manufacturing cost (including silicon material and crystallization, a very important cost factor), leading to a reduction in LCOE to €ct6/kWh (monofacial application), and higher yearly output (using a novel bifacial high-efficiency module architecture) plus longer lifetime targeting down to €ct3–4/kWh for most optimal bifacial operations.

Bifacial solar cells

The last few years have seen a steady improvement in cell and module performance. Currently, the standard technology – aluminium back-surface field (BSF) on p-type silicon – represents a very large proportion (>90%) of world production, with efficiencies of over 19% on Cz substrates [5]. This progress is largely due to the development of advanced metallization pastes, which allow the formation of a lightly doped emitter and reduced shadowing over the front side of the cell. Nevertheless, it is expected that the performance will be limited in the near future because of the rear surface (passivation and light confinement issues). Different lines of attack are therefore essential in order to produce cells of higher efficiencies.

For many cell producers, the passivated emitter rear cell (PERC) concept represents a natural continuation of standard technology. Such cells are already in production on a large scale in Asia, with an efficiency of over 20%, not taking into account light-induced degradation (LID). Compared with the reference technology, additional steps are necessary, such as rear-surface cleaning, dielectric layer deposition (Al_2O_3, SiO_2) and laser opening [6].

Alternatives technologies to the PERC concept can also be considered, such as the passivated emitter rear totally diffused (PERT), the a-Si:H/c-Si heterojunction (HJT) and the IBC (Fig. 3). All these three architectures have one thing in common: they can be bifacial. When such cells can benefit from an albedo, the gain in yield can be impressive, as stated by Kreinin [7], who reported that an 18.5% cell mounted over a surface with intermediate albedo can yield a bifacial gain of 20%, corresponding to an equivalent cell efficiency of 22%.

As in the case of PERC, the PERT cell has the advantage of being more compatible with existing production lines; indeed, only a few additional manufacturing tools are required to make the step from standard technology. The PERT cell architecture, depicted in Fig. 3, is made up of two diffused layers, namely p^+ for the emitter and n^+ for the BSF on each surface. Anti-reflection dielectric coatings (SiN) and symmetrical contacting grids are deposited on both sides.

The PERT cell is commonly developed on n-type Cz substrates to avoid the LID effect (absence of the boron–oxygen complex). This technology requires three main additional steps: 1) boron diffusion for the emitter formation (p^+); 2) emitter passivation; and 3) the use of specific screen-printing pastes for contacting the boron emitter. As regards the boron diffusion, a higher thermal budget in the range 900–1050°C is required, depending on the technology. So far, gas diffusion (BBr_3, BCl_3) is the approach most commonly adopted, and is currently used in production probably because it is a more mature process [8,9]. Ion implantation is an alternative, as excellent efficiencies with simple process flows have been reported [10,11]. The use of solid sources is another option via the use of PECVD doped oxides or spin-on dopants [12,13]: for example, the technology of PVG Solutions (30MW

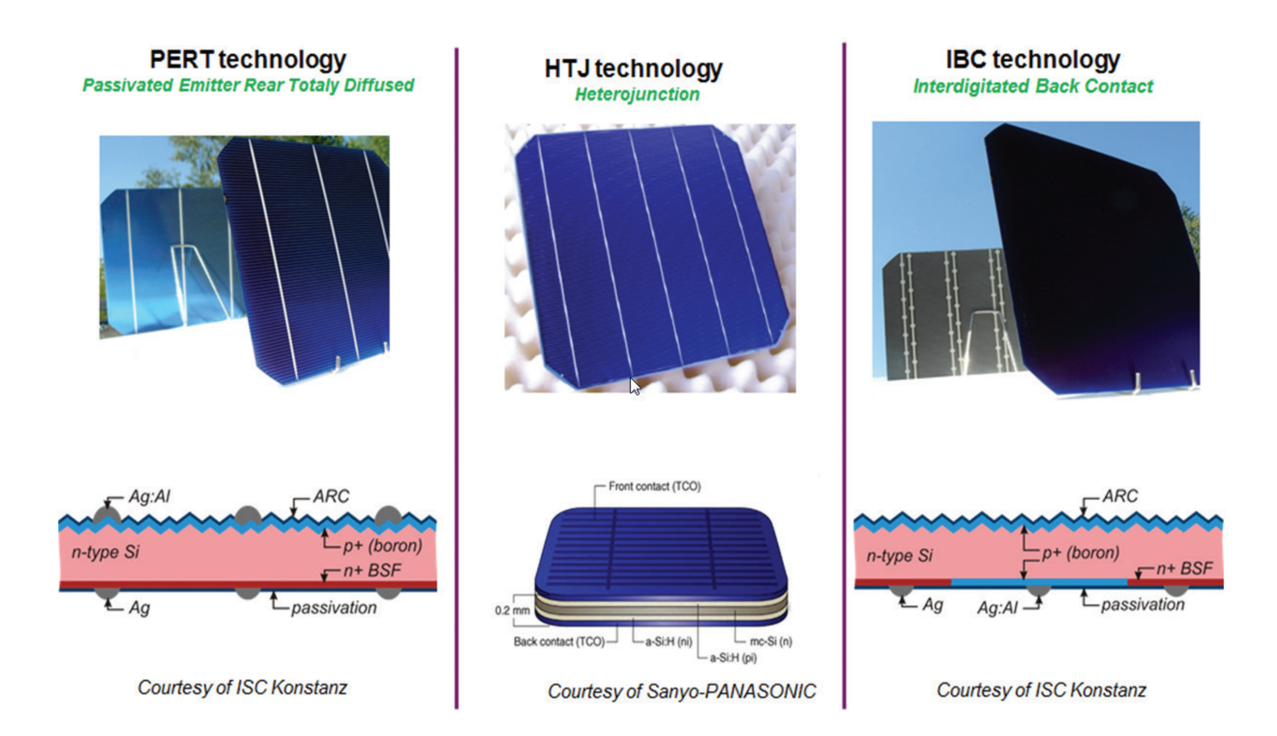


Figure 3. Most prominent n-type technologies with bifacial characteristics.

production line of bifacial cells) is based on the use of spin-on dopants [14]. The emitter passivation can be performed by silicon oxide growth (dry or wet), by Al_2O_3 layer deposition (PECVD, ALD) or by alternatives such as the nitric acid oxidation of Si (NAOS) concept (chemically grown oxide) [15,16]. Dedicated metallic pastes (Ag/Al) are finally deposited by screen printing to contact the boron emitter. As a consequence, quite different process flows are possible for the fabrication of PERT cells (Fig. 4). The compromise between cell efficiency and process simplification remains the principal guideline with regard to industrialization.

In 2009 ECN was one of the leaders in this technology, presenting an efficiency of 18.5% with its PASHA technology. Since then, many players (academics, equipment suppliers or cell producers), including ECN, have reported efficiencies of between 20% and 21.3% (see Fig. 5).

Experts in the field are confident that – for the diffused technologies – efficiencies over 21% should be achieved in 2015. The main factor that limits efficiency is the high recombination activity at the metal/p^+–Si emitter interface, which corresponds to 40% of the total cell J_0 [17]. Most players report a large gap between the implied V_{oc} value measured on the cell before metallization and the final V_{oc} value. Even if the Ag/Al pastes were regularly improved in order to print narrower fingers, efficiencies nudging 22% will be difficult to achieve if the issue above is not resolved.

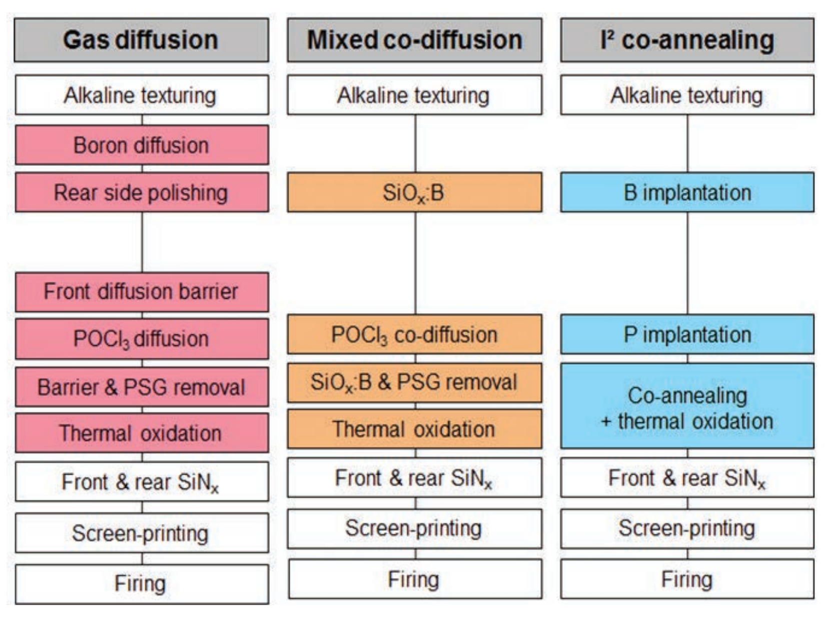


Figure 4. Examples of different process flows for the fabrication of PERT cells.

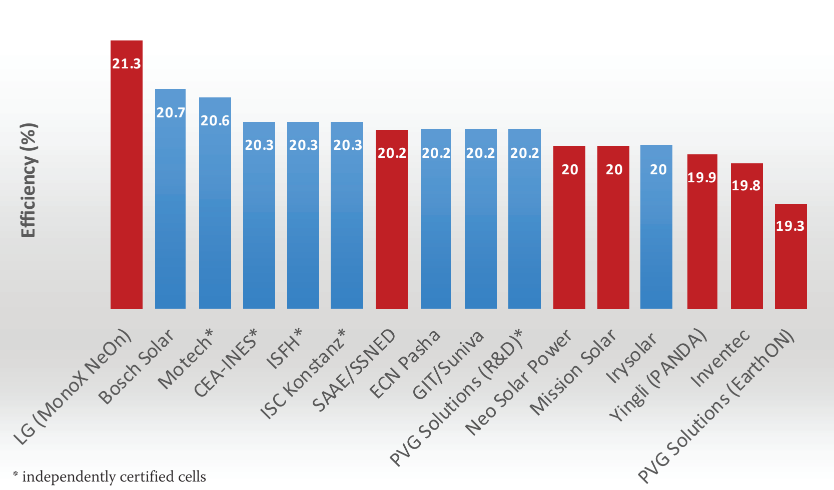


Figure 5. Reported efficiencies for bifacial PERT cells. (The red bars correspond to the performance of a PERT cell in mass production.)

Alternatives such as copper plating and passivated contact concepts are now under investigation to determine their feasibility in competing in the near future with alternative technologies like HJT and IBC. Nevertheless, since the V_{oc} value remains limited, the PERT cell is a lot less sensitive to the substrate quality.

There are currently four producers of bifacial PERT cells – Yingli (PANDA), LG (MonoX NeON), PVG Solutions (EarthON) and Neo Solar Power – and more producers of PERT cells are expected in 2015.

A possible evolution of the PERT cell could be in the direction of IBC; this cell structure is well known to have a very high efficiency potential because of the absence of metallization on the front side. ISC Konstanz has shown that such a device can also be bifacial [18] through its development of ZEBRA technology. Even if an IBC cell yields a better front efficiency than a PERT cell, some studies have reported that this is no longer the case when an albedo is considered.

Sanyo-Panasonic was the first company to market bifacial modules, which were based on its heterojunction with intrinsic thin layer (HIT) technology. This cell concept, grounded on a low-temperature process, is very well suited to the fabrication of high-efficiency bifacial cells. Indeed, the cell structure is made of very thin, hydrogenated, amorphous silicon layers (5–15nm) deposited on both sides of the wafer [19]. This technology presents many advantages:

- The band-gap difference between a-Si:H and c-Si leads to an excellent surface passivation, resulting in very high V_{oc}
- The complete process is performed at a low temperature: ~200°C
- The cells show an excellent temperature coefficient: P_{max} (–0.3%/°C)
- This symmetrical structure is compatible with thin substrates
- The fabrication process requires a limited number of fabrication steps

Finally, the efficiency potential in production is greater than 22%. On a lab scale, Sanyo-Panasonic has reported a record certified efficiency of 24.7% on 100cm² [20].

Unlike the PERT approach, this technology is not highly compatible with existing production lines. As the efficiency is driven by the very high V_{oc},

the substrate quality is also very critical. Some studies have reported that a difference of 1% abs. in efficiency could be obtained over an entire ingot, leading to a widespread or specific selection of the wafers. This is largely explained by a consequent effect of interstitial oxygen content and related defect distribution, as well as the effect of thermal donors. Although Sanyo-Panasonic has for many years been the only producer of HJT cells, with a production capacity of 900MW, new players demonstrating impressive results are now emerging: Table 2 summarizes the main players in the field [21,22].

Bifacial module design considerations

Apart from a higher energy output, bifacial solar modules offer inherent advantages compared with standard, monofacial modules. Usually, bifacial modules are available as a glass substrate or, in certain cases, with a transparent backsheet foil substrate. Backsheet foils typically have a certain water permeability, allowing water to penetrate the backsheet and enter the interior of the solar module. Glass, on the other hand, will totally prevent water from penetrating the module interior over the large area of the solar module back side, which will in turn inhibit any degrading effects over time, such as oxidation or delamination. The only region not protected in glass–glass modules is the edge area, which is typically sealed by double adhesive tape, a silicone seal or specially designed edge seal getters. The solar cells themselves are protected by the large distance between module edge and cell, and any water penetration has to diffuse from the edge before degradation can take place. The advantages of glass–glass modules are best exploited when using encapsulants that do not contain or produce any chemical components that degrade cell metallization or interconnections, such as peroxides, or acetic acids in the case of EVA encapsulants.

Another advantage of glass–glass modules is their greater flexibility, notably when using thin 2mm glass, as well as their mechanical robustness as a result of the solar cells being positioned in the neutral mechanical plane of the material sandwich, hence securing the cells against mechanical tensile or compressive stress. Since the mechanical stability is significantly increased for glass–glass modules, compared with glass–foil modules, frameless applications become the preferred mounting design. This favours direct applications in building-integrated photovoltaics (BIPV) and reduces system costs. Frameless designs may also minimize the risk of potential-induced degradation (PID) in systems with a high operating voltage, as the driving force for PID is the potential between the grounded frame and the cells.

The key challenge for bifacial solar modules is the design and placement of the junction box. Since any placement of junction boxes on light-sensitive areas on the module back side leads to undesired shading, the junction box either has to be reduced in size or must be placed in the edge region of the module, if module size is to be kept constant. At the same time, these smaller junction boxes have to handle higher currents because of the extra current generated by the module back side. The latter problem can be solved by cutting the cells in half, thereby reducing the cell current and, at the same time, the cell-to-module losses. Alternatively, these cell-to-module losses could be reduced by

Company	Cell area [cm^2]	Record efficiency [%]	Status
Sanyo-Panasonic	148	21–22	900MW production
Chochu	243	22.3	Production line in Q1 2015
Kaneka	171	24.2	Production line in 2015
AUO	239	23.1	Pilot line (BenQ)
Silevo	239	23.1	100MW in production Expansion plan 1GW 2016
R&R	239	22.1	Laboratory
CEA-INES	239	22.0	Pilot line (35MW)

Table 2. Record cell efficiencies achieved with heterojunction technology.

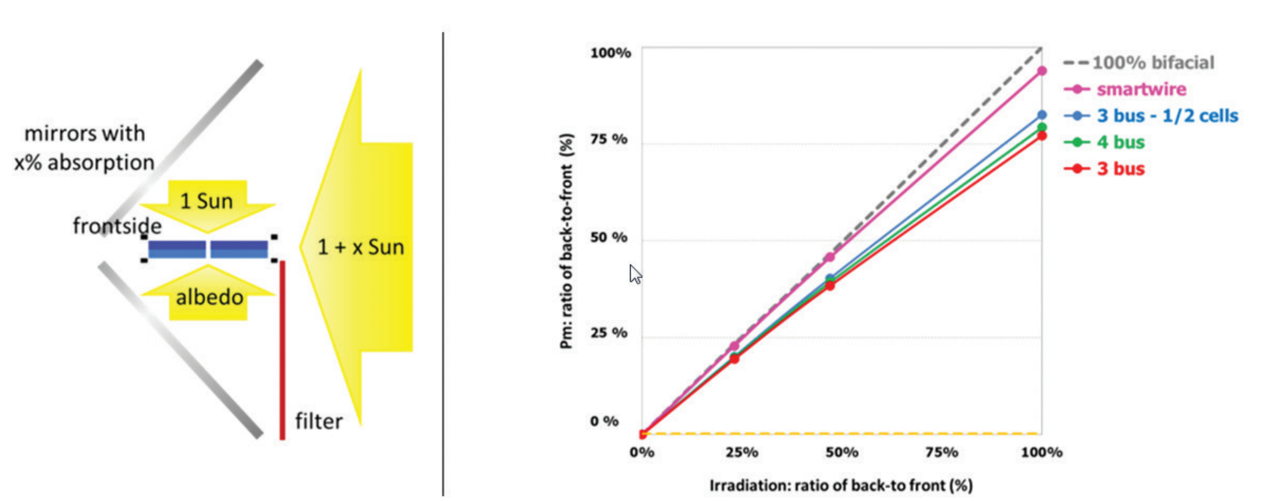


Figure 6. Gain in power P_m with a front-side irradiation of 1000W/m^2 and increasing back-side irradiation from 0 to 1000W/m^2, for different interconnection options (as measured in a solar simulator with symmetrical mirrors for simultaneous irradiation of front and back sides and a mesh filter to vary the back-side irradiation). SWCT and three bus half-cells were found to perform best [24].

an additional busbar at the cell level. A combination of both options leads to almost zero electrical losses from cell to module. This development has currently been implemented in standard glass-backsheet modules in order to further reduce costs by increasing module power, and is an attractive option for bifacial modules as well. Another interconnection option found to be very beneficial for bifacial cells and modules is SmartWire Connection Technology (SWCT) [23], which offers the best performance in a comparison of different interconnection options shown in Fig. 6 [24].

The assembly of bifacial modules by cutting the cells in half can also optimize the energy contribution of the module back side by making it less sensitive to non-uniform irradiation of the back-side surface in ground-mounted systems at low elevations.

> "Bifacial cells offer the potential to realize a significant reduction in the complexity of the cell interconnection process."

For bifacial solar cells the rear side consists of a similar finger/busbar grid to that of the front side (unlike standard, monofacial cells, in which the cell rear side is fully metallized). This makes the cells transparent to IR radiation and may lead to lower operating temperatures in the field. It also affects temperature distribution during soldering and this requires modification of the soldering time and temperature to obtain an optimal compromise between defect generation (cracks) and adhesion strength of the copper ribbons.

Bifacial cells offer the potential to realize a significant reduction in the complexity of the cell interconnection process. A simplification can be achieved by reversing the neighbouring cell so that the interconnection ribbon does not have to make a cross-over from the front to the back side, as illustrated in Fig. 7 [25]. This will allow an increase in productivity of the tabbing/stringing process, a reduction in cell spacing and, at the same time, an increase in module reliability in withstanding thermomechanical stresses caused by temperature cycling (typically tested from –40°C to +85°C). This concept of 'planar' interconnection requires cells with a high bifaciality factor (> 98%).

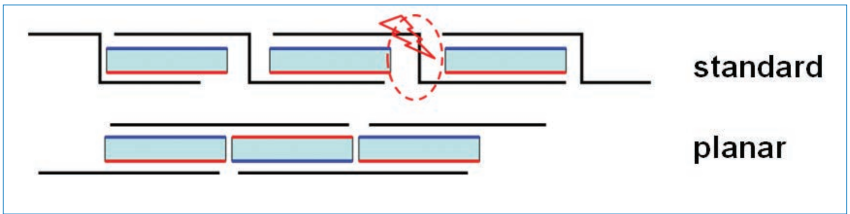


Figure 7. Top: standard cell interconnection, where the interconnection ribbons (black) connect the cell front side to the neighbouring back side. Bottom: planar interconnection process with bifacial cells.

Bifacial systems and applications

Bifacial modules can be implemented in PV systems in various ways, resulting in different bifacial gains as a result of variations in the albedo of the surroundings and the bifaciality factors of the modules: examples for ground-mounted and flat-rooftop systems are shown in Fig. 8. Systems with a module inclination (slanted) that is optimum in the case of monofacial modules result in the highest total energy production and, accordingly, in the lowest LCOE. Depending on the geographical location of the installation site and on the albedo of the underlying surface, horizontally mounted systems can also yield a high energy production.

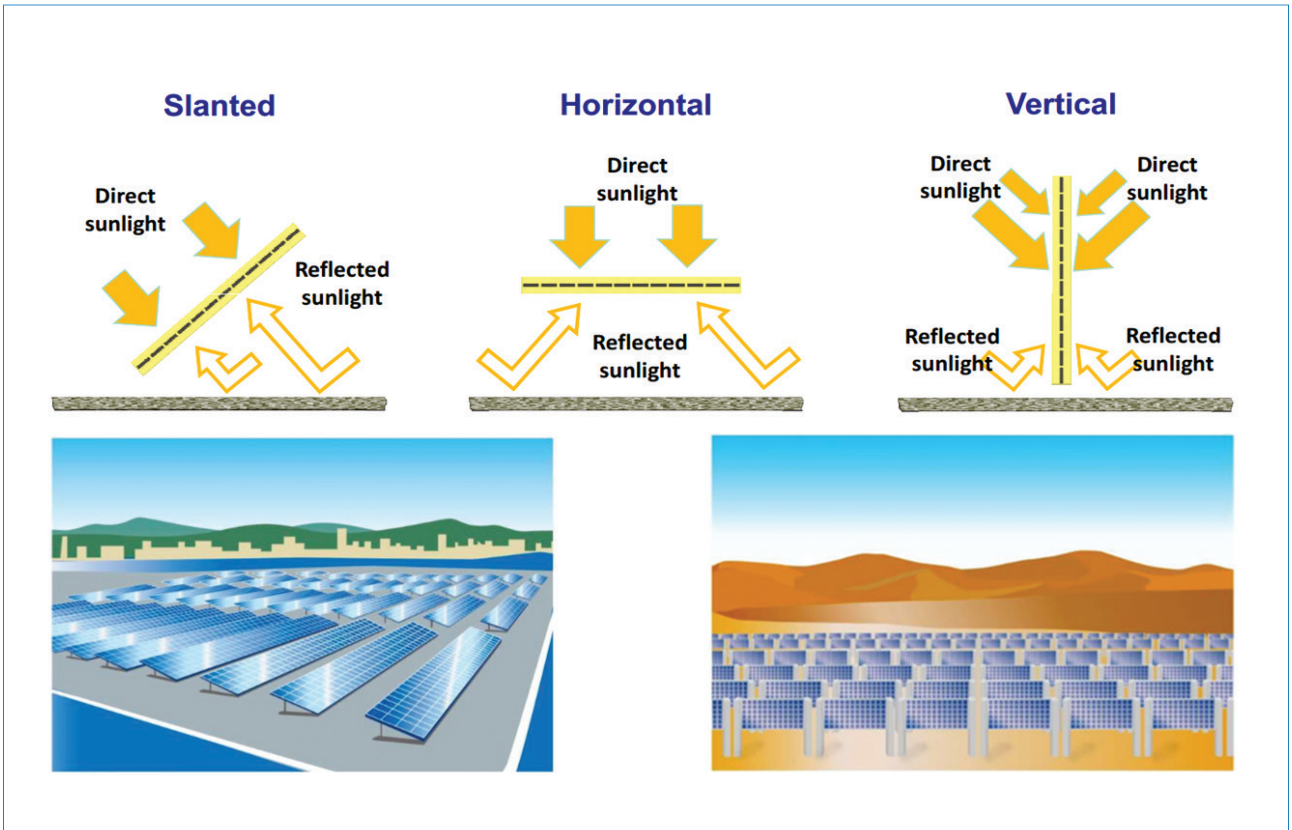
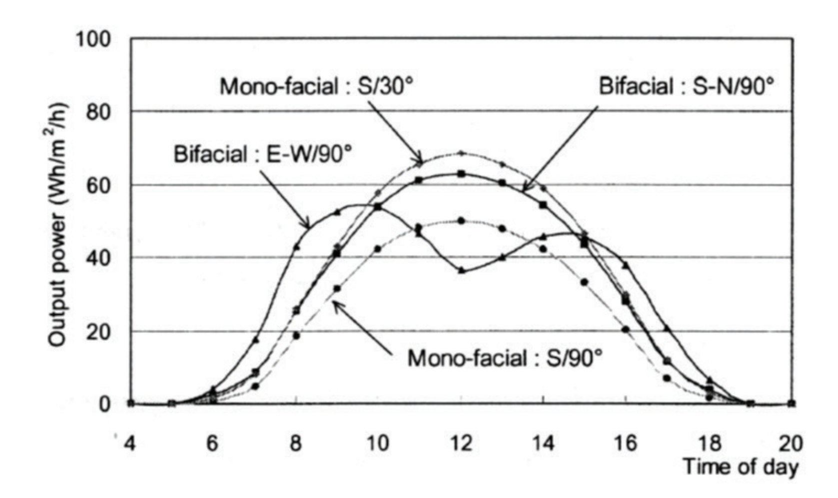


Figure 8. Different implementations of bifacial modules (landscape pictures taken from PVG Solutions [26]).

Vertical mounting has some interesting features. First, soiling is considerably reduced compared with that of modules mounted with a standard inclination, and is of particular interest for desert regions. Second, vertically mounted bifacial modules can be installed, for example, along highways or used for other applications where long single rows of modules are suitable (e.g. anti-noise barriers). Third, vertical modules facing east–west deliver the same energy yield (kWh/kWp$_{front}$) as south-facing monofacial modules mounted with a standard tilt. In addition, the east–west configuration of vertical bifacial modules has another interesting advantage: during the day two peaks of energy production are delivered – one in the morning and one in the evening – with a lower energy production at noon. As shown in Fig. 9, a combination of this configuration with standard, south-facing modules contributes to a more homogeneous electricity generation profile during the day ('peak-shaving') and is extremely beneficial in terms of integrating more PV power into the electricity grid.

As shown in Fig. 10, when bifacial modules are installed over surfaces with good or high reflectivity, bifacial gains (percentage increase in kWh/kWhp$_{front}$ of bifacial modules compared with kWh/kWhp of monofacial modules) of 15–26% are possible. This has a significant impact on the dimensions of the PV system: assuming a bifacial gain of 20%, and taking a traditional 1MW ground-mounted system composed of 250Wp multicrystalline modules as a reference, bifacial modules with a P_{mpp} (front) of 290Wp under front-side illumination enable the number modules to be reduced by around 30% while maintaining the same yearly electricity production (Fig. 11). Apart from reducing the amount of land required to install a PV plant with a given electricity production capacity, this also results in cost savings in all other area-related BOS costs: mounting structures, cables, and the preparation and maintenance of the installation site. As a result, bifacial PV technology allows a significant reduction in LCOE, compared with monofacial high-efficiency technologies, such as PERC.



Source: Joge et al. [27].

Figure 9. Electricity generation profile for vertically mounted (90 degrees) bifacial and monofacial modules in east–west and south exposures, compared with the generation profile of a standard configuration (monofacial, south-facing, 30-degree inclination).

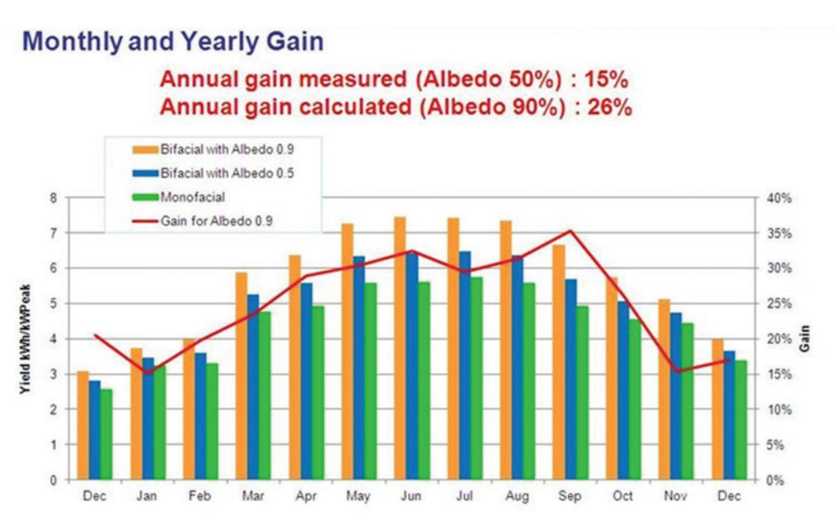


Figure 10. Bifacial gain for a PV system mounted on a flat rooftop, considering albedos of 0.5 and 0.9 [28].

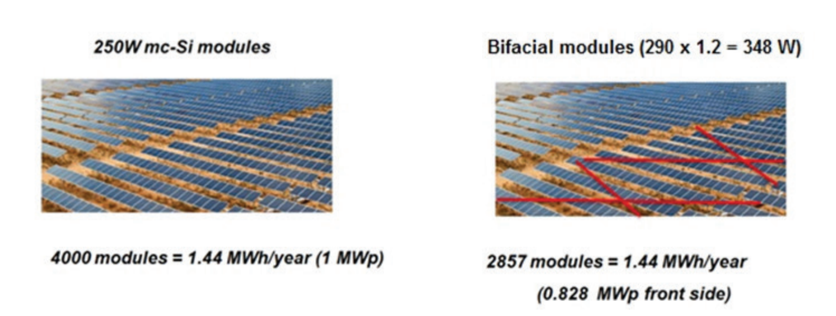


Figure 11. The use of bifacial modules requires around 30% fewer modules (for the same total kWh/year) and reduces the area-related BOS costs of the PV system.

Standardization of measurements, module qualification and system simulations

Standardization of measurements: cell and module

In most laboratories, PERT cells are measured on a gold-plated chuck, which tends to represent the optimal cell performance. As shown in Table 3, the efficiency can vary depending on the measurement method used: there is no real 'true value' – this will depend mainly on the module technology. In the case of bifacial cells intended for a bifacial module (glass–glass), measurements taken in bifacial mode (probes at the back with no light reflection) are the most suitable.

The bifacial performance of a bifacial cell can be estimated by determining the ratio of the measurements of the rear-side efficiency and the front-side efficiency in standard test conditions (STC): this gives the 'bifaciality factor'

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Ref	Measure	V_{oc} [mV]	J_{sc} [mA/cm^2]	*FF* [%]	*Eta* [%]
CEA*	Conductive chuck	639.5	39.1	79.5	19.9
	Bifacial mode	639.1	38.6	79.0	19.5
ISFH*	Conductive chuck	658.0	38.6	80.0	20.3
	Bifacial mode	657.0	38.2	79.5	20.0

* Measurements at both institutes produced the same results.

Table 3. Certified efficiency of bifacial cells measured in two different configurations.

(BF), i.e. BF = η_{rear}/η_{front}. Depending on the technology and the wafer quality, this BF factor can vary from 87% to 95%, according to the range of values reported in the literature. There is current debate in the community whether in fact this BF factor represents a relevant characterization method, since under working conditions, light arrives at both sides of the cells simultaneously, with a light power density of over 1000W/m^2. New *I–V* measurement systems are now being adapted for making bifacial measurements, where the solar cell is illuminated on both sides, with various power densities ranging from 0 to 1000W/m^2.

Figure 12. ISC Konstanz's measurement site in El Gouna, Egypt.

"A major hindrance to the proliferation of bifacial products currently seems to be a lack of standardization."

A major hindrance to the proliferation of bifacial products currently seems to be a lack of standardization. The pricing of a solar product is typically done on the basis of its peak power output under STC, rated in Wp. Other cell and module parameters – such as the temperature coefficients or the weak light performance – play only a minor role when it comes to pricing.

Bifaciality, until now, has not played any role at all in standardization, because it is not considered by state-of-the-art solar simulators with single flashbulbs, when measuring the peak power under STC conditions. The light source is typically placed far enough away from the measurement subject to achieve a sufficiently homogeneous illumination in the measurement plane. The housing at the sides and behind the subject is completely black so as not to compromise the illumination homogeneity. For bifacial devices, this results in very artificial conditions – a solar device in the middle of a black cavity, which is highly unlikely to be the case in any application. Indirect irradiance caused by scattering in the atmosphere and reflections of surrounding objects is completely masked.

The focus on STC conditions creates the absurd situation that, for a module producer selling its products on a Wp basis, it is advantageous to encapsulate bifacial solar cells with a white backsheet in order to increase the STC value because of internal reflections behind the cell and in the spacing between the cells. However, the user of the device would, in almost every application, harvest more kWh/year with the same module if a transparent backsheet were chosen.

Some companies compensate for the above-mentioned deficiency by quoting the *I–V* parameters both under STC conditions and under a range of conditions with varying additional rear illumination. Others quote *I–V* parameters under illumination conditions defined by the resulting I_{sc} increase as a percentage of the I_{sc} under STC. Some of these datasheet values seem to be measured, whereas others appear to be extrapolated. Details of the data and their determination are usually not quoted.

In summary, it is difficult for a consumer to compare these products and even more difficult to contrast them with monofacial alternatives.

Qualification: module

Since, in an installation with bifacial illumination, the maximum operating current of the module is increased, qualification entities ask themselves how the severity of qualification tests should be increased in order to take into account the rear-side current. Ideally these tests should reflect worst-case operating conditions, which can differ significantly from STC for installations with high albedo. TüV Rheinland therefore proposed to modify the current-driven tests to a current that is equivalent to 400W/m^2 of additional rear-side irradiation [29].

The same applies in the case of the electrical designer of a bifacial installation, who must also consider the increased currents when defining the wire dimensions, the appropriate inverter and protection devices. The designer's job is at least facilitated by the fact that the maximum albedo of a specific installation can be easily measured or estimated from tabulated values.

An accurate calculation or simulation both of the annual energy yield gain of a bifacial installation and of the performance of the system for each position of the sun depends on the spatial distribution of the rear irradiance, which is significantly affected by the geometric conditions of the specific installation [30].

Many bifacial test installations achieve high bifacial gain in conditions characterized by a low zenith angle of the sun, partial overclouding and high indirect irradiance. This explains why the annual yield gain is often higher than the maximum power gain on a sunny day.

In order to achieve a standardization of certification measurements, data sheet declarations and test conditions, and to connect these to maximum current and yield simulations, it was decided by a group of institutes, test laboratories, equipment manufacturers and producers of bifacial solar products during the latest bifacial workshop to establish four working groups addressing all standardization topics [1]. The first meeting took place at the EU PVSEC, in which the participants agreed on a roadmap for the next few steps.

Simulations: systems

It has also already been demonstrated at large-scale solar power plants that the energy yield of a solar system can be significantly enhanced by the use of bifacial modules [14]. In the desert at El Gouna (Egypt), ISC Konstanz compared a bifacial module with a monofacial module [31], both containing n-type screen-printed solar cells of similar technologies [32,33]. For both modules, the tilt angle was 20 degrees, the lower edge was 1m high and the front sides were facing south (Fig. 12). Fig. 13 shows the percentage gain in energy yield in terms of kWh/kWp in the first eight months of 2014 of the BiSoN bifacial module over the ^{n}Solar monofacial module. The overall average gain was as high as 22.3%, and in August an average monthly gain of 25.6% was recorded.

A second bifacial module, namely the ^{n}Solar bifacial module, with a BF of only 55%, was also installed at El Gouna. Fig. 14 shows its power output on May 15th, 2014, along with the irradiance throughout the day; a peak power output as high as 426W was recorded.

bSolar has developed a simulation tool for its bifacial module technology, whereby the electrical gain is calculated as a function of installation height, packing density and albedo, as shown in Fig. 15. For example, a very densely packed system, with an installation height of 1m and an albedo of 50%, can yield a yearly electrical gain of more than 20%.

Commercialization and outlook

As already mentioned, glass–glass modules are rapidly entering the market, as they offer several advantages over standard monofacial modules with white backsheets. Module manufacturers using this technology (SiModule, Apollon Solar, etc.) are therefore screening the market for bifacial solar cells which can be manufactured the same way as standard cells. Currently, there are only

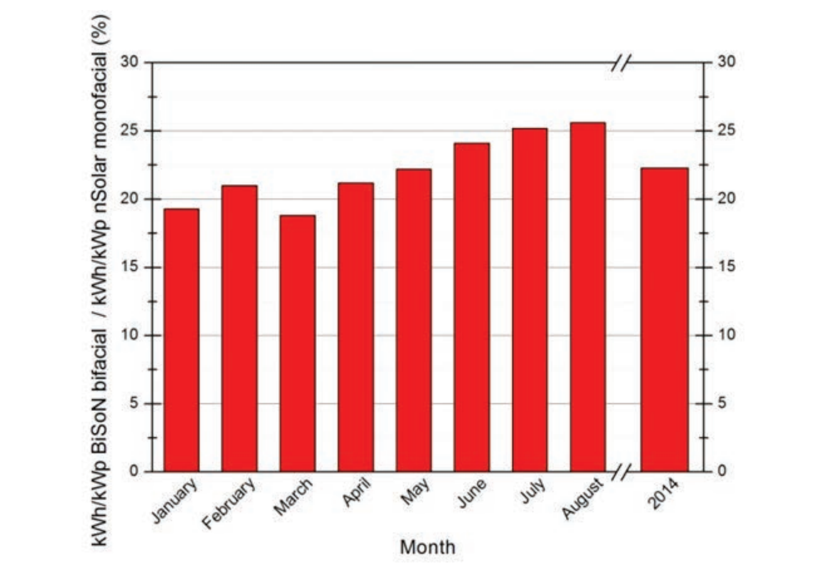

Figure 13. Percentage gain in kWh/kWp energy yield in 2014 of the BiSoN bifacial module over the ^{n}Solar monofacial module.

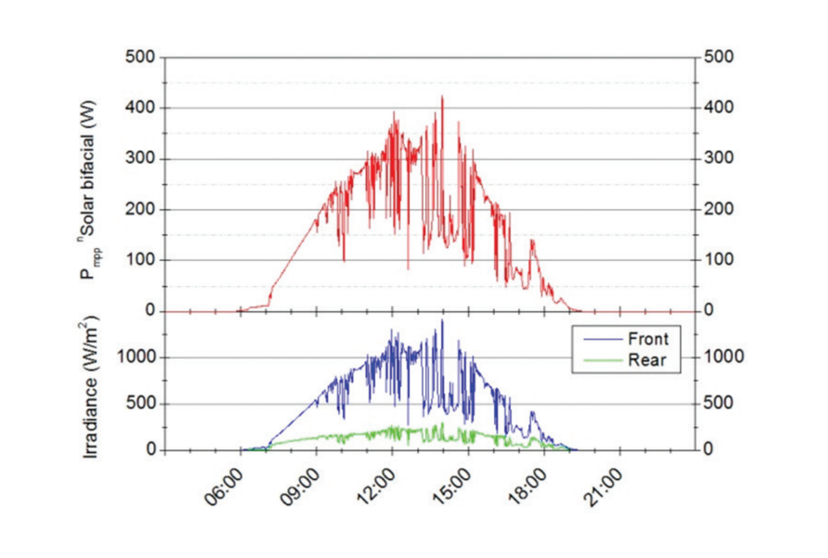

Figure 14. Irradiance and power output of the ^{n}Solar bifacial module at El Gouna on May 15th, 2014.

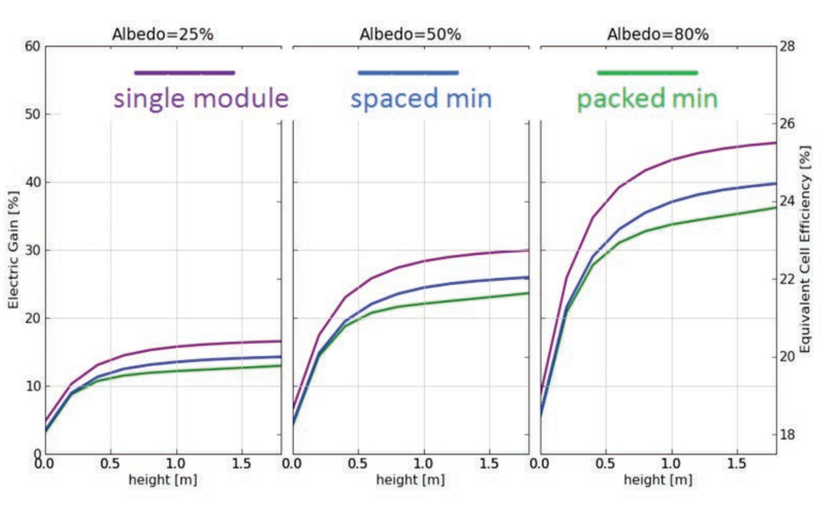

Figure 15. Simulations by bSolar of yearly electrical gain of south-facing bifacial PV installations as a function of installation height, packing density and albedo.

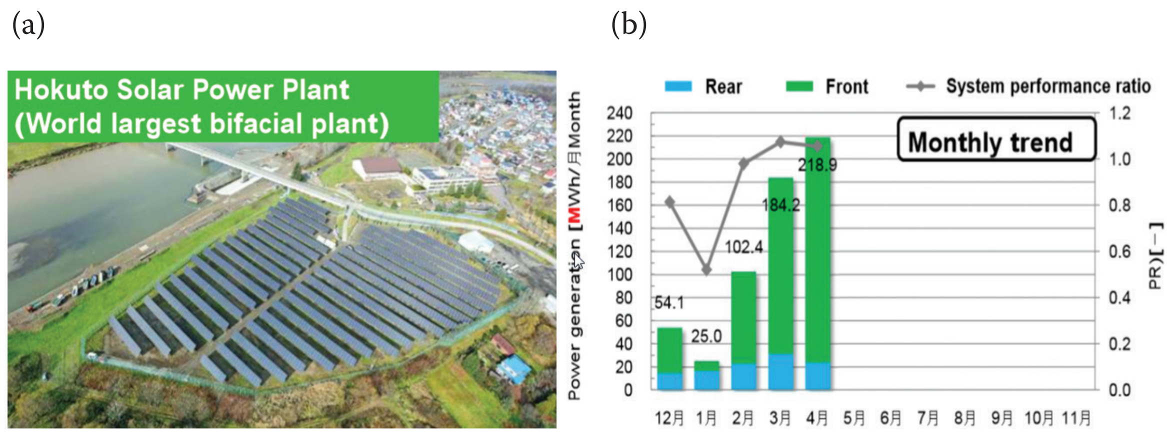

Figure 16. (a) Aerial view of the world's largest bifacial PV plant; (b) monthly energy contribution from the rear.

a few possibilities, such as those offered by PVG Solutions and NeoSolarPower (NSP); the newcomers MegaCell, Motech and Mission Solar Energy will offer bifacial solar cells in Q1/Q2 2015. Panasonic, Silevo and Sunpreme currently market bifacial modules, and First Solar will most likely follow next year as well.

Manufacturing equipment suppliers and technology transfer companies who offer bifacial cell and module technologies are the n-PASHA Alliance (Tempress, RENA, ECN), BiSoN Alliance (centrotherm, ISC Konstanz), French companies supported by INES (ECM Greentech, SEMCO Engineering), Schmidt and Meyer-Burger.

"Large bifacial power plants will be an important part of worldwide PV electricity generation in the future."

To summarize, it has been shown that it is now time to take the step towards bifaciality and that standardization and system simulations are necessary in order to support a sustainable market penetration. The authors are confident that large bifacial power plants will be an important part of worldwide PV electricity generation in the future – plants similar to the largest one at present from PVG Solutions in Japan, shown in Fig. 16.

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