Cost/kWh thinking and bifaciality: Two allies for low-cost PV of the future

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ABSTRACT

To bi(facial) or not to bi(facial) – that is the question, and has been for many years in the PV business. In early 2000 a renaissance of cost-effective bifacial PV started, and now more and more companies are beginning to believe in it. This paper summarizes the status of bifaciality and is a continuation of a previous article in *Photovoltaics International* on bifaciality and kWh cost reduction. The present paper concentrates more on the system side: bifacial gain data for large systems and for simulations of systems reveal that a bifacial gain of 30% on average can be obtained in an optimal situation. It is demonstrated in this paper that the future of the lowest-cost electricity generation from PV is not all about increasing cell and module efficiencies and minimizing cost/Wp, but rather squeezing the best out of a system using a few simple tricks, such as bifaciality, tracking and ground reflection improvements, to achieve the lowest cost/kWh.

Introduction

Bifaciality is becoming sexier every PV year. The EU PVSEC 2015 was announced to be a PERC conference, but in reality it was also a bifacial one. The reason for this is that the PV community has begun to realize that not only is direct sunlight responsible for high yield in a system, but also diffuse irradiance can increase system performance by up to 40% (Fig. 1). And this is true not only for free-standing modules but also for actual systems when properly installed.

> "Not only is direct sunlight responsible for high yield in a system, but also diffuse irradiance can increase system performance by up to 40%."

Even Solar World has now announced the development of a bifacial module, which will enter production in Q4 2015 [2]. In order to progress bifaciality into mass production, however, the three most important issues to be addressed are:

1. **Bankability:** proof of the bifacial gains for PV systems larger than 1MWp.
2. **Standardization:** creation of standards for bifacial measurements and lifetime testing conditions.
3. **Simulations:** improvement of bifacial simulations and their implementation in commercially available system-yield calculators, such as PVsyst.

This paper will address these three important points and report on their status (it is an update of an earlier bifaciality paper by Kopecek et al. [3], published in this journal).

The need for standards to sell the bifacial advantage: away from Wp mentality to kWh thinking

In PV R&D, as well as in the industry, module efficiency records (and sometimes power records) are quite often reported to show off the developers' muscles and to demotivate their competitors. However, the fact that these efficiencies were often achieved on a postage-stamp scale and complex and expensive processes were involved is not usually disclosed. If the cost of ownership (COO) were reported as well, then these records would be seen in another light. Basically, there should therefore be four categories for expressing cell and module records when the modules are implemented in a system:

1. Cell and module efficiency
2. Module power
3. Cost/Wp
4. Cost/kWh

The winners in each of these four categories are to be found within different technologies. Whereas categories (1) and (2) are led by SunPower (IBC cell efficiency: 25%), Sharp (heterojunction IBC: 25.1%) and Panasonic (heterojunction IBC: 25.6%) [4–6], category (3) is dominated by standard mc-Si module technologies at costs of around 50US¢/Wp (see Fig. 3).

In the author's opinion the most important category – the lowest levelized cost of electricity (LCOE), where the most powerful modules per area (occupied by the PV system) are necessary – is (and will be) dominated by bifacial technology when around 20% bifacial gain is achieved in large systems. This fact is explained in terms of numbers in Fig. 2.

The lowest-cost Cz-Si module per Wp is still a p-type Cz-Si module with

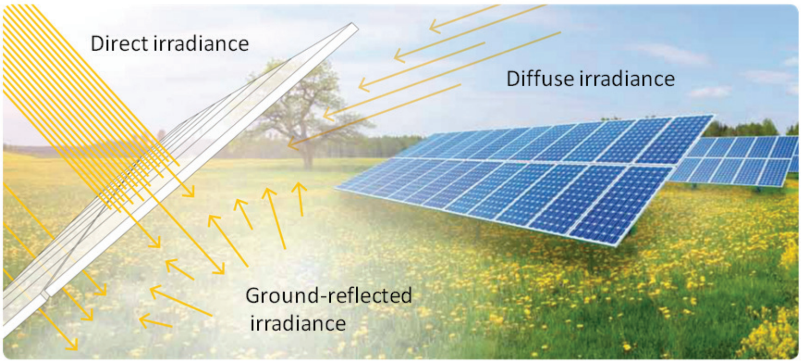


Figure 1. Visualization of indirect light striking the back side of a module, responsible for bifacial gains of up to 40% in a system [1].

Al-BSF or PERC technology. Monofacial modules with bifacial nPERT cells are 2–4US¢/Wp more expensive; even nPERT glass–glass modules are 1US¢/Wp more expensive, since more-efficient cells are required in order to achieve the 280Wp front-side power, because of the transparent rear side of the module. However, if the advantage of the effective peak power (which is what you actually have in a system compared with a monofacial module) were to be considered, then today's monofacial nPERT modules would already be comparable in cost (US$/Wpe) to monofacial p-type PERC modules, while a bifacial nPERT module would be even more cost-effective. If the LCOE is calculated for southern Europe with these modules, assuming a yearly global horizontal irradiation of 2,200kWh/m^2, the bifacial module with a bifacial gain of 20% already yields by far the lowest cost for electricity production. It will be seen later that even higher bifacial gains than that are also attainable in large systems.

The challenges of bifaciality lie in demonstrating its advantages in large systems and in setting standards in order to be able to promote this additional power generated by the rear side. Several meetings of a bifacial consortium led by Pasan, h.a.l.m. and others have already taken place, with the goal of setting standards for bifacial measurements, the most recent one being held at the EU PVSEC in Hamburg in September 2015. More and more companies are expressing their interest in participating in order to push this important topic.

Figure 2. COO and LCOE for different Cz-Si module technologies. (For the bifacial module, a bifacial gain of 20% was assumed.)

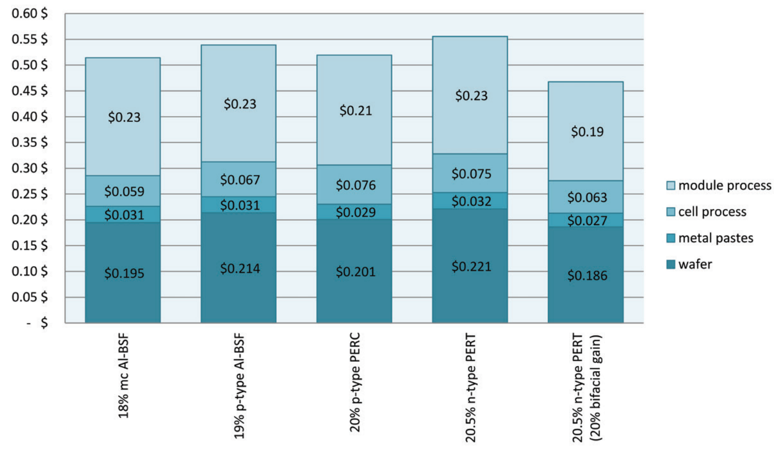
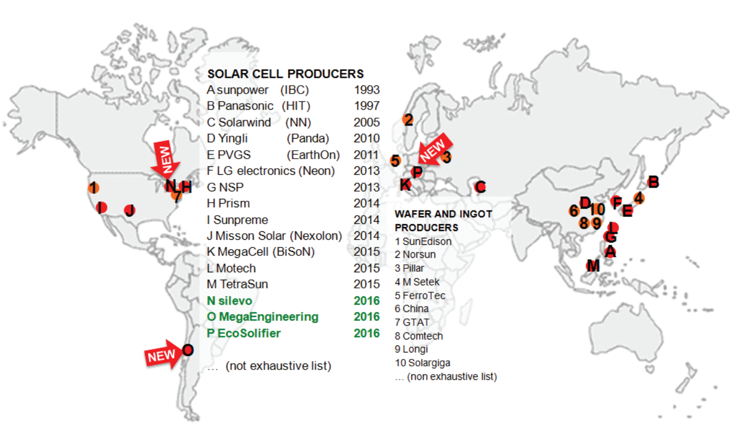


Figure 3. COOs for different technologies.



SOLAR CELL PRODUCERS
A sunpower (IBC) 1993
B Panasonic (HIT) 1997
C Solarwind (NN) 2005
D Yingli (Panda) 2010
E PVGS (EarthOn) 2011
F LG electronics (Neon) 2013
G NSP 2013
H Prism 2014
I Sunpreme 2014
J Misson Solar (Nexolon) 2014
K MegaCell (BiSoN) 2015
L Motech 2015
M TetraSun 2015
N silevo 2016
O MegaEngineering 2016
P EcoSolifier 2016
… (not exhaustive list)

WAFER AND INGOT PRODUCERS
1 SunEdison
2 Norsun
3 Pillar
4 M Setek
5 FerroTec
6 China
7 GTAT
8 Comtech
9 Longi
10 Solargiga
… (non exhaustive list)

Figure 4. Producers of n-type solar cells and wafers since 1993, and new companies entering the market in 2016.

Status of bifacial c-Si solar cells, module productions and PV systems

As already mentioned, the number of solar cell producers that build their business plans on bifaciality is steadily increasing, but mostly outside of China. The Asian Super League of the six largest solar cell producers (Yingli, TRINA, JA Solar, Jinko, Q-CELLS/Hanwha, Canadian Solar) produce about 90% of standard mc-Si BSF solar cells [7], mainly because of the lowest cost per Wp for this type of module. This, however, is extremely dependent on wafer costs, which in the last six months have changed in favour of Cz-Si technologies, as reported by PVinsights [8]: high-performance mc-Si wafers slightly increased in price, whereas mono Cz p-type and n-type dropped to US$1/piece and US$1.1/piece respectively. As shown in Fig. 3, even at the COO level, the costs for Cz-Si module technologies are getting closer to those for mc-Si modules.

The n-type solar cell and module producers

In 2015 n-type c-Si solar cell technology had a market share of around 6–7% [9]; Bloomberg has estimated that by 2025 it will have grown to 40% [10]. The dominating technology will be the PERT cell, with a 25% market share, which is bifacial in any case. Fig. 4 shows the list of n-type wafer and solar cell producers, beginning with existing n-type cell manufacturers which have been in the market the longest – SunPower and Panasonic (former Sanyo). PERT technologies, which are explicitly optimized for bifaciality, are produced by PVGS, NSP, Prism, Sunpreme, MegaCell, Motech, Inventech and Tetrasun.

In 2016 there will be new companies of note entering the n-type market, which are also outside of China: silevo in the USA [11], MegaEngineering in Chile and EcoSolifier in Hungary [12]. MegaCell also has plans to extend its cell and module production to Egypt.

Other companies – such as Panasonic, Yingli, LG electronics and Mission Solar – are instead producing monofacial modules with their bifacial solar cells. However, there is strong interest at the moment from companies like Panasonic and LG in also entering the bifacial market. In addition, many glass–glass module producers are buying cells from PVGS, NSP and MegaCell; they are doing so not just to optimize the LCOE but also on aesthetic grounds for the building integration sector.

If the COO of modules on the market in 2015 is examined (see Fig. 3), it can easily be seen that the mc-Si standard module is slowly losing its edge. The cost for the p-type PERC module is already extremely close to the lowest of the mc-Si costs. Monofacial PERT modules are slightly more expensive, but if the effective power (the additional contribution from rear-side irradiance) of bifacial PERT modules is taken into account, this module technology would at this stage already be the cheapest. This is exactly what machine builders have realized in the last two years: Centrotherm is putting BiSoN from ISC Konstanz on the market, Tempress is making available nPASHA from ECN, and Meyer Burger is offering its own HIT technology.

Bifacial c-Si PV systems

On the system side, many things can also be done to increase the bifacial gain. The modules can be mounted at a greater height off the ground, and the ground itself can be conditioned for increasing the reflection. When the installation is done perfectly, up to 40% can be gained as compared with a monofacial module: 30% of that comes from the bifacial performance gain and the other 10% from the reflection to the front side, even if this side is facing the sky. Even if a rather moderate gain of 20% is assumed, the LCOE for a bifacial system is lower than that of any of the monofacial technologies on the market, as illustrated in Fig. 5.

> “The LCOE for a bifacial system is lower than that of any of the monofacial technologies on the market.”

If a single-axis tracking system were applied to a bifacial PV system, depending on the tracking costs, an LCOE of 4US¢/kWh calculated for a large ground-mounted system with a yearly global horizontal irradiance of

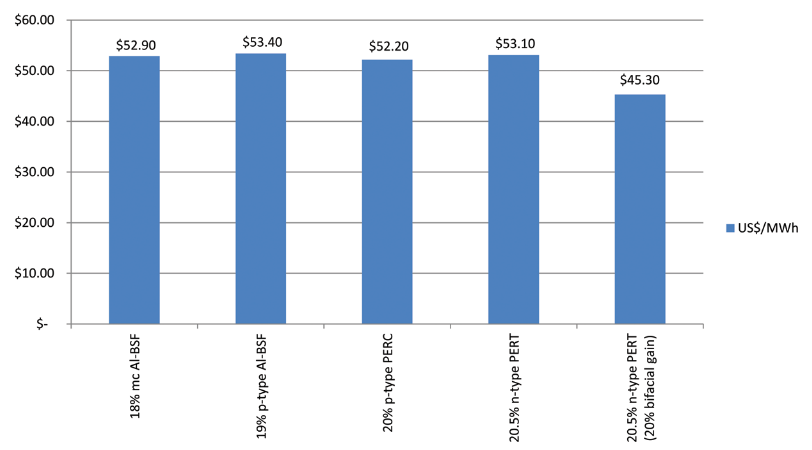
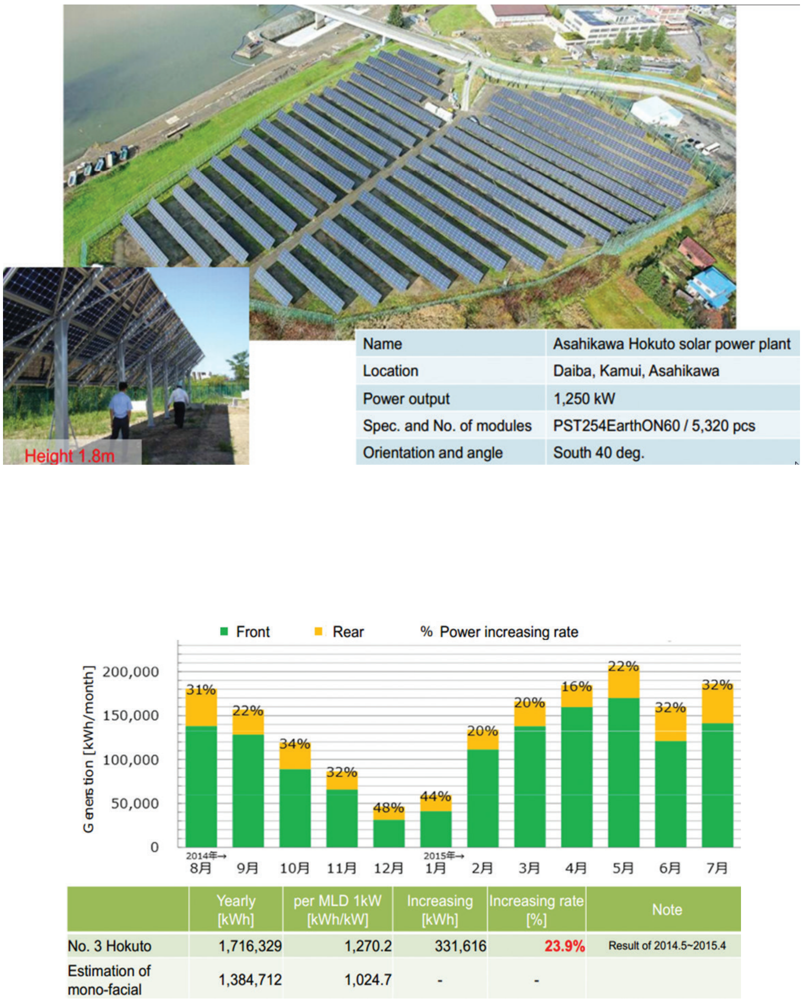


Figure 5. LCOEs for different technologies.

Figure 6. Commercial open-field installation in Saxony, Germany: 8 months with a 20% (0.2) reflectance ground albedo and 12 months with a 50% (0.5) reflectance ground albedo. Results: 17% bifaciality gain over the best module in the field and more than 60% gain in snowy conditions. (The bifacial system kept collecting solar energy through the back side even when the front side was covered with snow, in contrast to all the other systems, which stopped yielding power in these conditions.) The respective cell equivalent efficiency values are 21.7% and 29.6% [13].



Name	Asahikawa Hokuto solar power plant
Location	Daiba, Kamui, Asahikawa
Power output	1,250 kW
Spec. and No. of modules	PST254EarthON60 / 5,320 pcs
Orientation and angle	South 40 deg.

	Yearly [kWh]	per MLD 1kW [kWh/kW]	Increasing [kWh]	Increasing rate [%]	Note
No. 3 Hokuto	1,716,329	1,270.2	331,616	23.9%	Result of 2014.5~2015.4
Estimation of mono-facial	1,384,712	1,024.7	-	-	

Figure 7. World's largest bifacial PV system so far, located in Japan [14].

Figure 8. The bifacial PV system currently being set up by MegaEngineering and Imelsa. With a total power of 2.5MWp and 3.25MWpe [15], the 'BiSoN farm' will become the world's largest bifacial PV system.

2,200kWh/m^2 (e.g. for southern Europe, North Africa and India) would already be possible today.

The images in Fig. 6 show an old installation of bSolar, where bifacial gains of 17–30% were observed during the year. Similar observations have been well documented at the world's largest bifacial PV system, located in Japan, with a power of 1.25MWp (Fig. 7). Even though the bifacial installation is not ideal (notice the rear-side shadowing from the metal installation), monthly bifacial gains of 20–48% are indicated, with an average of 24%. During the winter months, when the system is covered by snow, the rear side still produces electricity, giving rise to faster melting of the snow off the front.

What will become the world's largest bifacial system is currently being built in San Felipe in Chile (Fig. 8), close to Santiago de Chile. A joint venture of MegaEngineering and Imelsa, it will comprise a fixed-tilt PV field with BiSoN bifacial modules from MegaCell, with a total power of 2.5MWp – hence double the size of the current largest installation. MegaCell wants to demonstrate the high potential of bifaciality with this bifacial field, aiming for average bifacial gains of more than 30%.

The next section summarizes the bifacial gains of existing bifacial PV systems.

Summary of bifacial gains in large PV systems: bankability

An important contribution to making bifacial PV bankable is the collection of real-world energy-yield data; this means the monitoring of the energy production of large bifacial PV systems in different geographical locations and with various installation configurations. Ideally, part of the plant includes standard monofacial modules, allowing accurate calculations of the bifacial gain to be made.

Regarding the geographical location, apart from the total irradiance, the diffuse irradiance fraction plays an important role in the bifacial gain that can be obtained: the more diffuse light there is, the higher the irradiance of the rear side of the bifacial modules will be. On the other hand, various installation configurations enable the advantages of bifacial modules to be gained in different ways: for example, MW-size ground-mounted systems that have fixed-tilt or one-axis tracking, with natural ground or artificially enhanced albedo (white sand, reflective plates or sheets, etc.), and kW-size to MW-size PV systems on flat rooftops. Bifacial PV systems vertically mounted in an east–west orientation reap particular benefits in snow-rich regions (no sticking of snow) or desert locations (no soiling), and also contribute to a more consistent energy production throughout the day ('peak-shaving'), thus improving the alignment between electricity production and demand.

In the past 10 years, some data regarding the energy yield of several bifacial PV systems have been published, for demonstration purposes, by various manufacturers of bifacial PV cells and modules, such as PVGS, bSolar and Sanyo/Panasonic. A summary of such data found in the literature is given in Fig 9. This data shows, on the one hand, that even under conditions that are not ideal (ground albedo less than 20%, which corresponds to, for example, grassland), the bifacial gain of a system is always higher than 10%; on the other hand, if measures are taken to increase the ground albedo to more than 60%, bifacial gains of 20% to 30% are possible (see, for example, the PV system by bSolar in Fig. 10).

If the values of the albedos for various ground types in Table 1 are examined, it becomes clear that an albedo between 20% (grassland) and 40% (dune sand) is possible without taking into account measures to artificially enhance the ground reflectivity. Accordingly, for many potential installation sites, sufficiently high bifacial gains can be achieved without additional investment for modification of the ground surface properties.

As mentioned in the previous section, a more recent installation is the 1.25MWp plant set up by PVGS in Japan, in operation since December 2013 and demonstrating a bifacial gain of 24.9% over a 12-month monitoring period [14]. That will be overtaken by the 2.5MWp plant in Chile which is currently being constructed by MegaEngineering and Imelsa; the system is planned to be connected to the grid by December 2015, and at that point it will be the largest bifacial PV system in the world.

Status of simulations

Another prerequisite of making bifacial PV technology bankable is the capability to predict the energy yield of bifacial PV systems with the same accuracy as that which is already possible today for monofacial systems using commercially available software tools. An accurate prediction of the total energy yield of a bifacial PV system during its entire lifetime is essential for making realistic calculations of the return on investment (ROI) and the LCOE of the system. In addition, the use of such simulation tools for determining the optimum installation configuration for a given location and a specific site contributes to minimizing the LCOE for the specific bifacial PV system. The simulation results for several studies have been published in the past; they demonstrate how various installation parameters impact the bifacial gain (for example, see Fig. 11).

ISC Konstanz (Shoukry [18]) as

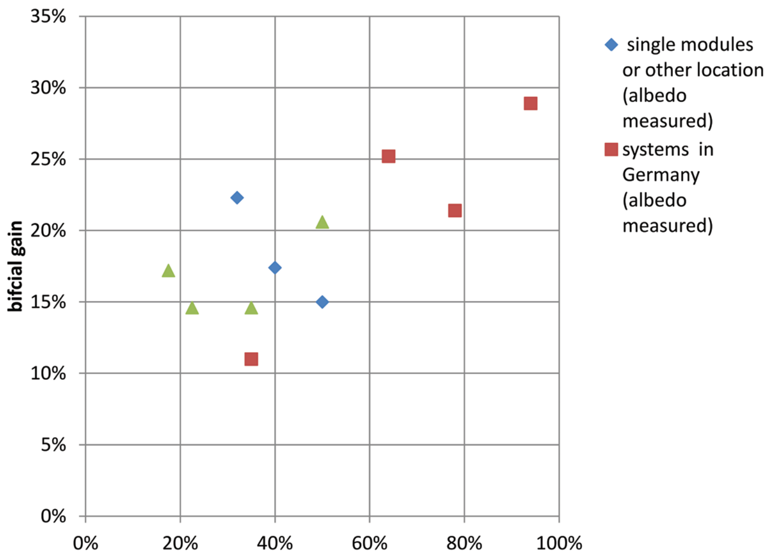


Figure 9. Bifacial gain as a function of the albedo of the surrounding ground at the installation site (data taken from the literature: bSolar, Sanyo/Panasonic, ISC Konstanz, PVGS).

Figure 10. A commercial installation in Geilenkirchen, Germany, monitored by Fraunhofer/ISE (20cm height above the rooftop, 78% reflectance white roof membrane, nine-month period). Results: bifaciality gain = 21.4%; effective cell efficiency = 22.5% [13].v

well as other researchers – such as Chiodetti [17] – have recently carried out extensive work on the modelling of bifacial PV systems. At ISC Konstanz an optical and electrical model has been developed and implemented as a software tool that allows the bifacial gain to be calculated for any geographical location (with available meteorological data) and for a variety of configurations. Some of the most interesting results will be presented next.

One of the questions that have been studied is how big the difference in bifacial gain is between a stand-alone bifacial module (which is a typical example that is often simulated and measured, but not very relevant for real-world applications) and a bifacial module located in the middle of a large ground-mounted solar farm. Consider the following scenario:

- Installation site: El Gouna (Egypt)
- Ground albedo: 50%
- Fixed module tilt: 25°
- Module height above the ground: 1.5m
- Row-to-row distance between modules: 2.5m
- Weather data for the year 2005, retrieved from the SoDa database [19]

In this case the bifacial gain over an entire year for a stand-alone bifacial module has been calculated to be 34% [18]. Values of the bifacial gains for modules located within a complete PV system are shown in Fig 12. In a large MW-size system the modules that are not located close to the edge (i.e. the red ones in Fig. 12) of the system, which feature a bifacial gain of 27.72%, represent a major part of the PV system; accordingly, the complete system will yield a bifacial gain of around 28%.

One possibility to further enhance the energy yield of a bifacial PV system is to use a tracking system; in the case of a cost-effective one-axis tracking system, this option will lead to a further reduction of the LCOE. A particularly cost-effective solution is the so-called sunbelt tracking system, whereby a module is rotated around a horizontally fixed north–south-running axis and tilted towards the east in the morning, upwards at noon, and towards the west in the evening. This is shown schematically in Fig. 13 and is ideal for installations in the equatorial regions.

Surface	Albedo
Dry dark soil	0.13
Grass	0.17 to 0.28 (avg. 22.5)
Dry sand	0.35
Dune sand	0.37
Old snow	0.4 to 0.7
Fresh snow	0.75 to 0.95

Table 1. Albedos for different ground types.

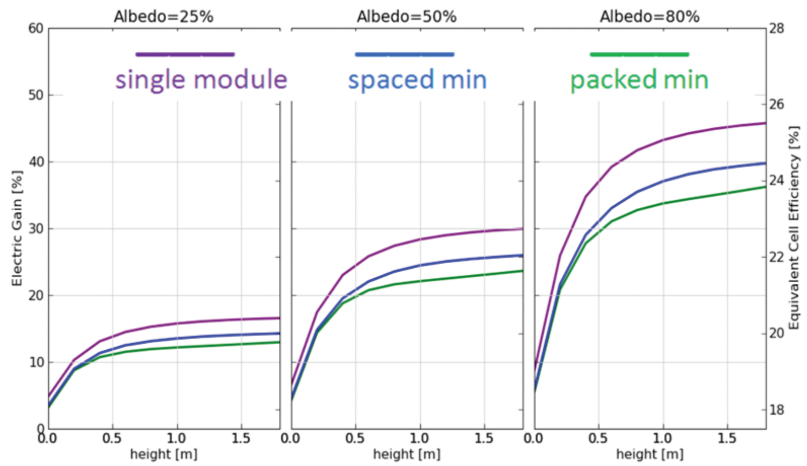


Figure 11. Simulations of the dependency of bifacial gain on both system configuration and ground albedo [16] ('packed min' = standard spacing between module rows; 'spaced min' = 150% of standard spacing).

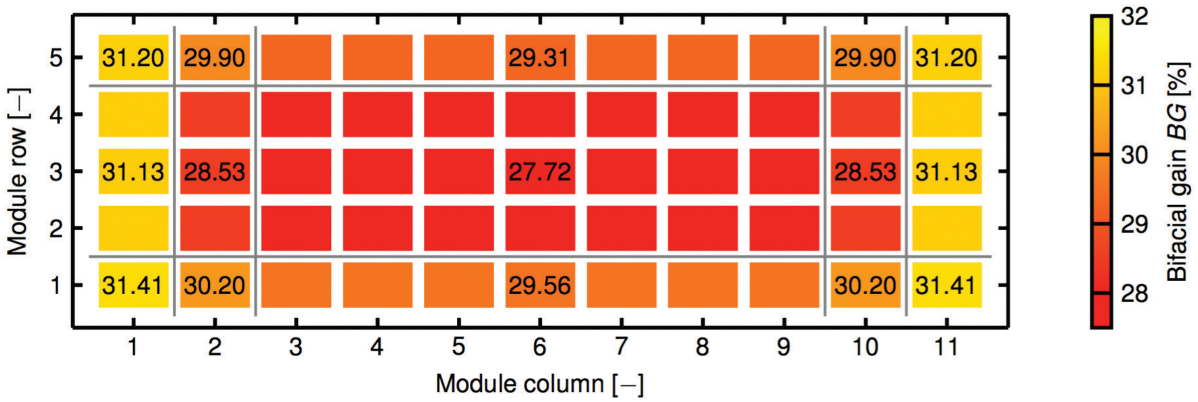


Figure 12. Results of the simulation of the bifacial gain of modules in various positions within a bifacial PV system. The location of the system (meteorological data and geographical latitude) is El Gouna (Egypt), and the modules (with a fixed tilt of 25°) are assumed to be installed at a height of 1.5m, with a row-to-row distance of 2.5m; the ground albedo is 50%.

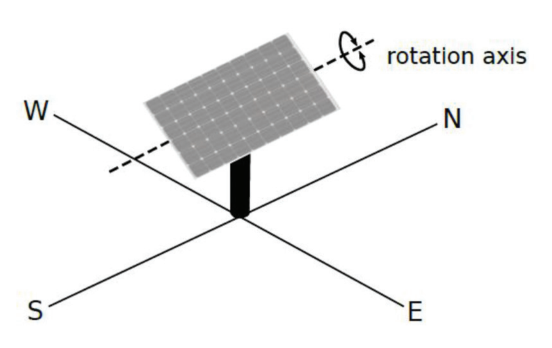


Figure 13. Sunbelt tracking system.

No.	A	→	B	Kasese, Uganda $\alpha = 0.2$	 $\alpha = 0.5$
1	Monofacial fixed	→	Monofacial tracked	14.71%	17.93%
2	Bifacial fixed	→	Bifacial tracked	12.82%	20.30%
3	Monofacial fixed	→	Bifacial fixed	16.47%	43.77%
4	Monofacial tracked	→	Bifacial tracked	22.12%	37.53%
5	Monofacial tracked	→	Bifacial fixed	1.53%	21.91%
6	Monofacial fixed	→	Bifacial tracked	40.10%	62.20%

Table 2. Results of simulations of the bifacial gain for various monofacial and bifacial PV system configurations [18].

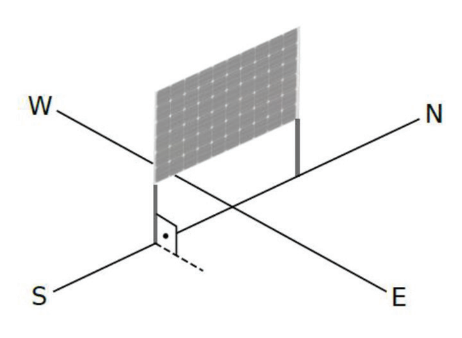


Figure 14. Vertical installation in an east–west orientation.

		El Gouna		Konstanz	
		$\alpha = 0.2$	$\alpha = 0.5$	$\alpha = 0.2$	$\alpha = 0.5$
BG	Monofacial optimum → Bifacial vertical	–14.88%	–5.99%	–4.52%	+15.77%

Table 3. Results of simulations of the yearly bifacial gain for a vertically mounted (east–west) bifacial PV module installed at El Gouna (Egypt) and at Konstanz (Germany) [18].

> "One possibility to further enhance the energy yield of a bifacial PV system is to use a tracking system."

The prediction of the energy yield of a bifacial PV system with one-axis tracking (sunbelt tracker) was therefore part of the study. The results were compared with monofacial tracked- and fixed-tilt installations as well as with bifacial fixed-tilt installations of PV systems in Kasese (Uganda), near the equator.

Table 2 shows the simulation results, which demonstrate in particular that adding tracking support to a bifacial system enables bifacial gains of 40% for an albedo of 0.2, and 60% for an albedo of 0.5 (compared with standard monofacial fixed-tilt systems). A comparison of the tracked bifacial system with a tracked monofacial system reveals a bifacial gain ranging from 22% (albedo 0.2) to 37% (albedo 0.5). These results show the huge potential for reducing the LCOE by combining bifacial PV with robust, cost-effective tracking technologies. Another important element in this context is the development of albedo-enhancing techniques that are environmentally friendly and cost-effective and feature a long-term stable high reflectivity.

As mentioned earlier, a vertical installation in an east–west orientation is a very interesting option for bifacial modules (Fig. 14). While the advantages of such systems from an application point of view (e.g. along highways as a noise barrier, or in desert regions to avoid soiling) have not been questioned, the quantitative benefits in terms of energy production are dependent on the installation site and configuration.

The bifacial gain was simulated for two different geographical locations and for two different albedos. The results of these simulations (Table 3) show that for a high energy yield, vertically (east–west) installed bifacial modules require – apart from a high albedo – a higher geographical latitude as well as a higher diffuse irradiance fraction (both apply to Konstanz when comparing with El Gouna).

Last, but not least, the accuracy of the predictions obtained by the simulation tool has been validated by comparing simulation results with actual data from outdoor monitoring of a bifacial module installed in El Gouna. The following data served as input parameters for the simulation:

- Actual installation configuration: tilt, height, neighbouring module (Fig. 15).
- Experimentally determined albedo of the ground: 30%.
- Weather data acquired at the installation site during the time period when the actual energy yield of the bifacial module (and the monofacial reference) was monitored.

On the basis of these data, the bifacial gain was predicted by the simulation tool and was compared

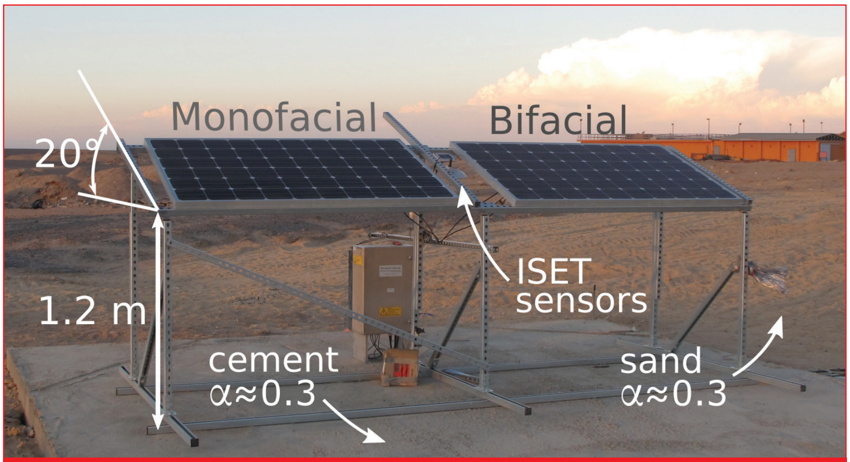


Figure 15. Relevant configuration parameters of the bifacial test installation in El Gouna, Egypt [18].

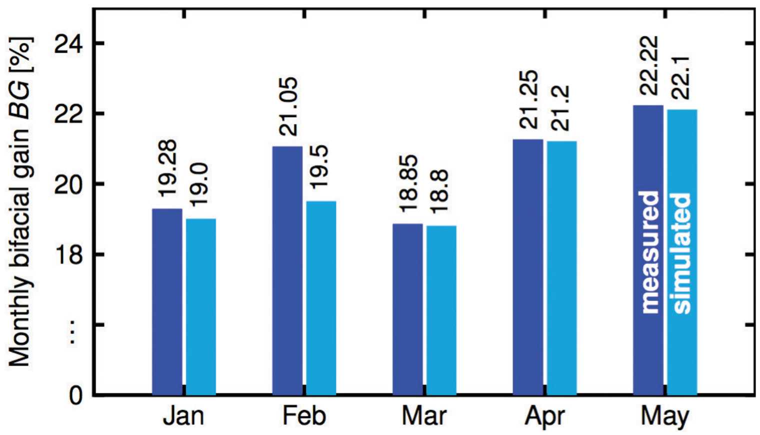


Figure 16. Comparison of simulated and measured bifacial gains, using data obtained from the ISC module test site in El Gouna, Egypt [18].

with the actual measurement data. The good correlation of the monthly values shown in Fig. 16 indicates that the simulation model is delivering realistic data, and therefore represents a very good starting point for the development of a tool that can be integrated into commercial software tools. Further development work will focus on faster computation times, a wider application range (e.g. to include various types of tracking) and further improvement of accuracy.

New companies entering the market

As already mentioned, new companies – such as silevo, MegaCell and EcoSolifier among others – are entering the n-type bifacial market. Furthermore, the p-type market is now working on bifacial solutions with PERT, PERCT and PERC structures. Even mc-Si is entering the bifacial equation: Schmid has developed a bifacial mc-Si cell architecture, and RCT has already transferred its mcPERCT technology to Lu'an, a large Chinese cell and module manufacturer.

bSolar founders are coming back to the market under the company name SolAround, with new ideas and cell concepts. Yet another company – Solar World – has announced a bifacial PERC solar cell, namely PERC+, and expects to enter the bifacial market in Q4 2015. EDF has also shown strong interest in bifacial technology, as the company plans to install large PV plants in the future.

> "How fast bifaciality penetrates the PV market will depend on how fast standards are developed and how fast the big investors are convinced about this technology."

Prediction of bifacial future

The future of bifaciality looks extremely bright. No one can stop this technology, as c-Si PV is naturally developing in this direction. Solar cells are becoming bifacial and cost-effective, and are finding their way into the region of the cheapest standard mc-Si technology.

How fast bifaciality penetrates the PV market will depend on how fast standards are developed and how fast the big investors are convinced about this technology. For these reasons, to speed up the market take-up, ISC Konstanz organizes bifacial workshops [20], two of which have already taken place – in Konstanz (2012) and in Chambery (2014). The 2016 bifiPV workshop will be held in September in Miyzaki, Japan, while the 2017 meeting is planned to take place in the USA.

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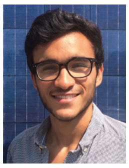

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