Who's who at the leading edge of bifacial PV technology

Cell and module technology | One of the defining trends to emerge so far in 2017 has been an explosion of interest in bifacial PV technology. In the first of three articles in our bifacial special report, Radovan Kopecek looks at some of the key technologies vying for position at the vanguard of fast-growing part of the market

Bifaciality is now strongly entering the PV market, as the technology is becoming more and more mature and bankable. In total, at the time of writing, we have about 200MWp bifacial PV systems installed – with exponential growth [1]. These are mostly ground-mounted PV systems on fixed-tilt mounting and a couple of flat rooftop systems using mostly n-type silicon technologies. Plans for large bifacial systems have been announced lately, for example a 90MWp system by EDF in Mexico [2]. In 2018 we expect to have about 1GW total installed bifacial system power – in 2022 20% of the yearly module market share is expected to be bifacial [3], representing about 20GWp.

The question is now: which technology will win the race in the future? The more bifacial one? The less expensive one? All for different applications?

State of the art in bifacial cells and modules

Currently almost all the existing 200MWp installed bifacial PV systems are based on nPERT (n-type passivated emitter rear totally diffused) or HJ (heterojunction) technologies. This might change in the future in favour of bifacial PERC (passivated emitter and rear cell), as more and more PERC producers are entering the bifacial stage – for example, China's LONGi [4] and Trina Solar [5] are strongly going in that direction. Germany's SolarWorld AG tried to survive the current cost crisis by getting rid of its mc-Si production and instead focusing on PERC and PERC+ (bifacial PERC) production – however that was too late and the company had to file for insolvency; now it seems set to continue as 'another' company, SolarWord Industries GmbH, bought by SolarWorld´s founder Frank Asbeck [6] most likely with a focus on bifacial. Table 1 summarises the most prominent cell concepts currently on the market.

Currently the PV market is still dominated by standard monofacial mc-Si and Cz-Si cells with fully Al-BSF (aluminium back surface field) [7]. The average efficiencies in production are around 19% for mc-Si cells and around 20% for Cz-Si cells. The bifacial factor is 0, as the rear side is fully covered with Al-paste resulting in a homogeneous back surface field. Opening of the Al rear contact in this case will not help, as the opened areas would remain "unpassivated" and the device will tremendously lose out in efficiency terms. Therefore a rear side passivation by a dielectric is needed, which will result in a PERC cell.

Since 2014/2015, after the previous PV overcapacity crisis, PERC technology has been rapidly moving into the PV market [7], as the additional efficiency benefit justifies the additional rear side passivation and lasering costs. PERC mc-Si solar cells currently reach efficiencies of >20% and Cz-Si PERC cells of >21% in production. The market share of PERC technology is about 13% [3, 7]. If you now open the rear side Al metal contact (printing grid or fingers) the passivation between the Al-metal keeping the high Voc and Isc and the light can penetrate into the rear side as well. Therefore, if you optimise the rear side metallisation geometry without reducing the fill factor too much, the PERC cell can be made bifacial with a bifacial factor of about 0.7. This number is limited by lateral conductivity in the solar cell, conductivity of the Al-paste and alignment precision of the Al-grid on the laser openings.

In nPERT and HJ devices the bifaciality factor is much higher – namely 0.85-0.95%. The reason is because high-quality n-type Cz-Si material is used, the lateral conductivity in the substrate is higher due to the use of a rear side conductive layer (P-BSF in the case of nPERT and P-doped amorphous Si for HJ) and the rear side metal contact is a highly conductive firing through or low temperature Ag paste (so no precise alignment is needed as with PERC). The average efficiency in production is now exceeding 21% as well, similar to PERC solar cells. However, due to the approximately 5-10% greater cost associated with n-type Cz-Si substrates at the moment, the cost of ownership is in most cases slightly higher. Therefore the market share for these bifacial n-type technologies is currently only about 5%. However, when it comes to efficiencies exceeding 22% it is much easier to go the nPERT or HJ way as the

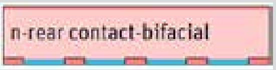
	Standard Al-BSF	pPERC	nPERT/HJT	nIBC
				
Market share 2017 [%]	80	13	5	2
Efficiency 2017 [%]	20+	21+	21+	22+
Bifaciality [%]	0	70+	90+	80+
Market share 2022 [%]	40	30	20	10
Efficiency 2022 [%]	21+	22+	23+	24+

Table 1. Technology share, efficiency and bifaciality numbers of screen-printed low-cost industrial cell concepts

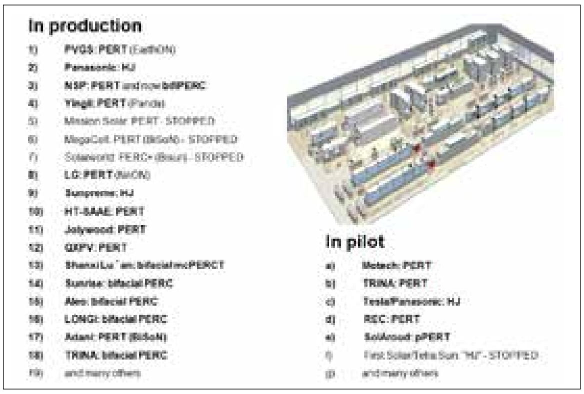
n-type material quality will not limit the cell efficiency. Therefore we believe that nPERT and HJ technology will gain more and more importance in future applications. The trend is visible already today and every large solar cell producer has an n-type roadmap on its agenda.

The last cell concept on the market is the IBC (interdigitated back contact) solar cell. In the case of the ISC Konstanz´s ZEBRA technology even this cell concept is bifacial [8] with a bifacial factor of 0.8%, so even higher compared to the bifacial PERC technology. IBC cells at the moment have a market share of ca.2% – mostly produced by Sunpower; however Sunpower´s cells are not designed to be bifacial. China's Jolywood has ambitious plans to go bifacial n-type IBC with 10GW production capacity [9].

By 2022 market shares will have shifted in favour of high-efficiency advanced cell concepts [3]. One of the reasons for this is that the module costs in a system are becoming so low that an increase of the power of the modules makes the PV system LCOE much cheaper as the balance of system is reduced. Therefore increasing the power of a module is much more important than further reducing its cost. For this reason standard Al-BSF technology will decrease its market share to about 40% [3] and PERC will be increased to 30%. The remaining 30% will be distributed among n-type technologies – nPERT, HJ and IBC. In addition the International Technology Roadmap for PV (ITRPV) forecasts a 20% bifacial technology share in 2022 [3]. We believe that most of that will be covered by n-type technologies – mainly by nPERT.

There are two additional technologies that might become interesting and therefore should be mentioned in this context: mcPERCT by RCT Solutions and pPERT by SolAround. Both technologies are designed to use low-cost p-type substrates and still have high efficiency and high bifaciality potential. Both concepts are p-type technologies with a B-diffusion on the rear side, which allows the use of higher resistive and therefore higher lifetime wafers. pPERT from SolarAround might become a good alternative for nPERT, if the cost difference between the p-type and n-type Cz-Si wafers will remain between five and 10% in future.

Figure 1 shows a list of companies that are involved in bifacial solar cell business at the moment. Most of them are involved in nPERT production such as PVGS, Yingli, LG electronics, HT-SAAE, QXPV and Adani. Now a "new star" rises on the horizon with Jolywood who announced 2.1 GW nPERT production in 2018 [10]. A couple of the cell producers is using the HJ process such as Panasonic and Sunpreme. If the Panasonic/Tesla Buffalo site will be involved in bifacial cell production remains unclear. However there are also many bifacial PERC producers such as NSP, Sunrise, Aleo, TRINA and LONGi. LONGi is the most aggressive among these companies, stating that bifaciality will become mainstream in two years from now [4].



In production

1) PVGS: PERT (EarthON)
2) Panasonic: HJ
3) NSP: PERT and now bifiPERC
4) Yingli: PERT (Panda)
5) Mission Solar: PERT - STOPPED
6) MegaCell: PERT (BiSoN) - STOPPED
7) Solarworld: PERC+ (Bisun) - STOPPED
8) LG: PERT (NeON)
9) Sunpreme: HJ
10) HT-SAAE: PERT
11) Jolywood: PERT
12) QXPV: PERT
13) Shanxi Lu´an: bifacial mcPERCT
14) Sunrise: bifacial PERC
15) Aleo: bifacial PERC
16) LONGi: bifacial PERC
17) Adani: PERT (BiSoN)
18) TRINA: bifacial PERC
19) and many others

In pilot

a) Motech: PERT
b) TRINA: PERT
c) Tesla/Panasonic: HJ
d) REC: PERT
e) SolAroud: pPERT
f) First Solar/Tetra Sun: "HJ" - STOPPED
g) and many others

Figure 1. Companies in production and pilot production of bifacial solar cells

Bifacial modules on the market were developed in a rather evolutionary process, as many module manufacturers were moving towards double-glass products anyhow. However bifacial cells can be included even in standard (glass/white backsheet) modules, glass/transparent backsheet modules and double-glass modules in a classical way. Only the rear side soldering has to be slightly adapted as the precision must be higher. Depending on the chosen module technology the bifacial benefits are of course different.

The best suited technology from a lifetime and maintenance perspective is the double-glass module technology, which can also be produced without a frame, saving costs in aluminium. The more and more used half-cell technology is also beneficial, as the current in bifacial modules will in this way be reduced. Special shallow junction boxes, which are placed at the module side, have already developed for bifacial products. Therefore the module market is well prepared for more and more bifacial cells becoming available.

Bifacial PV system trend

The coming trends in the installation of bifacial modules are likely to see this technology used largely for ground-mounted, fixed-tilt systems or for white flat roofs. However there are more and more PV system applications coming on to the market that will be able to incorporate bifacial modules, such as single-axis trackers specifically designed for bifacial modules [11] or vertical east-west oriented bifacial PV plants [12]. An interesting application would be also using the modules in vertical sound blocking systems on highways, particularly in countries such as Germany with numerous north-south highways. Bifacial modules are becoming so cost effective that more and more business cases of different applications are coming up. The building-integrated PV sector is also very keen on bifacial double-glass modules [13].

We believe that with bifacial technology we enter another era of innovative and lowest cost PV. With this evolutionary technology using double-glass bifacial modules in large ground-mounted and flat rooftop installations we not only increase the lifetime of the system but increase the power density in that systems, which lead to lowest LCOEs ever. With the standardisation for bifacial measurements and improvement of bifacial simulations supporting system planning for installers, bifaciality will become even more bankable and become an important part of PV´s future. ▶

Many of these topics will be explored in the bifacial workshop bifiPV2017 taking place in Konstanz, Germany, on 25 and 26 October this year. Further details are available at ***www.bifiPV-workshop.com***

Author

Dr. Radovan Kopecek is one of the founders of ISC Konstanz, which has played a central role in developing some of the bifacial technologies now being commercially deployed. He is currently the leader of the advanced solar cells department. ISC Konstanz is establishing a research centre in Antofagasta, Chile, focused on developing desert-ready solar technologies, including bifacial.

References

[1] R. Kopecek and Joris Libal, Quo vadis bifacial PV, PV International 35, 2017
[2] https://www.pv-magazine.com/2016/10/04/edf-wins-90-mw-solar-project-in-mexicos-second-auction_100026345/
[3] http://www.itrpv.net/Reports/Downloads/
[4] https://www.pv-tech.org/news/intersolar-europe-2017-bifacial-will-be-mainstream-in-two-years-says-longi
[5] http://www.trinasolar.com/en-uk/resources/newsroom/uktrina-solar-new-cost-efficient-solutions-intersolar-europe-2017
[6] https://www.pv-tech.org/news/solarworlds-founder-asbeck-buys-back-german-manufacturing-and-rd-assets
[7] https://www.pv-tech.org/editors-blog/china-and-oem-cell-production-in-2016-delays-shift-to-p-type-mono
[8] https://www.pv-tech.org/news/snec-2017-worlds-first-full-size-ibc-bifacial-module-to-be-displayed
[9] https://kknews.cc/finance/vpezo8a.html
[10] https://www.pv-magazine.com/2017/02/20/jolywood-breaks-ground-on-2-1-gw-bifacial-cell-factory/
[11] https://www.solarpowerworldonline.com/2016/10/case-study-soltec-sf-utility-tracker-chosen-test-project-chile/
[12] http://www.next2sun.de/
[13] https://www.solarpowerworldonline.com/2015/08/advantages-of-building-integrated-and-bifacial-pv/

IEC standard for power rating of bifacial PV devices

Module rating | The power gains offered by bifacial over monofacial PV technologies are not yet expressed through any common industry standard. Vahid Fakhfouri describes an international project he is leading to produce a new bifacial IEC standard that will eventually aid the clear labelling of bifacial modules

IEC standards [1][2] describe the Standard Test Conditions (STC) and appropriate apparatus for the measurement of photovoltaic current-voltage characteristics. Accurate electrical characterisation is important to set the value of photovoltaic devices. Currently, the specificities of bifacial PV devices and their I-V characterisation are not covered by these standards. This makes it difficult to accurately characterise them. The new standard project IEC 60904-1-2, initiated and led by Pasan (member of the Meyer Burger Technology Group), aims to fill this gap. The project team of 18 international experts, with the help of 20 guest experts, submitted a committee draft in May 2017 to the national committees and an official release of this standard is expected in autumn 2017.

The bifacial challenge

Identification of the PV stakeholder's needs and an understanding of the technical challenges were required in order to propose a coherent standard. I-V characterisation must provide comparability between bifacial devices and must highlight the gain offered by bifacial compared to monofacial technology.

In laboratory environments, comparable measurement results are required in order to provide measurement traceability. The needs and the possibilities are different in laboratories compared to PV production environments. In production environments, I-V characterisation must be well matched with the production throughputs, and the apparatus must be compatible with the production specificities, such as low footprints, automation of the equipment and device handling. Furthermore, I-V characterisation of bifacial devices should be available at a reasonable cost.

In the future standard, I-V characterisation is extended to quantify the bifaciality coefficients of the device and the power generation gain it can yield.

Measurement method

The approach chosen by the project team is very similar to the one used in the determination and the use of the temperature coefficients [3]. These coefficients are determined in laboratories, through a rigorous process, on samples of a cell or module technology. The results are then used in production environments to correct the measurement results of production batches of the same technology. Similarly, for the I-V characterisation of bifacial devices, the bifaciality coefficients and the bifacial power gain are to be determined on samples in laboratories. These are then used to assess the production output.

Bifacial characterisation in laboratories

In order to determine the bifaciality coefficients of the test specimen, the main I-V characteristics of the front and the rear sides must be measured at STC (irradiance $G=1000W{\cdot}m^{-2}$). A non-irradiated background must be used in order to avoid the illumination of the non-exposed side. The background is considered to be non-irradiated if the irradiance is measured to be below $3W{\cdot}m^{-2}$ on the non-exposed side of the device. In order to fulfil this requirement, it is highly recommended to limit the size of the test area to the one of the devices under test using apertures

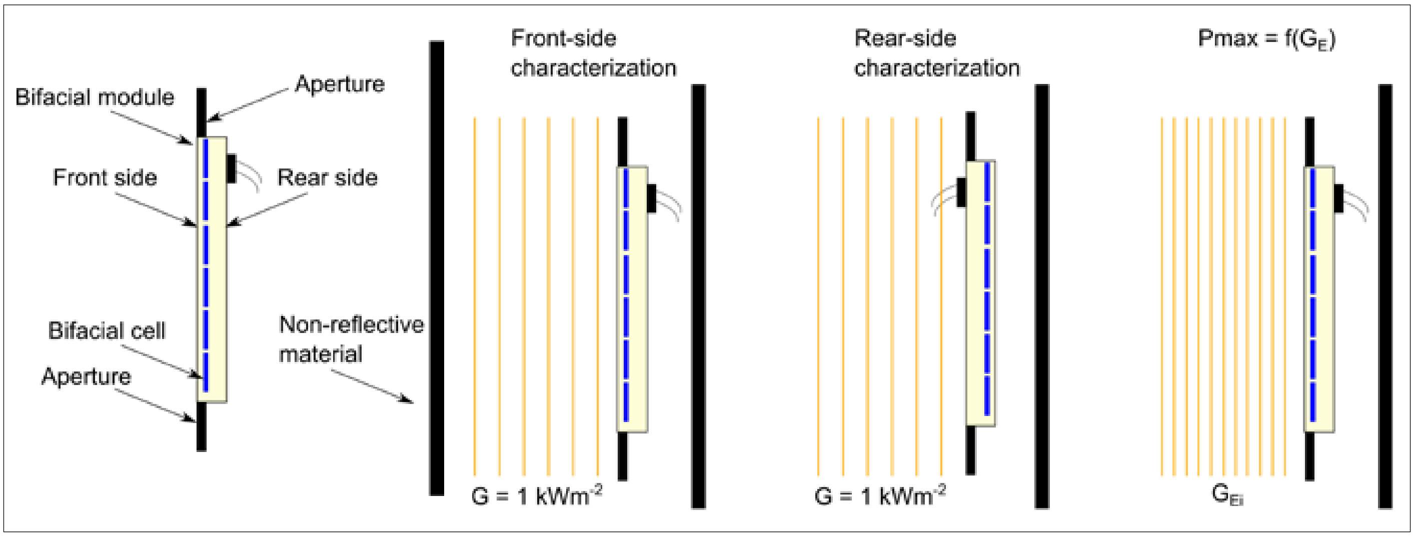


Figure 1. Left: scheme of a bifacial PV module and the required non-irradiated background and aperture. Right: bifaciality coefficients and bifacial power gain measurements

Figure 2. Pasan's bifacial-compatible contacting solution PCB^{TOUCH}: with non-irradiated background and the possibility for background compensation

as illustrated in Figure 1. Materials with minimised reflection in the wavelength range corresponding to the spectral responsivity of the test specimen, placed at a suitable distance from its non-exposed side, shall be used to reduce the irradiance level (non-reflective material).

In the case of bifacial solar cells, the use of low-reflectivity materials to manufacture cell holders may be insufficient to reach irradiance values below 3 W•m^{-2}. In that case, background compensation may be performed by extrapolating the short-circuit current as a function of the background irradiance.

Bifaciality coefficients φ_{Isc}, φ_{Voc}, and φ_{Pmax} are the short-circuit current, open-circuit voltage and maximum power bifaciality coefficients respectively, and correspond to the ratio of the key data of the front and the rear sides:

$$\varphi^{Isc}=\frac{Isc_r}{Isc_f},\ \varphi_{Voc}=\frac{Voc_r}{Voc_f}\ ;\text{and}\ \varphi_{max}=\frac{Pmax_r}{Pmax_f}$$

The gain in power generation yielded by the bifaciality of the device under test must be determined as a function of the irradiance on the rear side. *Pmax* of the device must be measured on the front side at equivalent irradiance levels corresponding to 1,000W•m^{-2} on the front side plus different rear side irradiance levels G_{Ri}. The equivalent irradiance levels are determined as functions of the bifaciality coefficient φ ($\varphi=Min(\varphi_{Pmax},\varphi_{Isc})$) according to the equation below:

$$G_{E_i}=1000\ W{\cdot}m^{-2}+\varphi{\cdot}G_{Ri}$$

At least three different equivalent irradiance levels are required (i=1,2,3,…).

Example: A device with bifaciality of φ=80%, must be irradiated, on the front side at G_{E2}=1160Wm^{-2} to provide the equivalence of G_{R2}=200 $W{\cdot}m^{-2}$.

Two specific *Pmax* values, $Pmax_{BiFi10}$ and $Pmax_{BiFi20}$, for G_{R1}=100 W•m^{-2} and GR2=200 W m–2 respectively, must be reported. If the equivalent irradiance levels do not correspond to G_{R1} and G_{R2}, $Pmax_{BiFi10}$ and $Pmax_{BiFi20}$ must be obtained by linear interpolation of the data series *Pmax* versus G_E.

Bifacial characterisation in production

In production environments, a reference device, assessed by an accredited agent and of the same technology as the devices to be tested must be used to calibrate the solar simulators at STC (G=1000 W•m^{-2}) according to IEC 60904-1. To assess bifacial gain $Pmax_{BiFi10}$ and $Pmax_{BiFi20}$ must be reported for each device tested in production. These values will be calculated based on the *Pmax* value determined at STC (i.e. without the contribution of the rear side) and the slope of the *Pmax* versus rear side irradiance function provided for the reference device.

Conclusion

The proposed standard is a pragmatic solution that enables "apples-to-apples" comparison of bifacial devices and highlights the bifacial gain. It is simple and compatible with existing measurement equipment and is applicable for both PV cells and modules. The aim of the standardisation work is to be an enabler in the further expansion of the bifacial technology. I take this opportunity to thank the project team members and guests for their valuable contributions. ▶

References

[1] IEC 60904-1: Measurement of photovoltaic current-voltage characteristics

[2] IEC 60904-9: Solar simulator performance requirements

[3] IEC 60891: Procedures for temperature and irradiance corrections to measured I-V characteristics

Author

Vahid Fakhfouri trained as a microengineer and obtained a PhD in nanotechnologies from the Swiss Federal Institute of Technology in Lausanne. Vahid worked for the watchmaking industry as a micro-nano manufacturing expert before joining Pasan in 2009. He is currently head of R&D at Pasan SA, a member of the Switzerland-based Meyer Burger Technology group. Pasan is the world reference for I-V measurement equipment in the photovoltaic cell and module manufacturing industries. Vahid is also an active member of the International Electrotechnical Commission (IEC) and has been leading the standard project for I-V characterisation of bifacial PV devices since 2016.

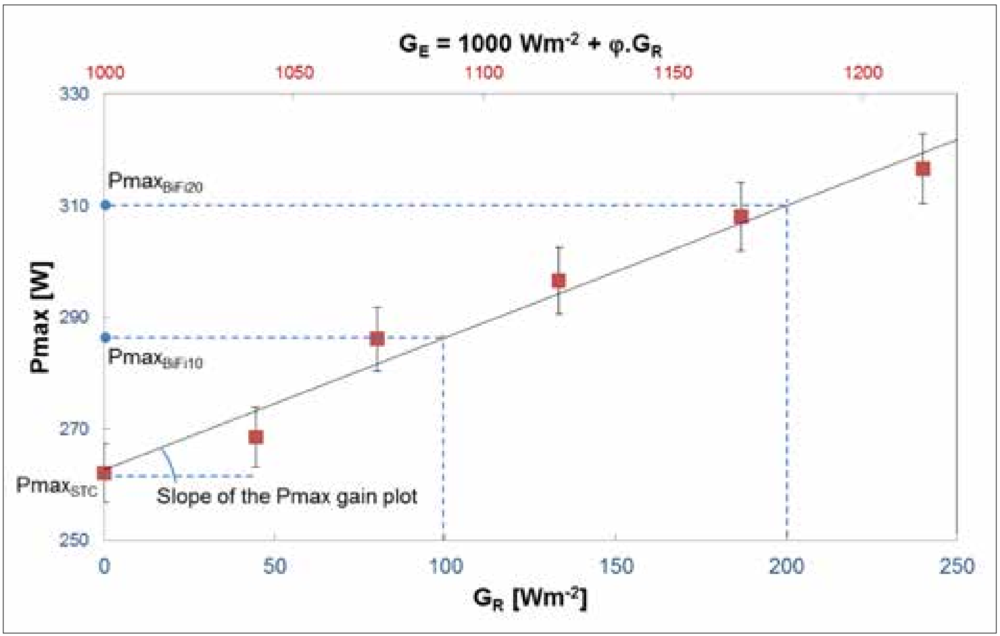


Figure 3. Example of a Pmax gain plot for a bifacial reference module

Understanding energy gain in bifacial PV systems

Bifacial systems| The additional power provided by the active rear side of bifacial modules depends on a multitude of factors. Naftali Eisenberg and Lev Kreinin look at how the gains in a bifacial PV system can be influenced by local conditions and system design decisions

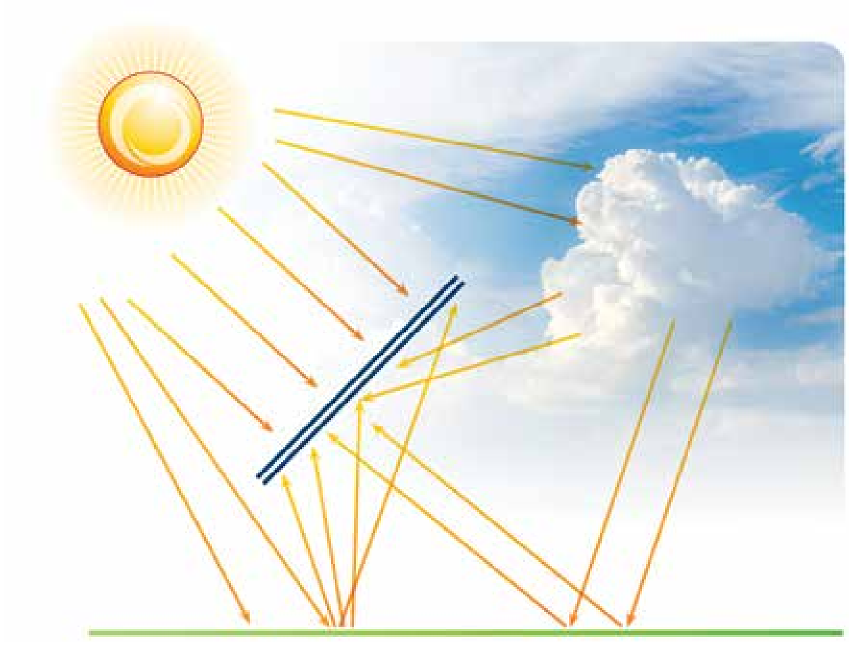


Figure 1. Terrestrial bifacial PV system

The beauty of bifacial PV systems is in the increased generation provided by the additional light energy collected on the back side of the modules. After the first space application of bifacial solar cells in the 1970s to supply additional energy, using the Earth's albedo [1,2] it was demonstrated that such cells are also very attractive for extra energy generation on terrestrial applications.

A module placed outdoors as in Figure 1 will generate energy according to irradiation incident on its front and back simultaneously. This irradiation is generally composed of direct (plus some diffused) sunlight on the front and reflected diffused (and sometimes direct) light on the back.

Whereas energy generation by regular monofacial modules is well studied and foreseeable, the forecast experience of energy production by bifacial modules is very limited. Among the factors affecting the back energy generation are:

1. Illumination conditions dependent on geographical, climatic and temporal factors:
    - Sun elevation
    - Diffused/global radiation
2. Module and system design parameters:
    - Module "bifacial factor" (back/front short current ratio)
    - Module inclination
    - Distance between rows
    - Stand-alone/field system
    - Module elevation above underlying surface
    - Distance between modules in the row
    - Albedo of underlying surface

All the above factors impact mostly on the back irradiation and therefore on the added energy generation, or 'energy gain' (EG). The energy yield of bifacial module E_b, with the subtraction of the energy yield of monofacial module E_m, under the same conditions will result in the energy gain. To exclude an effect of possible difference in the front powers of both modules the yield should be normalised relative to nominal front power of each module. Therefore the correct definition of the energy gain is:

$$EG = \frac{Eb}{Pfb} - \frac{Em}{Pfm}$$

Where P_{fb} is the power at standard conditions of a front-illuminated bifacial module and P_{fm} is the power at standard conditions of an illuminated monofacial module.

Energy gain is not constant for a given module and depends on the factors mentioned above. The range of possible energy gain values characterises the energy production ability of the module and system. In parallel to energy gain, additional factors can be used to characterise the energy production capability of a bifacial module. They are equivalent efficiency and equivalent nominal power.

Equivalent efficiency of a bifacial cell or module is the efficiency of a monofacial cell or module providing the same energy as the bifacial one.

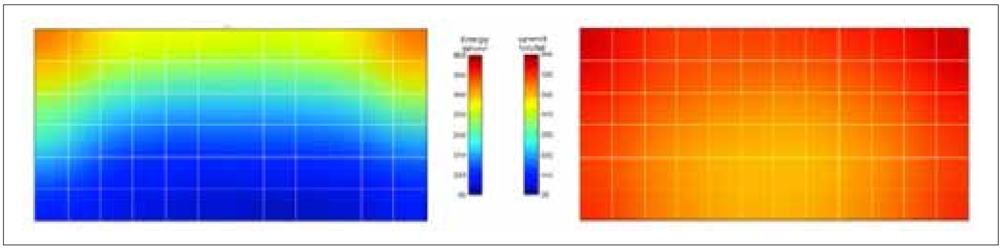


Figure 2. Non-uniformity of back side irradiance for a 30° tilted module as a function of module elevation. Left diagram 8cm and right diagram 58cm over ground

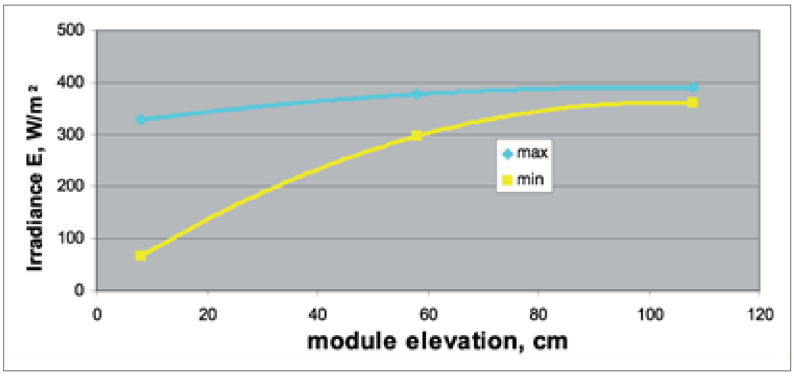


Figure 3. Illumination non-uniformity characterised by maximum and minimum back irradiance on the module as a function of module elevation (albedo of the underlying surface is 50%)

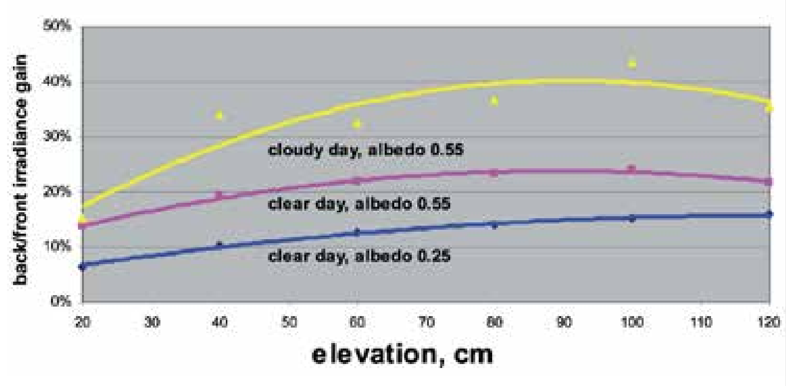


Figure 4. Irradiance gain as function of weather, albedo and panel elevation

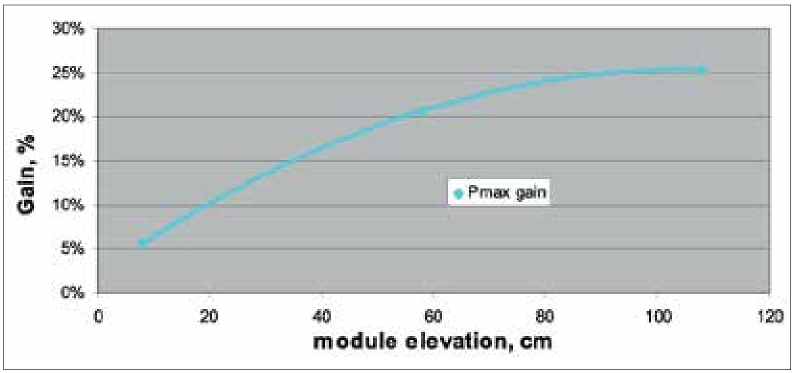


Figure 5. Maximum power gain (limited by minimal back irradiance) versus elevation for a bifacial module at a fixed tilt of 30° (bifacial factor is 71%)

Therefore the equivalent efficiency of a bifacial cell or module can be expressed by the following:

$$\eta_{b\ equ} = \eta_{fm} .(1+EG)$$

In the same way the equivalent power of a bifacial cell or module will be expressed by:

$$P_{b\ equ} = P_{fm} .(1+EG)$$

Module back irradiance characteristics

Rear irradiance non-uniformity is one of the important factors which should be taken into consideration when designing or evaluating bifacial system energy generation. Examples of the back module irradiance distribution are shown in Figure 2 [3]. Measurements were made in Jerusalem (31° north latitude) on 29 May at noon. Irradiance on horizontal surface, 1,006W/m^2; diffuse to global radiation ratio, 0.11; underlying surface albedo, 50%; tilt of module, 30° from horizontal.

As can be seen, the back irradiance is non-uniform, and the non-uniformity depends dramatically on the module elevation. The irradiance values are in the range of 66-328W/m^2 in the case of lower module elevation, i.e. varying ~five times, and in the range of 360-390W/m^2 in the case of highest elevation, i.e. varying ~ 10% only. Figure 3 summarises the changes of back module irradiance, i.e. non-uniformity, versus module elevation. The curves reflect the range between minimum and maximum back irradiance for the case where the module is fixed with a 30° tilt and mounted in a field where the distance between rows (in a south-north direction) is 150cm and between separate modules (in an east-west direction) 20cm.

The reflectivity of the underlying surface is the dominating effect on the back irradiance. Minimal back irradiance increases nearly proportionally to the albedo of the underlying surface, when the diffusion component of the solar irradiation is small. This can be seen in Figure 4 for two albedo cases: 0.25 (blue curve) and 0.55 (red curve). Minimal back irradiance will be used for the irradiance gain evaluation necessary for the power gain determination.

Uniformity of back irradiance is significantly better under conditions of predominantly diffuse radiation. Figure 4 also illustrates comparative data on irradiance of the panel rear side for different weather conditions. For the cloudy day the illumination conditions measured were: global irradiance, ~190 W/m^2; diffuse/global ratio, 0.98. In the case of cloudy weather (predominantly diffuse radiation) uniformity of irradiance is significantly better even at low elevations (yellow curve). Comparison between this curve and the red one shows also that the ratio of back to front irradiance is higher in the case of diffuse sun illumination (43%) than in the case of nice direct illumination (~24%).

Electrical contribution of the module back

The electrical measurements of the module back only (with the front covered with a non-transparent sheet) and of a module with both sides illuminated (front by sun, back by scattered light) shows that the back contribution is limited by the lowest irradiated area. This restriction of back contribution in the module maximal power, P_{max}, is illustrated in Figure 5 for the module, which has a bifaciality factor of 71%. The increase in gain with the elevation raise is largely determined by the irradi-

Figure 6. Rooftop test field in Jerusalem

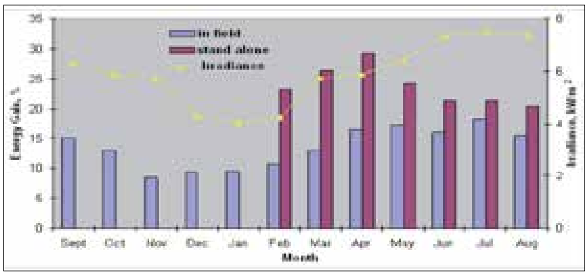


Figure 7. Monthly energy gain of a bifacial vs. a monofacial module

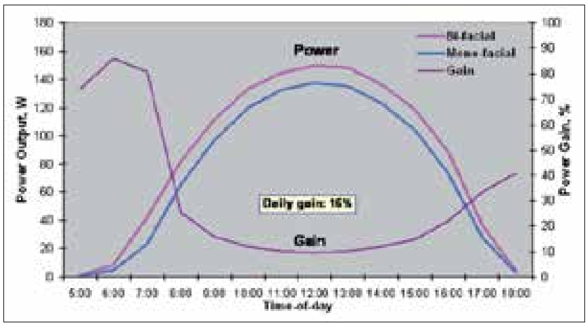


Figure 8. Daytime energy generation by regular and bifacial in-field installed modules

ance distribution improvement and to a lesser extent by the increase of absolute irradiance on the back (see Figure 3).

Outdoor monitoring

Comparative outdoor measurements of bifacial and monofacial modules and systems were undertaken in several geographic locations [3-6].

One of the monitoring sites is Jerusalem (latitude 31°47' north). Figure 6 shows a view of the roof test station. Comparative measurements of bifacial and monofacial modules were made when modules of both types were mounted inside the "field" of several module rows. The modules were oriented at a fixed position south with a 30° tilt. The distance between rows (in a south-north direction) and between separate modules (in an east-west direction) was 150 and 20cm, respectively. Elevation of the module lower edge was 70cm.

The summary of comparative monitoring of bifacial and monofacial modules is shown in Figure 7 as monthly energy generation gain [4, 5]. The bifaciality factor is 71%, the albedo of the underlying surface 50%. The generated energy gain is normalised by nominal module front power at standard conditions. The measured bifacial gain varies depending on time of year in the range 9 -20% with annual gain above ~15%. During this experiment, the energy production was determined by integrating the DC power of the modules measured every three minutes.

The gain for a standalone bifacial module for several months is also shown in this figure. As can be seen, the standalone bifacial module provides ~22 to ~30% energy gain (an additional ~3 to ~13% compared to in-field module energy gain). It should be mentioned, that the maximal power generated by a bifacial module in standalone conditions is the value which should be used as an analogue of the monofacial module power at standard conditions for a safe module and system design.

Some details of comparative monitoring of energy generation by monofacial and bifacial modules are presented as time-of-day dependence. An example of such dependence for a sunny day is presented in Figure 8. [4,5]. The increased gain can be seen for the morning and evening hours, when the portion of scattered radiation is larger. (Due to the site topography causing shading of the sun in the evening, when it is below ~20° above the horizon, the contribution of the back of a bifacial module is decreased in the afternoon). In the morning the direct sun rays hit the back (in the time frame between the spring and the autumn equinoxes). Because of the morning and evening effects, the daily gain is significantly higher than during the middle of the day.

The same type of measurements for a day with prevailing diffused radiation (Figure 9) shows a significant increase in gain when diffused radiation dominates: ~38% when the diffused/global radiation ratio is 88% compared to ~16% when 89% of radiation is direct sun radiation.

At low illumination (morning and evening) the energy generated from a monofacial system is low, and the DC-AC conversion efficiency of the inverter is low or even below working level. A bifacial system provides not only a gain in DC energy generation, but shifts the inverter into effective working mode. Therefore the energy generated by a bifacial system in the morning and evening is increased due to two reasons: bifacial gain and higher DC-AC conversion efficiency.

Another monitored system was located in Geilenkirchen, Germany, latitude ~51° north (Pohlen test site, monitored by Fraunhofer ISE) [5]. The flat rooftop systems with separate inverters were composed of six bifacial and seven monofacial modules. The modules' installation parameters were: height, 0.3m; tilt, 15°; N-S row distance, 2.5m. An albedo value of 78% was measured at the beginning of monitoring and ~ 55% after ~one year.

According to monitoring data, the energy generated due to the back contribution exceeds 20% every month. A jump in bifacial gain during January to February illustrates the additional advantage of bifacial modules: after snowfall, the contributions of the backside of the bifacial modules increase due to high snow reflection. In the same time, the front side covered by the snow generates less energy, and so the gain value increases significantly. A 23% annual bifacial gain is evaluated. The equivalent power of each of the bifacial modules (i.e. the power of a monofacial module able to generate the same energy as a bifacial one) is 307.5W, while its front power is 250W. The equivalent efficiency of the cells is 22.75%, while their front efficiency is 18.5%.

Simulation of system gain

Examples of bifacial system performance simulation for different field design parameters can be seen in Figure 12 (the location of the field is Hannover, Germany, latitude 52° 22') [6]. Panel tilt is equal to the latitude of the given place. This panel position provides the maximal energy collected by the panel front. The basic bifacial module used for the calculations was built with solar cells having a front

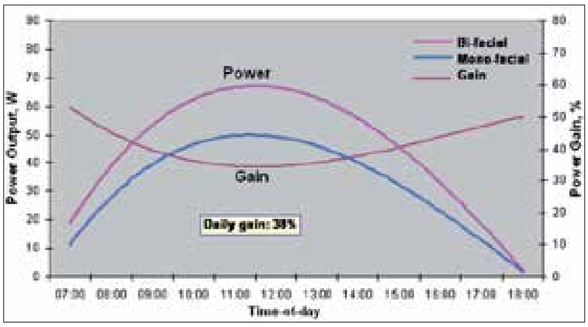


Figure 9. Monitoring of energy generation by regular and bifacial modules on a cloudy September day when diffused/global radiation ratio was 88%.

Figure 10. Rooftop test field in Geilenkirchen

Figure 11. Monthly energy gain of a bifacial versus a monofacial PV system

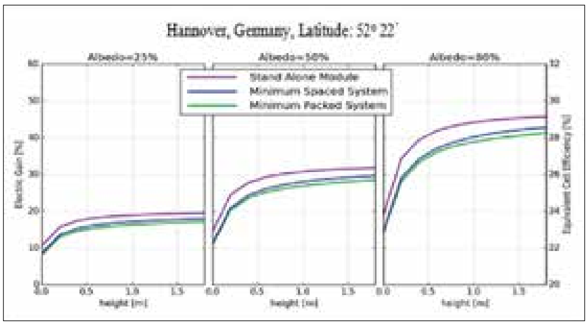


Figure 12. Examples of forecast calculations for bifacial PV system with different design parameters

efficiency of 20% and a bifaciality factor of 90%.

The electrical gain is shown as a function of the distance of the panel lower edge to the ground (panel height). The calculations are performed for three types of system: packed min, i.e. minimal north-south distance providing no shading on 21 December, noon; spaced min, i.e. minimal N-S distance x 1.5; single panel. Three albedo values were chosen in the range of typical coatings: tarred roof, dry soil (25%), white agricultural canvas, polluted white roof coats (50%) and cool white roof coat, snow (80%).

It can be seen that two design parameters are most influential on the gain: panel elevation and the albedo of the underlying surface. Increasing the elevation of the panel above the underlying surface results in multiplication of the gain. The positive effect of the panel height increase is starting to saturate at 0.4-0.5m. The increase in gain due to higher albedo is obvious – the gain is approximately directly proportional to the albedo.

There is no dramatic effect from the row spacing of the field. Therefore the north-south distance between the rows can be selected without taking the gain into consideration. Even using bifacial cells with moderate front efficiency in a PV system is equivalent to the creation of monofacial systems based on cells with 26-28% efficiency, what is close or above the achievable maximum.

Conclusions

Simultaneous monitoring of I-V characteristics of mono- and bifacial modules and systems demonstrates the superiority of bifacial over monofacial types of PV energy generators.

The yearly energy gain of an in-field bifacial versus a monofacial module in a low latitude position (Israel) with an underlying surface albedo ~0.50 and a module bifaciality factor of 71% is above 16%. For a higher latitude location (Germany) the energy gain is above 23%. These values can be easily increased above 23% and 30% respectively by optimisation of the PV field design and by increasing the bifacial factor to 90%. This was shown both through outdoor monitoring and simulation.

According to calculations, the equivalent efficiency of bifacial solar cells with 20% front efficiency embedded in the modules of bifacial systems is in the range 26 -28%. The values of energy generation and equivalent efficiencies, which can be realised using modern bifacial cells, are far above the levels of the best regular monofacial silicon cells. ■

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References

[1] N.M. Bordina, N.A. Borisova, G.S. Daletskii, A.K. Zaitseva, A.P. Landsman, V.A. Letin , "Using the radiation reflected from the Earth for increasing the power of solar arrays". *Cosmic Researches*, Vol. 14, 2, 266, 1976.

[2] G.M. Grigorieva, M.B. Kagan, K.N. Zviagina, V. Kulicauscas, L. Kreinin, N. Bordin, and N. Eisenberg, "Future of bifacial Si solar cells for space application". *The 23rd European Photovoltaic Solar Energy Conference and Exhibition, Valencia, Spain, 1-5 September 2008.*

[3] L. Kreinin, N. Bordin, A. Karsenty, A. Drori, D. Grobgeld, N. Eisenberg, "PV Module Power Gain due to Bifacial Design", Preliminary Experimental and Simulation Data". *37th IEEE Photovoltaic Specialist Conference*, pp. 2171, 2010.

[4] L. Kreinin, N. Bordin, A. Karsenty, A. Drori, N. Eisenberg, "Experimental Analysis of the Increases in Energy Generation of Bifacial Over Mono Facial PV Modules". *The 26th European Photovoltaic Solar Energy Conference and Exhibition, Hamburg, 5 – 9 September, 2011.*

[5] N. Eisenberg, L. Kreinin, N. Bordin, A. Karsenty, A. Drori "Outdoor Bifacial Module Characterization: Energy Generation and Gain". *Bifacial cell workshop, Konstanz, April, 2012.*

[6] L. Kreinin, A. Karsenty, D. Grobgeld, N. Eisenberg, „PV Systems Based on Bifacial Modules: Performance Simulation vs. Design Factors". 43rd *IEEE Photovoltaic Specialists Conference, Portland, Oregon, 5- 10 June, 2016.*