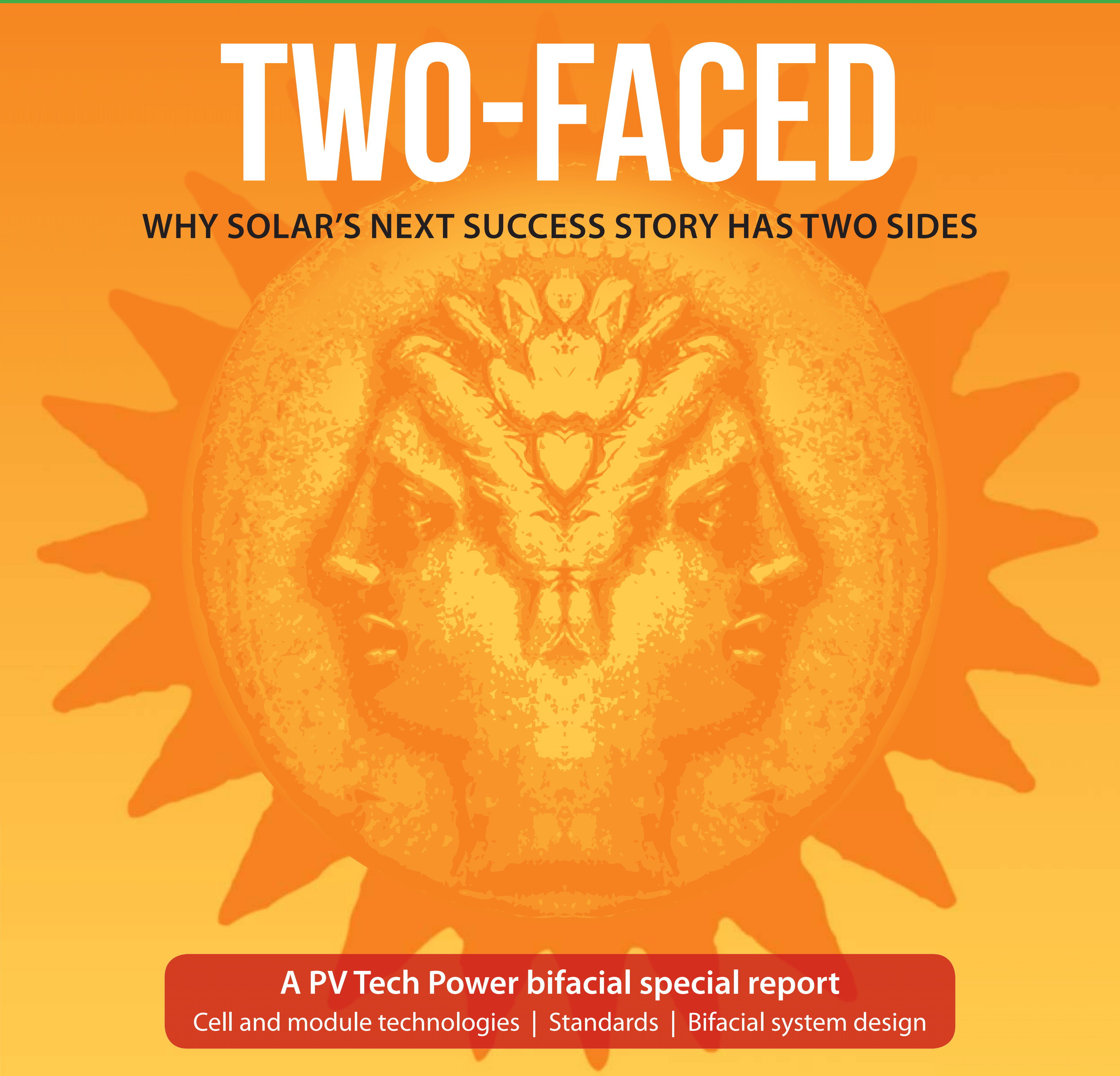
PV TECH POWER

Volume 12 PV POWER PLANT TECHNOLOGY AND BUSINESS September 2017



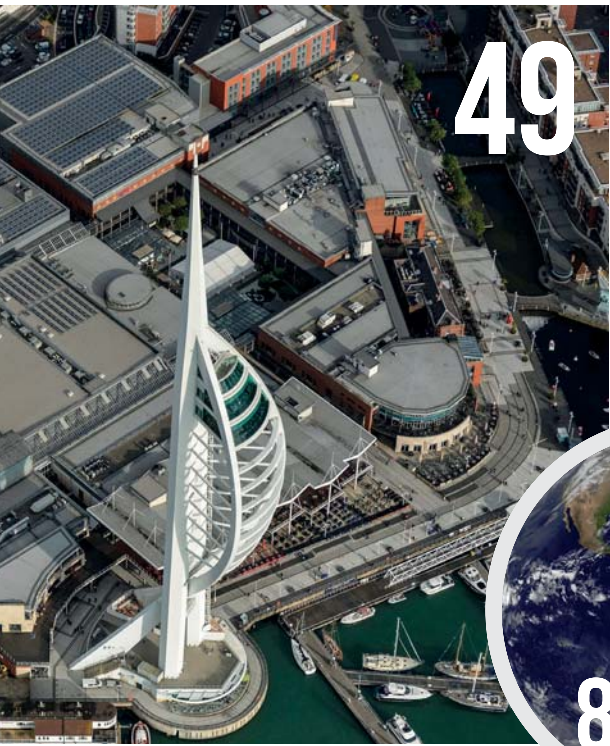
TWO-FACED

WHY SOLAR'S NEXT SUCCESS STORY HAS TWO SIDES

A PV Tech Power bifacial special report

Cell and module technologies | Standards | Bifacial system design

Contents



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

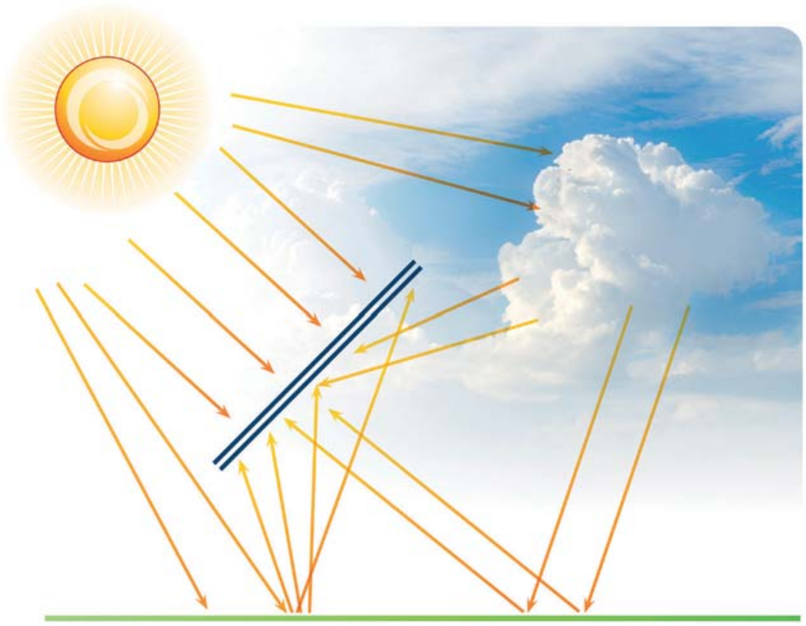


Figure 1. Terrestrial bifacial PV system

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.

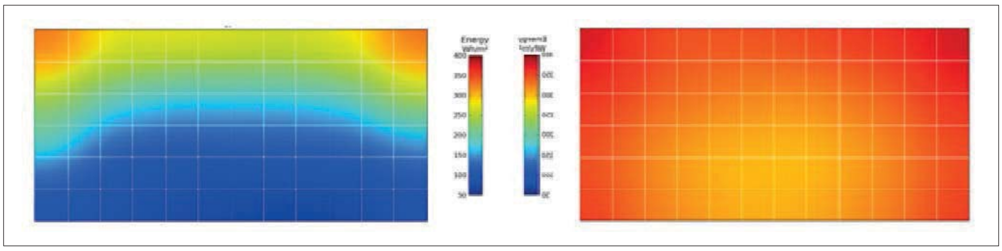


Figure 2. Non-uniformity of back side irradiance for a 30° tilted module as a function of module elevation. Left diagram 8cm and right diagram 58cm over ground

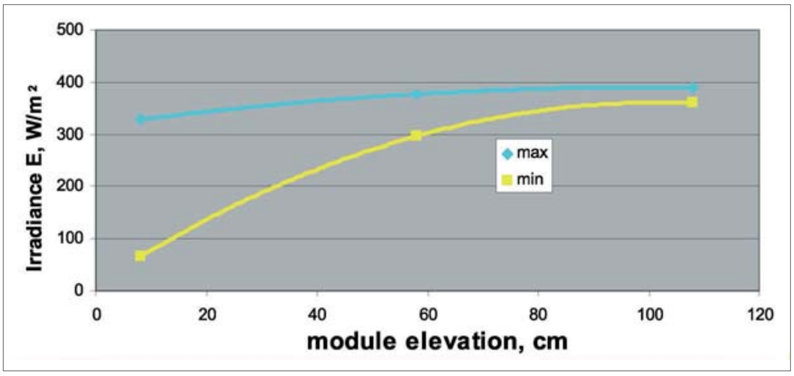


Figure 3. Illumination non-uniformity characterised by maximum and minimum back irradiance on the module as a function of module elevation (albedo of the underlying surface is 50%)

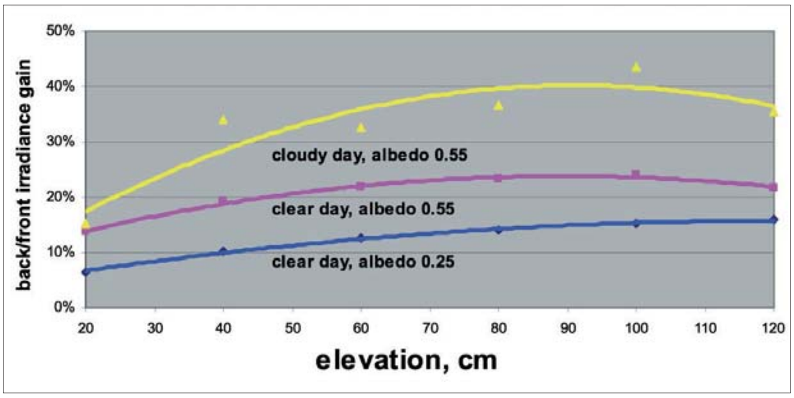


Figure 4. Irradiance gain as function of weather, albedo and panel elevation

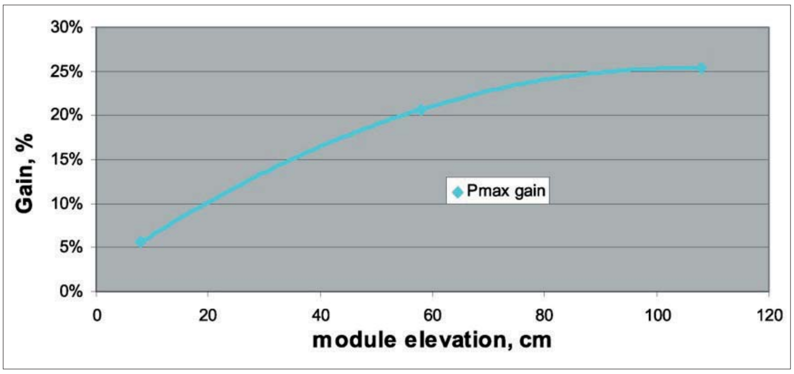


Figure 5. Maximum power gain (limited by minimal back irradiance) versus elevation for a bifacial module at a fixed tilt of 30° (bifacial factor is 71%)

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/m²; 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/m² in the case of lower module elevation, i.e. varying ~five times, and in the range of 360-390W/m² 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/m²; 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

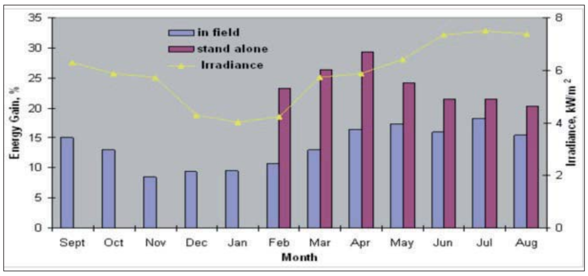


Figure 7. Monthly energy gain of a bifacial vs. a monofacial module

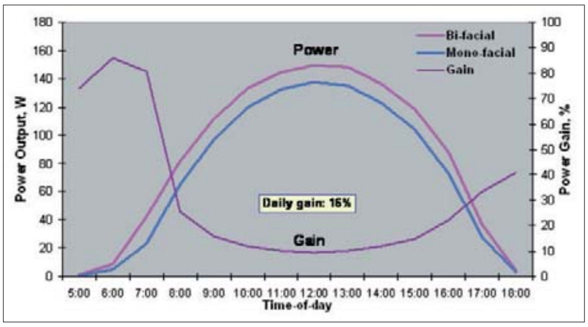


Figure 8. Daytime energy generation by regular and bifacial in-field installed modules

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

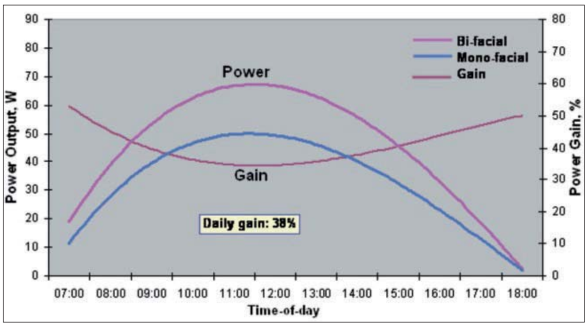


Figure 9. Monitoring of energy generation by regular and bifacial modules on a cloudy September day when diffused/global radiation ratio was 88%.

Figure 10. Rooftop test field in Geilenkirchen

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

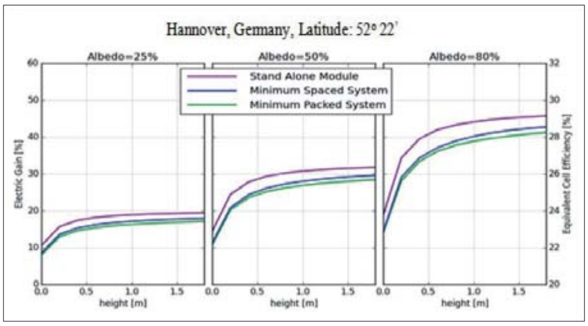


Figure 12. Examples of forecast calculations for bifacial PV system with different design parameters

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. ■

Authors

Professor emeritus Naftali Eisenberg is founder and CTO of Solaround, an Israel-based company developing advanced p-type bifacial cells and modules. He is the head of the Jerusalem College of Technology Center for PV Solar and the former chief scientist of the solar energy pioneer company Luz, which installed 360MWp solar thermal systems in the 1990s, and founder and CTO of B-Solar, the first company that developed p-type bifacial cells and modules.

Dr. Lev Kreinin is chief scientist of Solaround based in Israel. His career started in solar cell R&D for the Russian space programme, specialising in bifacial cells for the first space solar arrays. From 1992 he was an associate professor in the Jerusalem College of Technology. From 2009 to 2013 he was chief scientist of bSolar Co based in Israel, focused on the development, testing and production of p-PERT bifacial solar cells. The same R&D direction was continued in the frame of Solaround.

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.*


PVMODULETECH
CONFERENCE
7 - 8 November 2017
KUALA LUMPUR, MALAYSIA
New event from PV-Tech dedicated to module performance and quality metrics, to optimise asset-owner return-on-investment and solar plant performance ratio's.
• How to guarantee optimum plant design and operation, by specifying quality module supply
• Key materials used in module assembly lines, and how these can impact on field operations
• What determines leading module suppliers today, and how to ensure reliability and certification?
• How the industry can reduce risk in deploying GW levels of new module designs, such as PERC
moduletech.solarenergyevents.com
To get involved either as a speaker, partner or attendee please email:
marketing@solarmedia.co.uk
PVTECH
Photovoltaics International
PVTECH RESEARCH