CALCULATING THE ADDITIONAL ENERGY YIELD OF BIFACIAL SOLAR MODULES

1. INTRODUCTION

Bifacial solar modules can collect sunlight not only on the front side but also on the rear side. Although the development of bifacial solar cells dates back to the 1970s, current technology is still based on expensive cell structures; as a result, bifacial solar cells have remained a niche product in the photovoltaic market. In 2015, SolarWorld AG and the Institute for Solar Energy Research Hamelin (ISFH) introduced bifacial cells based on high-performance PERC (solar cells with passivated emitter) cell technology. This new approach could do much to pave the way to the mass market for bifacial photovoltaic modules.

The new Sunmodule Bisun from SolarWorld consists of 60 bifacial solar cells integrated into a glass-glass module with a transparent back and a 72-cell module format with a transparent backsheet. This allows both the front and rear of the module to produce energy. A bifacial module produces more energy than a monofacial module with the same power rating under the same conditions. The amount of additional energy yield of a bifacial module, the so-called energy boost, depends on two main factors: the installation height of the solar module and the light reflectance of the surface underneath the module (albedo).

The following publication explain how the installation height and albedo influence the additional energy yield, how the albedo influence the additional energy yield, how the albedo can change over time due to aging, soiling and how it is measured on the site. The white paper also identifies typical values for the additional energy yield under various installation conditions and provides recommendations for inverter sizing.

2. BIFACIAL CELL TECHNOLOGY

In contrast to monofacial cells, bifacial solar cells collect sunlight not only on the front but also on the rear side as they capture light reflected from the surface beneath the module and from the environment. Bifacial technology is time-tested; in the early 1980s, Cuevas et al. reported an increase in module output of 50 percent by using special light-concentrating systems and solar panels featuring bifacial solar cells.[1] Most current bifacial developments are based on complex solar cell architectures on the basis of n-type silicon substrates or hetero-junction solar cells. These result in high production costs due to their vast consumption of expensive silver paste.

As a result, the market share of bifacial modules has remained very low. For 2015, the estimate was only 5 percent.[2]

With the novel industrial manufacturing process for an economically viable bifacial cell and module technology from SolarWorld AG and ISFH,[3] standard silicon and manufacturing processes. It is based on PERC technology, which SolarWorld successfully integrated into series production[4] and, with a cell efficiency of 22.04 percent,[5] recently set a new world record.
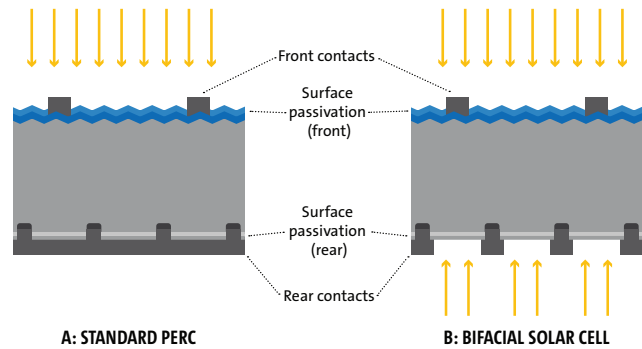

FIGURE 1: *Schematic cross section of a PERC structure (A) and a bifacial solar cell (B)*

In contrast to a standard PERC cell, the bifacial solar cell features openings in the screen-printed rear contact to allow light to reach the active region of the cell from the back. The full-area aluminum screen printing of the PERC cell has been replaced with an optimized grid, similar to the front of the cell.

3. BIFACIAL MODULE

With their transparent rear sides, glass-glass modules provide the ideal module technology for bifacial solar cells. A second sheet of glass, or transparent backsheet on the rear of the module allows reflected sunlight to reach the cells from the back. In this way, individual modules generate higher yields. Embedding the cells in a glass composite protects them from environmental and mechanical influences. The high durability and minimal degradation ensure a maximum service life for the module.[6] Because SolarWorld is among the manufacturers that produce glass-glass modules at an industrial scale, the new bifacial product also profits in this way from a mature technological process.
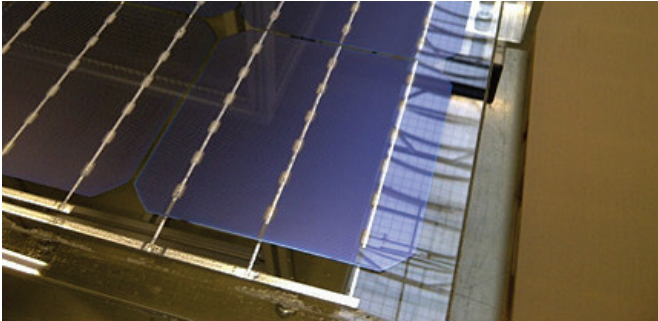
FIGURE 2: *Rear side of a bifacial module in production*

In addition to front-side power, a new relevant parameter has been added: the bifaciality B, which describes the ratio between the power produced from light captured by the front side maximum power at standard test conditions ($P_{mpp\,front}$): the bifaciality B, which refers to the ratio of the front to the rear power measured under standard test conditions (STC).

$$B = \frac{P_{mpp,\,rear}}{P_{mpp,\,front}}$$

The first generation of bifacial SolarWorld modules has already achieved a bifaciality of over 65 percent. Further improvements are expected as a result of ongoing solar cell development.

The transparent and active rear sides of bifacial photovoltaic modules enable an additional energy yield, also known as the "energy boost". This is the name given to the increase in specific energy yield (kWh/kWp) of the bifacial module compared with the monofacial module in the same system with the same nominal power as the front of the bifacial module.

4. INFLUENCES ON THE AMOUNT OF ADDITIONAL ENERGY YIELD

The amount of additional energy yield of a bifacial module depends on two main factors: the light reflectance of the surface beneath the module[7] and the installation height of the module. Direct or diffuse light is reflected from the ground, while a portion is scattered onto the rear cell of the module (Figure 3). When a bifacial module is installed at a height of about 0.5 meters (distance between the bottom edge of the module and the ground)—for example, above a white TPO roof membrane with high reflectance –up to 25 percent additional yield can be generated (Table 3).
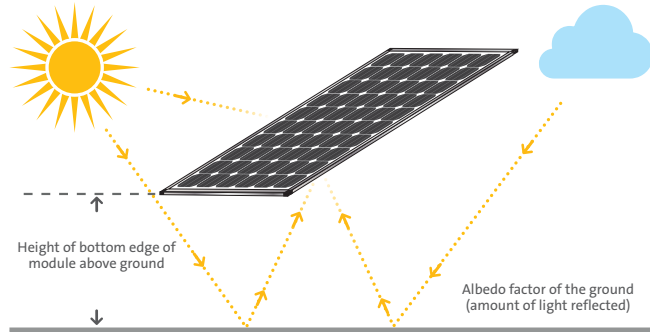

FIGURE 3: *Example of a system using bifacial modules*

4.1 ALBEDO –THE BRIGHTER THE BETTER

The albedo describes the reflectivity of a non-luminous surface. It is determined by the ratio between the light reflected from the surface and the incident radiation.

$$Albedo\ of\ the\ surface = \frac{Reflected\ light}{Incident\ light}$$

Albedo is a dimensionless quantity and is usually expressed as a percentage—the higher the reflectivity of a surface, the higher its albedo. For example, a black surface that absorbs a large amount of light has a low albedo, while a white surface that reflects a large amount of light has a high albedo.

Measured albedo values of common ground surfaces are listed in Table 1. The albedo measurement for green field is 23 percent. For concrete (>10 years weathered), the value is 16 percent. Adding white paint (Figure 5) boosts the albedo to 62 percent. Depending on the thickness and type of paint, albedo values of over 80 percent are possible. Additional roofing materials are also listed in Table 1. Surprisingly, the value for white gravel (Figure 4, no. 2) is only 27 percent. Due to the open-pored structure, a large amount of reflected light is lost within the voids. Other flat standard construction materials like roofing membranes or sheet metal have an albedo of 50 to 60 percent. The highest albedo is measured for special membranes that were developed for solar applications—for example, Renolit's Alkobright with an albedo of 91 percent.[9]

4.1.1. ALBEDO –WEAR AND TEAR

The albedo of the surface under the system, one of the decisive factors influencing the amount of the additional energy yield, changes in the field over time. Albedo describes the extent to which light is reflected from a surface.

Therefore, the albedo itself depends on the properties of the surface under the module such as color, thickness, surface finish or type of vegetation. All these factors can change over time due to environmental influences like aging, soiling or the natural alteration of ground conditions. For example, a new white TPO roof can have an initial albedo value of 88 percent, but after three years, the albedo can decrease to 75 percent.[8] Although values from the literature or data sheets can provide a good orientation, an albedo measurement should be performed on site for a detailed calculation of the additional energy yield.

SURFACE TYPE	ALBEDO
Green field (Grass)	23 %
Concrete	16 %
White painted concrete	60-80 %
White gravel	27 %
White roofing metal	56 %
Light grey roofing foil	62 %
White roofing foil (for solar applications)	> 80 %

TABLE 1: *Albedo values of certain ground surfaces measured with test setup according to Figure 4*

FIGURE 4: *Ground surface albedo test: 1) white painted concrete 2) white gravel*

Soiling of the surface beneath the module leads to effects similar to the environmental aging of the surface material and the albedo is reduced. How strongly soiling reduces the albedo depends greatly on the location of the installed photovoltaic system. In many cases, rain can be sufficient to wash away dirt and dust from the roof membrane. However, in cases of heavy soiling or in areas with little precipitation, additional cleaning of the roof is necessary to maintain high albedo values. If this is required, the cost of cleaning must be weighed against the earnings from the additional energy yield made possible by the cleaning.

The results of such a calculation depend heavily upon the individual installation conditions of the PV system and must therefore be individually recalculated for each system. Considerations include cleaning costs and maximum achievable additional energy yield.

Table 2 shows the albedo values for roofing material under the following conditions: un-weathered, Uncleaned, wiped, rinsed, detergent-washed and treated with algae-cleaner.[10] The uncleaned albedo values refer to a roofing membrane that was exposed to environmental influences for at least 10 years. Akbari et al. demonstrated in their experiments that the solar reflectance of an aged and weathered roofing membrane could be restored to at least 80 percent of the initial solar reflectance values by wiping and rinsing (simulating the annual rainfall), as long as algae did not cover the roof membrane. Treatment of roof membranes with detergent and algae cleaner restored the original value of the un-weathered material.[10]

SAMPLE		SOLAR REFLECTANCE					
No.	Location	Uncleaned	Wiped	Rinsed	Detergent Washed	Algae Cleaner Washed	Un-weathered
1	Springfield, Mass.	0.54	0.68	0.70	0.70	0.82	0.80
2	Springfield, Mass.	0.55	0.73	0.72	0.76	0.77	0.82
3	Lancaster, Ohio	0.59	0.76	0.75	0.80	0.81	0.81
4	Heath, Ohio	0.57	0.72	0.72	0.78	0.79	0.80
5	West Hampton, N.J.	0.71	0.71	0.71	0.73	0.77	0.81
6	West Hampton, N.J.	0.69	0.69	0.71	0.72	0.77	0.81
7	Plantation, Fla.	0.35	0.43	0.64	0.65	0.79	0.82
8	Plantation, Fla.	0.32	0.42	0.59	0.68	0.80	0.79

TABLE 2: *This table shows albedo percentages as a function of location and surface condition of white roofing membranes.* [10]

4.1.2 HOW TO MEASURE ALBEDO?

An albedo measurement can be performed using a solar module, a pyrometer or a reflectometer. For the albedo measurement described below, a solar module was used as a measuring instrument. The test setup requires a functional monofacial solar module, a voltmeter (multimeter) and a frame for fixing the solar module. Although the albedo value does not depend on the irradiation angle of the sunlight or on the tilt angle of the solar cell, measurement on a cloudless day during the midday hours is recommended for the most accurate results.
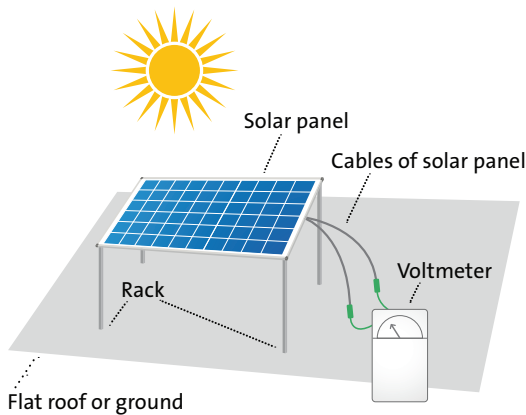

FIGURE 5: *Schematic test setup for measuring albedo with a solar module*

The tester should measure the surface reflectance at at-least three randomly selected testing spots on the roof or ground where the photovoltaic system is to be installed. The spots should be representative of the test surface. The solar panel is then fixed on a frame in such a way that the solar cells of the module face the sky at a 180° angle to the hypothetically flat ground. Alternatively, an actual prospective framed system may be used. If the bifacial module is to be assembled later at a 10° angle, the test described here may be performed with a frame system with a 10° pitch.

The frame should be at least high enough so that no shadow from the frame, module or person falls directly under the solar module. Then the short circuit current of the module is measured twice. For this, the solar cells of the module are oriented once to the sky (I_{sc}, sky) and once to the ground (I_{sc}, ground), measuring the associated short circuit currents. Based on the measured short circuit current values, the albedo of this testing spot can be calculated according to the following formula:

$$Albedo\ of\ the\ measurement\ spot = \frac{I_{sc\ sky}}{I_{sc,ground}} \cdot 100\%$$

Now, the albedo of each selected testing spot is determined. The overall albedo of the surface is the arithmetic mean of the measured albedo values for each individual testing spot.

$$Albedo\ of\ the\ surface = \frac{Sum\ of\ the\ measured\ albedo}{Number\ of\ measurement\ spots}$$

The measurements represent the albedo at the particular time when the measurement was made. Due to environmental influences, these values may change over time (see section 4.1.1 Albedo—Wear and Tear).

4.2 INSTALLATION OF THE MODULE—THE HIGHER THE BETTER

The second main influence on the energy yield of a bifacial module is its installation height. Figure 6 shows simulation data for the additional energy yield for a landscape-mounted bifacial module (one module per row, 30° pitch, south orientation, 2.5 meter row pitch, 80 percent albedo) with variable installation height. The installation height is measured between the lower edge of the module and the ground.
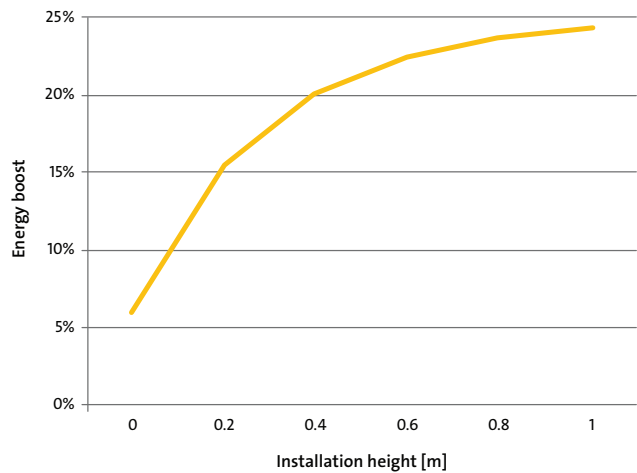

FIGURE 6: *Energy boost of a bifacial photovoltaic system with landscape-mounted module, south oriented, 30° pitch and a row pitch of 2.5 meters, 80 percent albedo*

The greater the installation height of the bifacial photovoltaic module—the greater the additional energy yield. However, Figure 6 shows that the saturation curve reaches its inflection point at an installation height of about 0.5 meters. Beyond this point, the additional energy yield only increases slightly—although the installation height continues to increase constantly. The curve reaches its saturation point for installation heights above 1 meter.

The recommended height of a ground-mounted system is approximately 1 meter. On flat roofs, the installation height is limited by increasing wind loads. The smaller the increase in uplifting loads—the higher the module is positioned on the roof. A mounting structure with an installation height greater than 0.3 meters between the lowest module edge and the roof—exhibits an optimum tradeoff among the cost of the substructure and ballast weight as well as the energy yield.

5. AMOUNT OF ADDITIONAL ENERGY YIELD

The advantages of the Sunmodule Bisun, such as its mechanical resilience, longer service life and additional energy yield, make the bifacial module the ideal solution for all commercial, industrial and agricultural applications—in particular, in a flat-roof or ground-mounted system. For such applications, the module is installed so that sufficient light hits the active module rear. When combined with a bright surface beneath the module, e.g. whitewashed concrete or white roofing foil, even more light is reflected onto the module. In this way, the energy yield can be further increased.

Figure 7 below, shows a mounting concept for bifacial solar modules. The depicted system has a module tilt angle of 30° and a distance of about 0.3 meters between the lower module edge and the roof. The additional energy yield that can be generated in such systems is shown in Figure 5 and Table 3.
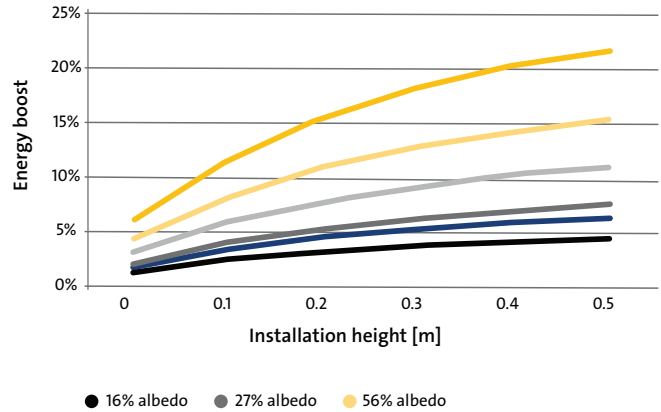
FIGURE 8: *Additional energy yield of a bifacial photovoltaic system with landscape-mounted module, 65 percent bifaciality, south orientation, 30° pitch and a row pitch of 2.5 meters for various albedo values (source: own calculation)*

	concrete	green field	white gravel	sand	white roofing metal sheet	bright white roofing foil
SURFACE TYPE						
ALBEDO						
	16 % albedo	23 % albedo	27 % albedo	40 % albedo	56 % albedo	80 % albedo
0.0	1.20 %	1.70 %	2.00 %	3.00 %	4.20 %	6.00 %
0.1	2.30 %	3.30 %	3.90 %	5.80 %	8.10 %	11.60 %
0.2	3.10 %	4.40 %	5.20 %	7.70 %	10.80 %	15.50 %
0.3	3.60 %	5.20 %	6.10 %	9.10 %	12.80 %	18.20 %
0.4	4.00 %	5.80 %	6.80 %	10.10 %	14.10 %	20.20 %
0.5	4.30 %	6.20 %	7.30 %	10.80 %	15.10 %	21.50 %

(INSTALLATION HEIGHT (m))

TABLE 3: *Additional energy yield of a bifacial module for different surface types and installation heights (landscape-mounted module, 65 percent bifaciality, south oriented, 30° pitch and a row pitch of 2.5 meters) (source: own calculation)*

FIGURE 7: *Mounting system concept for bifacial modules on flat roofs*

6. CALCULATION OF ADDITIONAL ENERGY YIELD

The values in Figure 5 and Table 3 are determined according to the following formula:

$$Additional\ yield = Albedo \cdot bifaciality \cdot \left[a \cdot \left(1 - \frac{1}{\sqrt{A}}\right) \cdot \left(1 - e^{-\frac{b \cdot H}{A}}\right) + c \cdot \left(1 - \frac{1}{A^4}\right)\right]$$

Key to formula:

a = 1.037
A = row pitch between the modules
E = 2.718
B = 8.691
H = distance between the lowest point on the module frame and the roof or ground
c = 0.125

The formula applies to installations under the following conditions:

Module tilt: 10 to 30 degrees
Module orientation: South
Module mounting: landscape or portrait

A calculation of the additional energy yield for the Sunmodule Bisun could look like this:

$$\text{Additional yield} = 0.8 \cdot 0.65 \left[1.037 \cdot (1 - \frac{1}{\sqrt{2.5}}) \cdot (1 - 2.718^{\frac{8.691 - 0.3}{2.5}}) + 0.125 \cdot (1 - \frac{1}{2.5^4}) \right] = 0.215$$

a = 1.037
A = 2.5 meters
e = 2.718
b = 8.691
H = 0.3 meters
c = 0.125
Albedo = 0.8 (80 percent surface reflectance)
Bifaciality = 0.65 (65 percent cell bifaciality)

The result of the calculation is an additional energy yield of 21.5 percent. SolarWorld offers the possibility of calculating the additional energy yield online on its website using a small calculation program that includes the same formula as shown above.

7. INVERTER SIZING EQUIVALENT TO MONOFACIAL MODULES

Inverter sizing is a much-discussed problem. The following section will provide a recommendation for inverter sizing for photovoltaic systems that include bifacial modules. Inverter sizing generally depends on the following module characteristics:

- Input current and voltage
- Thermal coefficient
- Nominal power

7.1 VOLTAGE AND THERMAL COEFFICIENT

The voltage range and thermal coefficient of bifacial modules based on crystalline PERC cell technology (Sunmodule Bisun) are the same as for monofacial modules based on the same technology (Sunmodule Plus, Sunmodule Protect). The bifaciality does not affect the thermal properties of the cell and has only a negligible effect on the voltage of the module (compare Figure 9 and Figure 10). Since the voltage and thermal coefficient of bifacial and monofacial modules are identical, the same planning and design rules apply for both types of modules in terms of inverter sizing.

The input current range of the inverter may need to be checked. The data sheet specifications for the electrical values under optimized conditions can be used for this purpose. Usually, modern inverters have higher tolerances with regard to the input currents and can also process the higher currents without problems.

7.2 NOMINAL POWER

The modules produce the type plate power under standard test conditions (STC) with a solar irradiation of 1,000 W/ m² and a temperature of 25° Celsius. These favorable conditions usually occur only during certain times of the year, e.g. on sunny days in fall or spring, when it is not too hot. In the winter, the solar irradiation is not strong enough to raise the module output to its nominal power. In the summer, the cell temperature is usually above 25° Celsius, so that the module power decreases according to the thermal coefficient.

EXTRA ENERGY		6 %	10 %	20 %	25 %
Maximum power	P_{max}	285 Wp	295 Wp	319 Wp	331 Wp
Open circuit voltage	U_{oc}	39.0 V	39.0 V	39.0 V	39.0 V
Maximum power point voltage	U_{mpp}	31.0 V	30.9 V	30.6 V	30.5 V
Short circuit current	I_{sc}	9.84 A	10.21 A	11.14 A	11.60 A
Maximum power point voltage	I_{mpp}	9.20 A	9.55 A	10.42 A	10.85 A
Module efficiency	η_m	16.99 %	17.57 %	19.03 %	19.72 %

EXTRA ENERGY		SW 260	SW 265	SW 270
Maximum power	P_{max}	260 Wp	265 Wp	270 Wp
Open circuit voltage	U_{oc}	38.9 V	39.0 V	39.2 V
Maximum power point voltage	U_{mpp}	30.7 V	30.8 V	30.9 V
Short circuit current	I_{sc}	8.18 A	9.31 A	9.44 A
Maximum power point voltage	I_{mpp}	8.56 A	8.69 A	8.81 A
Module efficiency	η_m	15.51 %	15.81 %	16.1 %

FIGURE 9: *Data sheet values for electrical properties of Sunmodule Bisun (top) and Sunmodule Plus (bottom)* [1]
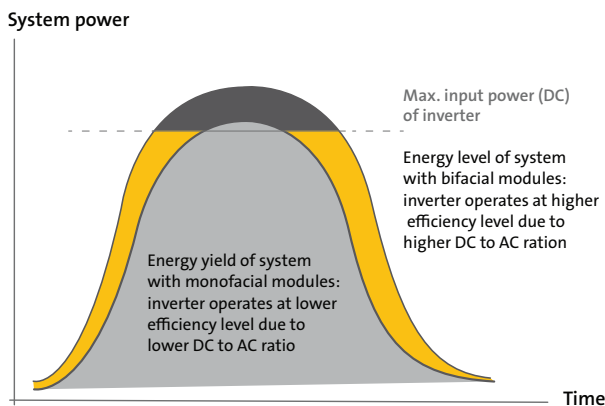
When the DC power produced by the PV array exceeds the maximum input level of the inverter, the inverter adjusts the direct current to reduce the DC power. This process is also referred to as clipping.

SUNMODULE BISUN 270 WP MONO THERMAL CHARACTERISTICS	
NOCT	46 °C
TK I_{sc}	0.040 %/K
TK U_{oc}	-0.30 %/K
TK P_{mpp}	-0.41 %/K

SUNMODULE PLUS 270 WP MONO THERMAL CHARACTERISTICS	
NOCT	46 °C
TK I_{sc}	0.040 %/K
TK U_{oc}	-0.30 %/K
TK P_{mpp}	-0.41 %/K

FIGURE 10: *Data sheet values for thermal coefficients of the monofacial Sunmodule Plus 270 Wp mono (right) and the bifacial Sunmodule Bisun 270 Wp mono (left)* [11]

In general, clipping occurs only when the PV system is operated under optimal conditions similar to standard test conditions. The inverter operates at a lower efficiency over 95 percent of the time over the course of the year. An inverter sized according to the nominal power of the front side of the bifacial module has a higher DC load (higher DC/AC ratio). It can therefore be operated at higher efficiencies for most of the year due to the additional yield produced by the rear side of the cell. In this system, clipping might occur sooner or more often than in a photovoltaic system with the same nominal power as monofacial modules. Nevertheless, these clipping losses are lower than overall gain that is produced when the inverter operates at a higher efficiency throughout the year (Figure 11).

System power

Max. input power (DC) of inverter

Energy level of system with bifacial modules: inverter operates at higher efficiency level due to higher DC to AC ration

Energy yield of system with monofacial modules: inverter operates at lower efficiency level due to lower DC to AC ratio

Time

- Energy losses due to clipping at lower efficiency levels (occurs on 1–5% of days per year)
- Energy losses due to clipping at higher efficiency levels
- Additional energy yield generated by bifacial energy boost and inverter operating at higher efficiency level (occurs every day of the year)

FIGURE 11: *Idealized energy yield curves of photovoltaic systems with monofacial modules and with bifacial modules*

8. CONCLUSION

In late 2015, SolarWorld AG introduced a new generation of bifacial modules to the market. The Sunmodule Bisun is a bifacial solar panel with a bifaciality of 65 percent and more. The additional energy yield of the Sunmodule Bisun depends on installation conditions, particularly the height of the mounting frame and the light reflectance (albedo) of the roof membrane or the ground conditions beneath the module. System planners and developers can influence both factors.

General findings show that the greater the installation height of the module, the higher the energy yield. Although technical features such as wind loads can limit the actual height of the mounting frame, installation heights of at least one meter are recommended for ground-mounted systems and 0.3 meters for installations on flat roofs.

The same rule applies for the albedo as for the installation height: the higher the albedo, the higher the energy yield. The highest value the albedo can theoretically reach is 1 (extremely bright or reflective surface), and the lowest value for albedo is 0 (perfect black surface). Un-weathered bright roof membranes reach albedo values of 80 to 90 percent. Aging and soil can reduce these values to varying extents. However, cleaning can restore the albedo of a weathered roof membrane to 80 percent or more of the initial un-weathered value.

An equally important factor in the design of a photovoltaic system is inverter sizing. Here, it is recommended that the inverter be sized for a bifacial module in the same way it is for a monofacial module—exclusively using the power produced by the front of the bifacial module. Because the voltage range and thermal coefficient do not change compared with a monofacial module of the same cell type and performance, the same rules can be applied for them as for monofacial modules.

An optimal combination of reflective surface and the highest possible system height can achieve an additional energy yield of up to 25 percent. In the field, this makes it possible to further reduce the cost of energy produced by photovoltaic modules for all applications.

REFERENCES

1. Cuevas et al., "50% more output power from an albedo collecting flat panel using bifacial solar cells;" Solar Energy Vol. 29 No. 5 pp. 419-420, 1982

2. International Technology Roadmap for Photovoltaic (ITRPV.net), 2014 Results, April 2015. Available at http://www.itrpv.net/Reports/Downloads/2015/ [accessed on 17 June 2015]

3. Dullweber et al, "The Perc+ Cell: A 21%-Efficient Industrial Bifacial Perc Solar Cell," 31st European Photovoltaic Solar Energy Conference, Hamburg, Germany, 2015

4. T. Weber et al., "High Volume Pilot Production of High Efficiency PERC Solar Cells - Analysis Based on Device Simulation," SiliconPV, 2013

5. SolarWorld news release 14.01.2016 http://www.solarworld.de/konzern/presse/aktuelles/pressemitteilungen/single-pressemitteilung/article/solarworld-praesentiert-solartechnik-der-naechsten-generation/

6. SolarWorld news release, May 2015. Available at http://www.pv-tech.org/news/intersolar_europe_solarworld_to_launch_glass_glass_bifacial_modules [accessed on 17 June 2015]

7. Amy Lindsay, Matthieu Chiodetti, Patrick Dupeyrat, Didier Binesti, Eric Lutun, Khalid Radouane. Key Elements in the Design of Bifacial PV Power Plants; PVSEC 2015

8. Cool Roof Rating Council, Rated Products Directory, data for product ID: 0628-0011, available at http://coolroofs.org/products/results [accessed on 08 December 2015]

9. Cool Roof Rating Council, Rated Products Directory, data for product ID: 1116-0001, available at http://coolroofs.org/products/results [accessed on 08 December 2015]

10. Hashem Akbari, Asmeret A. Berhe, Ronnen Levinson, Heat Island Group, Lawrence, Stanley Graveline, Ana H. Delgado, Ralph M. Paroli. Aging And Weathering Of Cool Roofing Membranes, Lawrence Berkeley National Laboratory, 2005

11. SolarWorld AG, product data sheet, available at http://www.solarworld.de/en/products/products/solar-modules/downloads/