WHITE BIFACIAL MODULES – IMPROVED STC PERFORMANCE COMBINED WITH BIFACIAL ENERGY YIELD

Bas B. Van Aken*, Lars A.G. Okel, Ji Liu, Stefan L. Luxembourg and John A.M. Van Roosmalen
ECN – Solar Energy
P.O. Box 1, 1755 ZG Petten, the Netherlands
* Corresponding author, e-mail: vanaken@ecn.nl

ABSTRACT: We present a novel module design to increase the power output of bifacial modules without compromising the increased energy yield due to the bifaciality. This innovation includes a highly reflective interlayer between and around the bifacial solar cells and laminated between the front and rear encapsulant. Although bifacial solar cells in modules with transparent front and rear sides can absorb light incident at either side, the transmission of (infrared) light through the rear side reduces the Pmax. The lower Wp rating is seen as a drawback for bifacial modules. The innovative white bifacial modules show almost the same front side Isc and Pmax as a monofacial module and a 2.2% higher Pmax, due to increased Isc, compared to transparent bifacial modules. The same increase is found for the rear side Pmax. The bifacial energy yield for white bifacial modules, due to the higher Pmax for both sides, is much higher than the slightly higher ground reflected "albedo" light of regular bifacial modules.
Keywords: Bifacial, PV module, energy performance, optical properties

1 INTRODUCTION

Bifacial solar cells can absorb irradiance from both front and rear sides if transparent materials are applied on both sides of the PV module. Double glass modules (and modules with a transparent back sheet) will not benefit from the back sheet scattering, but are able to harvest the light that is incident on the rear. The annual energy yield of bifacial modules and PV systems is widely reported to be significantly higher.

Standard crystalline Si PV *monofacial modules* have a rear side of white back sheet. A part of the light that hits the white back sheet is reflected back towards the (rear of the) solar cells via one or more internal reflections. The use of a transparent rear side reduces the maximum power output compared to using a white back sheet, when the modules are measured under the standard test conditions (STC) for monofacial modules, because this scattering mechanism is replaced by transmission out of the module. This apparent lower Wp rating is seen as a drawback for *transparent bifacial modules*.

In contrast, increases of the annual energy yield for transparent bifacial modules between 5% and 30% are reported in the literature [1,2], compared to monofacial modules. The exact values depend on device parameters like cell technology and rear side metal fraction and on environmental parameters such as the fraction of diffuse light and the scattering properties of the underground (albedo). Shading of the underground by the PV system reduces the generation of ground-reflected light. The small amount of transmitted light through regular bifacial modules will only have a small, albeit positive influence on the amount of ground-reflected light.

In this work, a new, innovative module stack is introduced. To increase both the maximum power output under standard test conditions compared to transparent bifacial modules as well as increase the annual energy yield compared to both monofacial and to transparent bifacial modules, a highly reflective interlayer is applied between the bifacial solar cells and on the area between the cells and the edge of the modules. We will refer to the bifacial module with the highly reflective, white, interlayer as *white bifacial module*.

2 EXPERIMENTAL SET-UP

2.1 Bifacial solar cells

Bifacial solar cells, n-type, three bus bar, were processed on semi-square 156 mm wafers in a single batch [3]. The processing was optimised for front-side efficiency and reproducibility. The best cells were selected for module manufacturing. These cells averaged 9.16±0.07 A (average ± standard deviation) for the short-circuit current and 19.69±0.16% conversion efficiency, measured on a conductive, brass measurement chuck. A selection of these cells were also measured on the rear, averaging 7.62±0.22 A and 16.4±0.6%. These cells, based on processing optimised for monofacial application, show a bifaciality factor of 83%.

2.2 Monofacial and bifacial modules

The three full-size modules have been manufactured from hand-soldered 10-cell strings. Front and rear side glass panels are identical. Three full-size modules were made from the same batch of cells: a monofacial module with standard white back sheet; a bifacial module with front and rear 2 mm solar glass; and a white bifacial module with a highly reflective interlayer between the front and the rear encapsulant covering all non-cell area. All other manufacturing parameters, e.g. encapsulant, tabs and layout, were identical.

3 RESULTS & DISCUSSION

3.1 IV-measurements

In Figure 1 photographs of the front and rear side of the white bifacial module are shown. The rear view photo shows clearly the cross-connectors and the four terminals for the junction box connection. Note that the rear sides of these non-optimised bifacial solar cells are slightly less black than the front side.

All modules were measured under STC in a room with black walls with a Pasan module flash-tester, class AAA. For the bifacial modules, both front and rear were measured. The short-circuit currents of the modules and the module powers are summarised in Table 1. For the

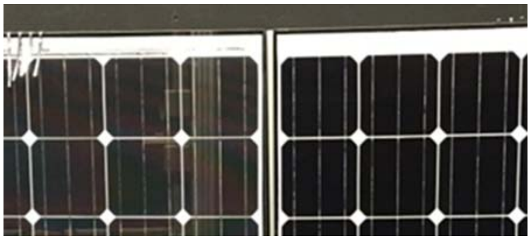

Figure 1: Close up photograph of the rear (left) and front (right) view of the white bifacial, double glass module. The white area between the cells and around the aperture area are well visible.

monofacial module typical cell-to-module (CtM) changes are observed, i.e. 1% lower current and about 4% power loss due to interconnection resistive losses and the small loss in current. The transparent bifacial module also shows CtM results as expected: the 2.7% reduction in current is due to the transmission through the module (lack of scattering on the rear side panel); the same resistive losses as for the monofacial module are observed, leading to -6% Pmax CtM

Table 1: Overview of Isc and Pmax for the three modules, front and rear side measured, and cell-to-module (CtM) changes. Note: the rear side results are influenced by some outliers that do not influence the front side performance.

	Isc [A]	Isc CtM	Pmax [W]	Pmax CtM
Monofacial module	9.07	-1.0%	271	-3.9%
Bifacial module white interlayer	9.10	-0.6%	271	-3.9%
rear side	7.69	+0.9%	230	-2.0%
Bifacial module transparent	8.92	-2.7%	265	-6.0%
rear side	7.46	-2.0%	226	-3.7%

In contrast to the transparent bifacial module, the white bifacial module shows similar values for the front side Isc and Pmax as the monofacial module. Compared to the transparent bifacial module, a 2% higher Isc is observed for the white bifacial module. This results in a correspondingly 2.2% higher Pmax for the white bifacial module. The same increase is found for the rear side Pmax of the white bifacial module compared to the transparent bifacial module. All other IV-characteristics are not changed by the choice of rear side material or presence of interlayer.

Our novel bifacial module architecture combines the double glass module design including high-efficiency n-Pasha bifacial cells with the introduction of a highly reflecting white interlayer in the open area between and around the solar cells. Front and rear side incident light striking the area between the cells is scattered in all directions, whereby a large fraction will strike the front or rear surface of the bifacial solar cells, depending on the location of the scattering event. Note that the scattering takes place at about the same “depth” in the module as the front or rear surfaces of the solar cell, compared to 400 to 600 micron below the rear surface for scattering at the white back sheet in monofacial modules.

As a result, the interlayer will improve the front side Isc and Pmax, e.g. as measured under standard test conditions for monofacial modules, to values very close to those obtained for monofacial, white back sheet modules. The same argument applies for the rear side measurement of the white bifacial module.

3.2 Ray tracing

To get a better understanding of how the reflection from the back sheet or glass area behind the cell and from the intercell area contribute to the short-circuit current a simple ray tracing model was set-up. Light was incident perpendicular to the module stack either on the cell area (dark blue) or on the area between the cells (white) as shown in Figure 2. The analysis for light incident on the cell area was performed using a realistic optical model of the cell (including texture and ARC). For the light impinging on the area between the cells the solar cells was treated as a black absorber. Both cases were calculated a) with a white back sheet, simulating a monofacial module, and b) with a rear side glass panel, simulating the bifacial modules. For the second case, also a white reflective foil was placed at the intercell area between the two EVA layers. Optical parameters for the white back sheet and the white reflective foil were calculated from reflection and transmission measurements.

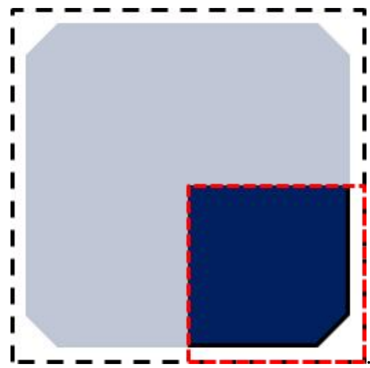

Figure 2: schematic view of the simulated solar cell and intercell area for the ray tracing simulation. The intercell area is defined as the white area between the red dashed box and the dark blue solar cell area.

From the ray tracing simulations, the fraction of incident light absorbed in each layer or transmitted out of the simulation stack, front and rear, was determined. From these spectrally resolved (330-1100 nm) absorption graphs, the contribution or loss to the short circuit current is calculated. In this analysis it is assumed that all light absorbed in the silicon is contributing to Isc. In the monofacial case, for light incident on the cell area only, the contribution to Jsc is 38.65 mA/cm^2; the double glass case gives 37.91 mA/cm^2. This difference of 2% is due to the reflection of mostly near infrared light back into the solar cell by the white back sheet. In contrast, for a bifacial double glass module, most of that near infrared light is transmitted through the rear glass panel and thus lost.

In Figure 3 and Figure 4 the spectrally resolved absorption graphs are shown for the case when the light is incident on the intercell area for (Figure 3) white back sheet and (Figure 4) white interlayer. The general picture is the same, but there are still some major differences. First, the fraction of light that falls on the solar cell on any surface, green area(s), is somewhat lower, namely 32% against 36%, for the monofacial module than for the white interlayer. Secondly, the absorption in the scattering layer, red area, is much higher, namely 25% against 11%, for the monofacial module.

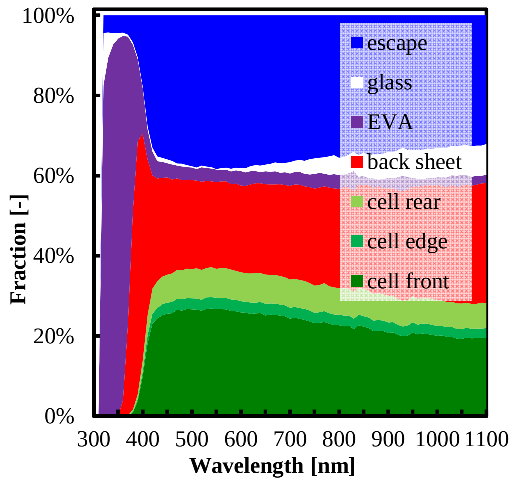

Figure 3: Ray tracing results for the monofacial module for light incident on the intercell area.

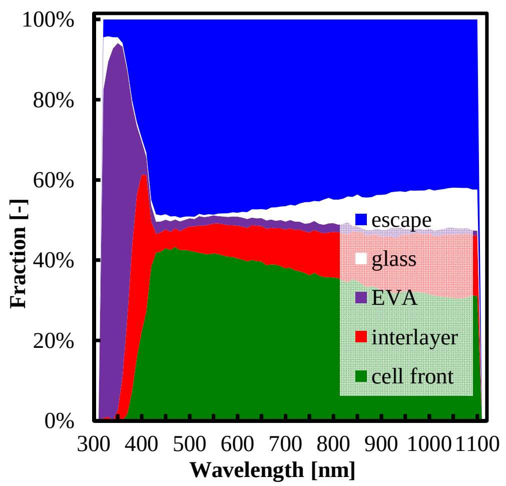

Figure 4: Ray tracing results for the white bifacial module for light incident on the intercell area.

The fractions absorbed in the layers of EVA and the glass are small and very similar, for both modules totalling 9% of the maximum photo current. Consequently, the fraction of light, incident on the intercell area, that is directly reflected or indirectly scattered out of the front glass is much higher for the interlayer module, namely 45% against 35% for the monofacial module.

The differences between the graphs follow from the two major differences in the optical stacks considered. First, the scattering takes place either 450 micron below the rear side of the cell (white back sheet) or at the same depth as the front side of the cell (white interlayer). Secondly, the reflection, which is >90% diffuse for both materials, is significantly lower for the white back sheet than for the white interlayer as was determined experimentally.

The increased absorption in the back sheet versus the interlayer is a logical consequence of the latter point. Therefore, we can say that from the light reflected of either the back sheet or interlayer a similar fraction ends up on the cell. Thus, the reduced absorption in the silicon for the monofacial case is also caused by the absorption in the scattering layer.

Since for the interlayer module the reflection takes place at a depth similar to the front side of the solar cell, all light absorbed by the solar cell is incident on the front side through internal reflection of the glass. In contrast, for the white back sheet module, about 30% of the light absorbed by the solar cell is incident on the rear side.

From the ray tracing we can also deduce whether the light absorbed by the front (rear) of the solar cell, is absorbed close to or further away from the wafer edge. Figure 5 shows the edge fraction on the front side of the solar cell for the reflector case and, for the back sheet case, the edge fractions of both the front and rear sides of the solar cell. On the front side, independent on the module layout, only 20% is absorbed on an edge with width 1.5 mm. In sharp contrast, the rear side absorbs 50% of the light that is scattered on the rear side in an edge region of only 300 microns wide from the edge and 90% for an edge that is 1.5 mm wide.

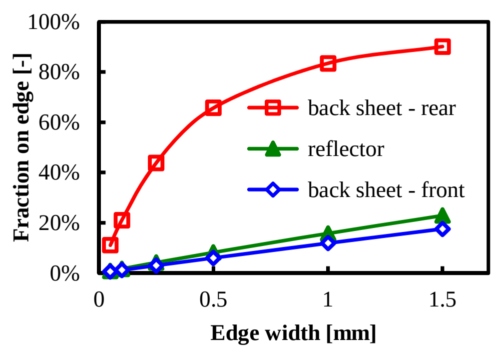

Figure 5: Fraction of the light incident on the edge of the front/rear side of the solar cell, as function of the edge width.

Knowing the contributions for light incident on the cell area and on the intercell area, the total Isc can be calculated for the three cases: a) the monofacial module, b) the bifacial double glass module and c) the bifacial module with white interlayer. The cell area contributes 9.24 A for the white back sheet and 9.06 A for the bifacial modules. The intercell area contributes nothing for the double glass module, 0.28 A for the white back sheet module and 0.36 A for the white interlayer module.

For simplicity we have assumed that all light falling onto the cell after reflection from either the back sheet or interlayer is absorbed and contributes to Isc. The intercell area contribution for the white back sheet takes into account a bifaciality factor of 85% for rear illumination. It does not take into account the fact that 50% of the rear illumination is absorbed by an edge region of 300 micron width, that may have a reduced efficiency compared to that of the bulk.

Also the scattering properties of AR-coatings and texture on either side of both glass panels is not taken into account. This will affect the contribution of the intercell area of the double glass module the most, as it is now, by default, zero. We think that the, partially quantified, arguments mentioned above, support the observed similarity in the experimentally derived Wp values for the monofacial and white bifacial modules.

3.3 Effect on annual energy yield

First, the difference between the partially transparent bifacial module and the fully non-transparent white bifacial module will be discussed. We have done annual irradiance and energy yield modelling for a typical system in the Netherlands. In general, the shadow of the modules lowers the ground-reflected albedo light by about 20%, assuming 100% blocking of the light by the modules. The transparency of a standard bifacial module, about 5%, will increase the ground-reflected albedo light, but the effect on the total annual irradiance is only a non-significant 0.1%. However, the white bifacial module shows a 2.2% better conversion efficiency, this increases the energy yield with the same fraction, on top of the increase in energy yield due to the bifaciality.

The AEY model requires an optical, a thermal and an electronic model, all adapted for bifacial irradiance. Details have been reported before [4]. The optical model is derived according to [5], where the irradiance on both tilted module surfaces is calculated in terms of contributions by the beam, by diffuse light and by ground-reflection caused by beam and diffuse light. Specific for bifacial modules is that the ground reflection has to be reduced by self-shading. The annual energy yield AEY is the summation of the calculated power output, using time resolved meteorological data. For yield predictions meteorological data at a certain location have been synthetically generated from monthly average values obtained from data bases.

Using this AEY model for a single module, the annual energy yield for the three types of modules discussed here are modelled for five locations, each simulated with albedo of 0.2 and 0.5. Results are plotted in Figure 6. Note the minimal effect of albedo for the monofacial module AEY at all locations.

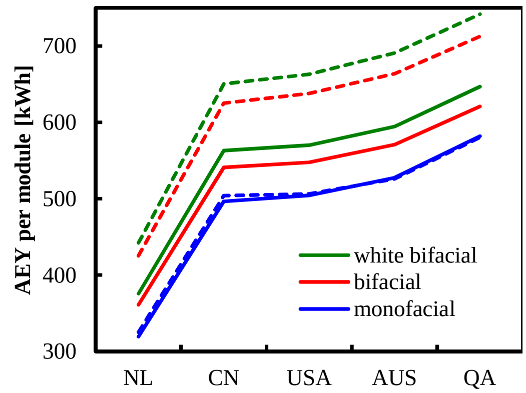

Figure 6: Modelled annual energy yield for the three different module types at five locations. Solid (dashed lines) are simulated with an albedo of 0.2 (0.5). Same colour represents same module type. Details of the locations are given in Table 2.

Table 2: overview of the five locations used for the AEY modelling. Horizontal irradiances are given in kWh/m^2.

Label	City	Country	Latitude	Longitude	Mean tempera-ture [°C]	Global horizontal irradiance	Direct horizontal irradiance	Diffuse horizontal irradiance
NL	Amsterdam	the Netherlands	N 52° 24′	E 4° 54′	10.7	1067	501	566
CN	Baoding	China	N 38° 54′	E 115° 30′	13.3	1579	1027	552
USA	Sacramento	United States	N 38° 31′	W 121° 30′	15.7	1803	1229	574
AUS	Rockhampton	Australia	S 23° 23′	E 150° 29′	22.4	2013	1279	734
QA	Doha	Qatar	N 25° 16′	E 51° 30′	28.1	2274	1500	774

For each combination of module type, location and albedo the optimal tilt angle is determined. These are plotted in Figure 7. As expected, the closer the location is to the equator, the lower the optimal tilt angle is. The combination monofacial module with low albedo yields the lowest tilt angle for each location. The high albedo simulations always yield an optimal tilt angle larger than for the low albedo value. There are no differences between the optimal tilt angle for the regular bifacial module and the white bifacial module.

Three modules, see Table 1, have been placed on ECN's roof top for outdoor characterisation. Figure 8 shows a typical power against time curve for these three modules on a sunny day. Clearly the bifacial modules give a higher power output during the whole day. The higher gain in the afternoon, is due to the slightly off-South orientation of the modules.

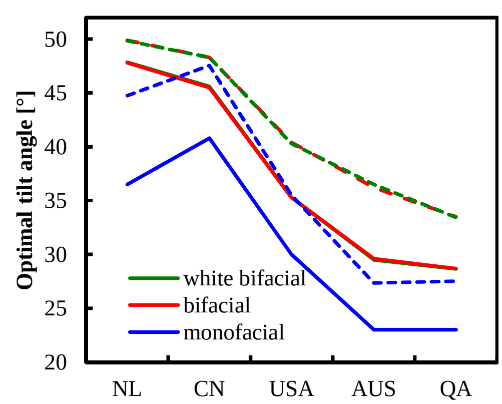

Figure 7: Optimal tilt angle for each combination of location, module type and albedo. Colours and dashes same as in Figure 6.

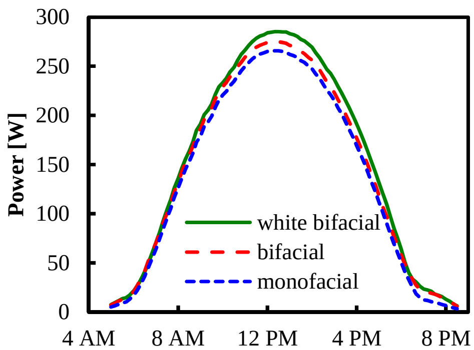

Figure 8: Example of the daily transient of the power output of the three modules on a sunny day.

Maximum power for the data shown in Figure 8 is reached around solar noon as shown in Table 3. Whereas the monofacial module was 5 W short of its rated power, the bifacial module produced 10 W more. The white bifacial showed the highest output with 14 W more than the rated power. Note that these modules were fabricated from the same batch of solar cells.

Table 3: comparison of rated power (indoor) and observed maximum power for the data of Figure 8.

	Indoor STC power [W]	observed maximum power [W]
monofacial	271	266
bifacial	265	275
white bifacial	271	285

Based on the outdoor IV data, we can estimated the daily energy yield in kWh. In Figure 9**: Daily energy yield per module for the first five days of June.**Figure 9, the daily energy yield for the three modules is plotted for the first five days of June. The energy gain for the bifacial module is >5% for sunny days, up to 8% when the total irradiance is low. Note that the albedo of this location is not high. The white bifacial module performs even better, even though the same solar cells were used for module manufacturing. The energy gain is >10%, even on sunny days, when the irradiance is dominated by direct sunlight.

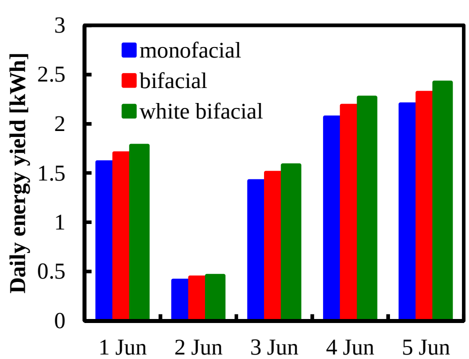

Figure 9: Daily energy yield per module for the first five days of June.

4 CONCLUSIONS

We have manufactured a bifacial double-glass module with an innovative white, highly reflecting interlayer that is positioned between and around n-Pasha solar cells. The Wp rating of this module was very similar to an identically processed monofacial white back sheet module solar cells from the same production batch. The 83% bifaciality of these front side-optimised n-Pasha solar cells was maintained in the white bifacial module. Because the white bifacial module is 0% transparent, there will be a slightly darker shadow behind the modules, compared to the 5% transparent bifacial module. This will reduce the amount of direct-light generated ground reflection by tenths of a percent of the total irradiance. In contrast, and 10× more significant, the annual energy yield of the white bifacial module will be improved by the higher front and rear Pmax.

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REFERENCES

[1] T. Mishima, M. Taguchi, H. Sakata and E. Maruyama, "Development status of high-efficiency HIT solar cells", *Sol En. Mat. Sol. Cells*, **95** (2011) 18-21.
[2] L. Kreinin, et al., "Experimental analysis of the increase in energy generation of bifacial over monofacial PV Modules", Proc. *26th EU PVSEC* 4CO.7.1, (2011).
[3] G.J.M. Janssen, et al., "Front side improvements for n-Pasha solar cells", *Proc. 29th EU PVSEC*, Amsterdam (2014).
[4] G.J.M. Janssen, B.B. Van Aken, A.J. Carr and A.A. Mewe, "Outdoor performance of bifacial modules by measurements and modelling", *Energy Procedia* **72** (2015) 364-373.
[5] J.A. Duffie and W.A. Beckman, Solar engineering of thermal processes, 2nd ed., John Wiley & Sons, (1991).