RELATION BETWEEN INDOOR FLASH TESTING AND OUTDOOR PERFORMANCE OF BIFACIAL MODULES

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ABSTRACT: Flash tests under standard test conditions yield lower power for bifacial modules due to transmittance of the transparent back sheet or glass. Nevertheless, these bifacial modules are expected to outperform their monofacial equivalents in terms of yearly energy output in the field, depending on local climate conditions, albedo, orientation (relative to South) and tilt angle. Modules with transparent back sheet on the rear give very similar power output in standard test conditions and with extra background scattering when compared to bifacial modules with AR-glass as rear cover. This gives the freedom to design either a glass-glass or a glass-back sheet bifacial module, depending on other considerations. For a location with low albedo, bifacial modules produces more kWh/W_p than monofacial modules in the early and late hours of the day, when the sun is more or less parallel to the plane of the modules. With increasing albedo, the bifacial gain increases from 5% to 20%; the gain is constant for a broad range of irradiation conditions.
Keywords: Bifacial modules, crystalline Si PV, energy yield

1 INTRODUCTION

Bifacial modules show lower efficiency or power output per unit area when measured under standard test conditions compared to monofacial modules due to the transparency of the rear side material and non-scattering (black) environment. However, their annual output can be significantly higher, depending on albedo, orientation and tilt angle [1, 2].

The outdoor annual energy output and the kWh/kW_p of bifacial modules are higher than monofacial modules, depending on latitude, climatic conditions and the local albedo. Claimed values for the bifacial gain vary widely between 5 to 30%. However, measured data reported in the literature are relatively sparse; recent examples are by Sanyo +11% [1]; by Bosch [2] +20%; and B-Solar +30% [2].

In this paper, flash tests are reported at different angles of incidence, with zero-albedo (STC) and with scattering panels at some distance behind the test sample to vary the degree of albedo.

Full outdoor data for a complete year has been collected for a monofacial and a bifacial module. The bifacial effect will be demonstrated and explained in terms of time of the day and over the whole year.

We are working on a model to be able to correlate the (adapted) STC measurements to outdoor surface response curves enabling the prediction of the annual energy output for a bifacial module at a given location and orientation as a function of albedo. For this purpose we have developed in-house an IV-tracer capable of measuring full IV-traces of single cell laminates up to full size modules and even in extremely low light conditions, << 50 W/m^2. For bifacial analysis, the irradiation is measured on both planes of the module separately. Results on measurements with varying albedo are presented.

2 EXPERIMENTAL SET-UP

2x2-cell laminates were built to test the influence of transparent rear side materials on the power output, performing indoor measurements, as reported in section 3.1. We compared standard float glass with AR-coated glass and transparent back sheet. The laminates were fabricated using three bus bar n-type monocrystalline Si bifacial n-Pasha solar cells from a single processing batch. Interconnection was made by soldering tabs to the bus bars and cross-connecting the tabs from each side. Four-probe measurements were enabled by soldering two bussing connectors to each cross-connector. Laminates were made with EVA and AR glass on the front.

72-cell modules were manufactured for outdoor energy output determination at low albedo location, which is reported in section 3.2. The full-size modules were made using six 12-cell strings made of bifacial solar cells with efficiencies of 19.0-19.5%. Cells were binned on efficiency. Variations in I_{mpp} and V_{mpp} from the module average were very small. The laminates were made with solar glass with state-of-the-art anti-reflection coating to maximise the light coupling. Monofacial and bifacial modules were created with white and transparent back sheet, respectively. All other module aspects were kept the same.

Two other 2x2-cell laminates were built from three bus bar n-type monocrystalline Si bifacial n-Pasha cells from a single processing batch. The modules were made for outdoor measurements at tilted South orientation, the results of which are discussed in section 3.3. AR-coated glass was used at the rear side of the bifacial module and white back sheet at the rear of the monofacial module.

The full-size modules, outdoor measurements were performed on the roof of an ECN building in the Netherlands, located at 52°47' N, 4°40' E using a clamping system. The location is characterised by close proximity to the North Sea and no shadow. Direct irradiance was measured with a Pyranometer and reference cell in the plane of the rack; the albedo of the blue corrugated metal wall and dark concrete floor behind the modules is rather low. The horizontal irradiance, a measure for the amount of indirect light, was measured with a second Pyranometer.

The outdoor measurement system is set up to record an IV-trace per module every 10 minutes and logs the irradiation, ambient temperature and module temperature. During the next 10 minutes the modules are kept at their respective measured V_{mpp}.to simulate nominal operating conditions in the absence of a power tracker. Evaluation of the performance of the two modules was done relative to the sum of the contributing cells' power, to circumvent differences in STC W_p due to differences in module rear panel. In particular, the power output differences when a) the irradiation is at low angles (early/late hours) and b) for bright, but diffuse light situations will be used to determine the increased energy production of the modules with transparent back sheet relative to the standard lay-up with white back sheet.

3 RESULTS AND DISCUSSION

3.1 Back sheet material

In Figure 1 the short-circuit current I_{sc} of the three 2x2-cell laminates with different rear side materials is plotted for three different angles of incidence. These data were taken in a room with negligible back scattering of light that is transmitted through or around the test samples. Clearly, the laminate with a float glass rear side panel shows for all angles a lower I_{sc} than the laminate with the AR-coated glass rear side panel. Apparently, the texture of the AR-coated glass also scatters light that passes through or around the Si wafers back to the open rear side of the n-Pasha solar cells. The transparent back sheet laminate shows an intermediate result at perpendicular incidence, but at 60° angle of incidence the transparent back sheet material performs even better than the AR-coated glass sample.

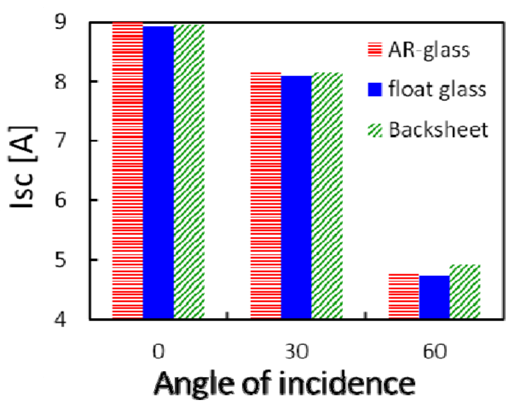

Figure 1: Isc of bifacial modules as a function of the angle of incidence with three different back sheet materials

To simulate the effect of albedo on the power output of these samples, we have compared flash test results without and with Styrofoam panels against the rear wall of the IV-flash chamber. The distance between the test laminates and the rear wall is about 1 metre.

Figure 2 shows the Isc as a function of the "albedo" for these three laminates. Adding one panel yields an increase in Isc by about 8% for all test samples, two additional panels increase this difference to about 19%. Although the I_{sc} under standard test conditions for these three panels is different, the behaviour under influence of the increased albedo is nearly identical.

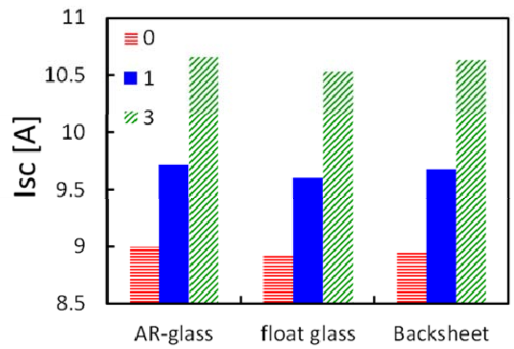

Figure 2: I_{sc} of bifacial modules with three different back sheet materials measured with various albedo, created by placing Styrofoam panels against the rear wall of the IV-flash chamber

3.2 Outdoor monitoring at low albedo location

Two full-size 72-cell modules have been monitored outdoors for almost a full year, at a low albedo location. As the average cell efficiency of the monofacial module was 0.4%abs higher than that of the bifacial module, we will compare the energy production normalised to the summed peak powers of the contributing cells.

To illustrate the bifacial effect, we have binned the full IV-data set twice, once to the hour of the day and separately to the month. We calculated the energy production, in kWh, based on the observed maximum power points for each 10-minute interval. The summed energy production per bin for each module is divided by the sum of the cells' peak power, thus we ignore the differences in module peak power due to transparent or white back sheet The difference of the bifacial kWh/kW_p with the monofacial kWh/kW_p is calculated, normalised to the monofacial kWh/kW_p. The normalised difference is plotted against the hour of the day in Figure 3. Around midday the difference is negligible. When the time is more differing from midday, the difference increases in favour of the bifacial module. Before 6.00 in the morning and after 19.00 in the evening, plateaus are observed in this difference, but the absolute values of these plateau levels differ quite a lot.

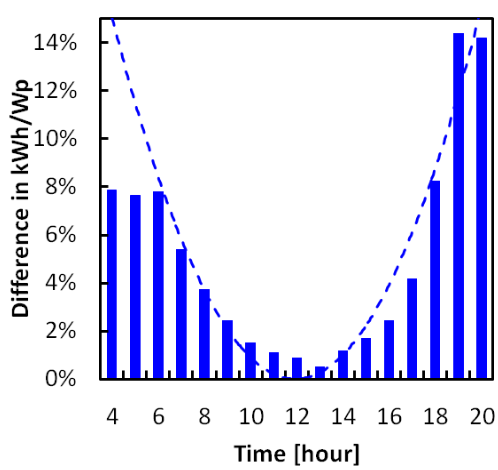

Figure 3: Normalised difference of the bifacial and the monofacial kWh/Wp, as a function of the time of day. The summed energy production in kWh is taken over the whole year

As the solar noon, CET winter time, is at 12:40, the most direct irradiation of the modules takes place near 1pm and thus the bifacial effect is minimal around midday. In first order approximation, the data is symmetric around the solar noon point. The bifacial effect or the relative contribution of the indirect light increases when the sun is further from the South. When the sun is “behind” the plane of the module, i.e. at negative angles of incidence, little direct light can reach the modules and all energy is generated by indirect light, which is most favourable for the bifacial module. As most of the light is indirect, the irradiation no longer depends on the relative angle of the sun and the PV system orientation. Therefore, the bifacial:monofacial difference is constant before 6am and after 7 pm, and no longer depends on the time of the day.

Because our set-up is slightly rotated to the East, with an azimuth of 170°, the monofacial module will have a slightly lower output in the late afternoon than in the early morning. This effect is best understood by considering the extreme case of a fully East-oriented monofacial module, where the power output will be minimal during the full afternoon. As the bifacial module will have a significant contribution from the rear side irradiation, in this case the bifacial gain is higher in the late afternoon plateau than in the early morning plateau.

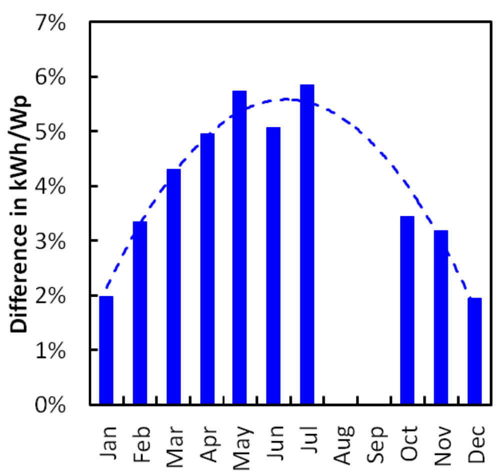

Figure 4: Difference between the bifacial and monofacial kWh/W_p over the year, normalised to the monofacial kWh/W_p

Figure 4 shows the behaviour of the normalised difference, calculated for monthly bins, instead of hourly bins. August/September data is excluded due to a failure in the measurement electronics on one of the two modules. The difference is highest in the summer and lowest in January and December.

The observed minimum in the normalised difference in the winter months seems to contradict the hourly data, in Figure 3, where we observed the lowest differences around midday when the irradiation is most perpendicular. In the winter, there is only 8 hours of daylight, whereas in the summer this could be as high as 16 hours. The hourly data showed that the bifacial effect is negligible in the middle of the day, but increases strongly at the early/late hours. The hours that have the strongest bifacial effect are thus confined to the summer period.

3.3 South facing tilted modules

As the full-size modules were at a location with low background and underground albedo, a second set of measurements was done at a location with a 360° free view of the sky and the possibility to change the underground (albedo), using 2x2-cell monofacial and bifacial modules. The modules were facing South at a tilt angle of 38º. Due to partially clouded conditions, the in-plane irradiation varied between 200 and 1400 W/m^2. Measurements were taken from 3 hours before to 3 hours after solar noon. To obtain a highly reflective underground, comparable to painted white roofs, as are common, e.g., in South-western USA, 4x4 m^2 of white back sheet was applied around the two tilted modules, as shown in Figure 5.

Figure 5: Photograph of the set-up showing the monofacial and bifacial mini-modules with the white underground. Note the less dark shadow of the bifacial module due to its transparency.

Figure 6 shows the difference in maximum power between the monofacial and the bifacial mini-module as a function of the front irradiance G_i. Both modules show a nearly linear relation between P_{max} and $G_{i,}$ but the slope of the bifacial mini-module is 5% higher due to the contribution of the rear irradiation. Interpolating the trend line to 1000 W/m^2, the bifacial mini-module exhibits an encapsulated cell efficiency of 18.6%, whereas the monofacial one, consisting of identical cells, yields 17.7% on a concrete underground.

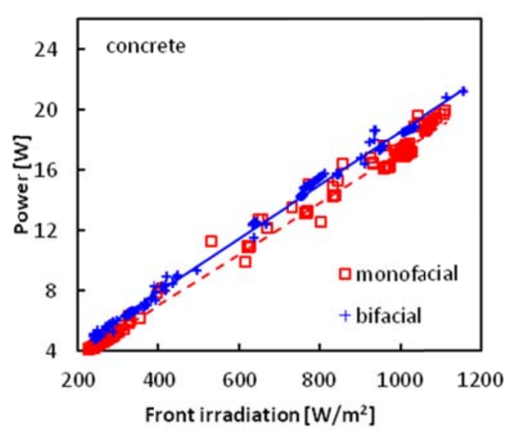

Figure 6: Maximum power as a function of front irradiation for a monofacial and a bifacial 2x2 mini-module at 38° tilt, south facing installation. The underground is concrete

Figure 7 shows the effect of changing the background. The monofacial module shows the same slope when measured with high albedo, again yielding an encapsulated cell efficiency of 17.6%. In contrast, the output power of the bifacial mini-module is strongly increased by the increased albedo. The apparent encapsulated cell efficiency is now 21.1%, which is 20% higher than that for the monofacial one on the white underground, compared to 5% higher for the concrete underground case.

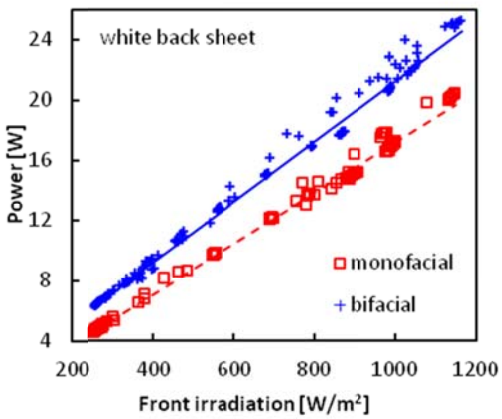

Figure 7: Maximum power as a function of front irradiance for a monofacial and a bifacial 2x2 mini-module at 38° tilt, south facing installation. The underground is 4x4 m^2 white back sheet

It is not trivial to calculate the absolute annual energy yield for the situations in Figure 6 and 7. The annual energy yield depends, amongst others, on the distribution of the irradiance, the azimuth and elevation angles of the sun relative to the module and various seasonal dependencies, including module temperature. However, we can draw conclusions on the relative (annual) energy yield for this bifacial module compared to this monofacial module.

In all cases here, the trend line of the power as a function of the irradiance is linear, with a very small offset. Consequently we can assume that the effect of the incidence angle is negligible. For any fixed irradiance the bifacial over monofacial power ratio is constant and determined solely by the ratio of the gradient. We can therefore deduce that the relative power gain of this bifacial module over this monofacial module is 5% when place at 38 tilt above concrete. Finally, the bifacial effect reaches about 20% when the modules are located above appropriate white underground.

4 CONCLUSIONS

Both AR-coated glass and transparent back sheet on the rear show a similar module performance in STC and adapted STC flash test measurements, and perform somewhat better than float glass on the rear of the module. These results can be used to optimise the cost-of-ownership for a module producer and leave some freedom to design either a glass-glass or a glass-back sheet bifacial module.

The bifacial effect has been demonstrated even at a location with low albedo. The bifacial effect, i.e. the kWh/W_p ratio for bifacial over a monofacial module, is highest at the early and late hours of the day when diffuse light contributes most, if not all of the generated power. Furthermore, the bifacial effect is higher in the summer when these conditions are met during the longer daylight hours.

The influence of albedo is verified by comparing measurements on concrete with measurements on white underground. The extra rear side contribution increases the bifacial gain from 5% to 20%. The ratio between power output for the bifacial over the monofacial module is constant, i.e. the bifacial module on high albedo has 20% more power for a broad irradiance range.

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