Relating Indoor and Outdoor Performance of Bifacial Modules

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***Abstract* — Although flash tests under standard test conditions yields lower power due to transmittance of the back sheet, bifacial modules are expected to outperform their monofacial equivalents in terms of yearly energy output in the field. Different transparent rear side materials have been compared. We compare flash tests for these bifacial modules at various incidence angles with and without a light scattering panel behind the modules. The results of an outdoor study comparing modules with transparent back sheet and modules with state-of-the-art AR coating on the front glass will be presented.**

***Index Terms* — photovoltaic systems, silicon, solar power generation.**

I. 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 transparent rear side material. However, their annual output can be significantly higher, depending on albedo, orientation and tilt angle [1, 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. Furthermore, a series of IV-curves have been measured at various tilt and azimuth angles for different bifacial test modules. 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 extreme light conditions, << 50 W / m^2. For bifacial analysis, the irradiation is measured both parallel and anti-parallel to the plane of the module.

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.

II. EXPERIMENTAL DETAILS

2x2 laminates were built to test the influence of transparent rear side materials on the power output. 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.

72-cell modules were manufactured for energy output determination when placed outdoors. The full-size modules were made using six 12-cell strings made of solar cells with efficiencies of 19.0-19.5%. Cells were binned on efficiency. Variations in Impp and Vmpp from the module average were very small. The laminates were made using two glass types: standard textured solar glass or 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.

Outdoor measurements are performed on the roof of an ECN building, located at 52°47’6” N, 4°40’25” E using a clamping system. The location is characterised by close proximity to the North Sea and no shadow. Direct irradiation will be measured with a Pyranometer and reference cell in the plane of the rack; the albedo of the blue corrugated metal wall and concrete floor behind the modules is rather low. The horizontal light intensity, a measure for the amount of indirect light, is 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 Vmpp. Evaluation of the performance of the three module types is done on the amount of energy produced relative to the STC Watt peak rating due to differences in module build-up. 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 and the antireflection textured glass relative to the standard lay-up with white back sheet and conventional glass texture..

III. RESULTS AND DISCUSSION

A. Back sheet material

In Figure 1 the short-circuit current Isc of the three laminates with different rear side materials is plotted for three different angles of incidence. For clarity, the 60° data is shown on a separate axis with the same scale, albeit a lower value. 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 Isc 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.

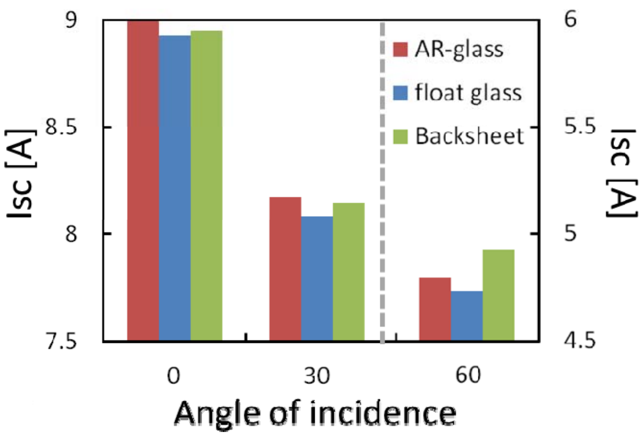

Fig. 1. Isc of bifacial modules with three different back sheet materials measured under various angles of incidence, 60° data are plotted on the right axis. All incorporated cells have similar Isc.

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.

Fig. 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, a further two panels increases this difference to about 19%. Although the Isc under standard test conditions for these three panels is different, the behaviour under influence of the increased albedo is nearly identical.

B. Outdoor data

Two full-size 72-cell modules have been monitored on the rooftop location introduced in section II. 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 sum of the peak powers of the incorporated cells. Resulting peak power, measured at 1000 W/m^2 and 25°C, was 334 W and 314 W, respectively for the monofacial and bifacial module. The location of the system has a low albedo.

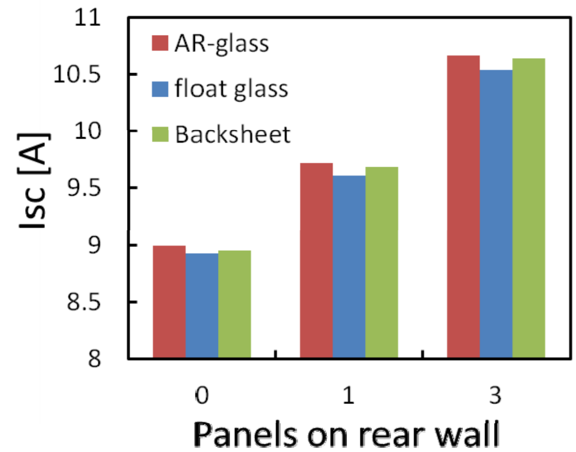

Fig. 2. Isc of bifacial modules with three different back sheet materials measured with various albedo, created by placing Styrofoam panels against the rear wall of the IV flash chamber.

To illustrate the bifacial effect, we have binned the IV-data to the time 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 energy production is divided by the summed cell power for both modules and the ratio of the bifacial kWh/Wp over the monofacial kWh/Wp is calculated and plotted in in Fig. 3 and 4. Note that the rear side passivation layer of the n-Pasha solar cell was not optimised for application in a bifacial module.

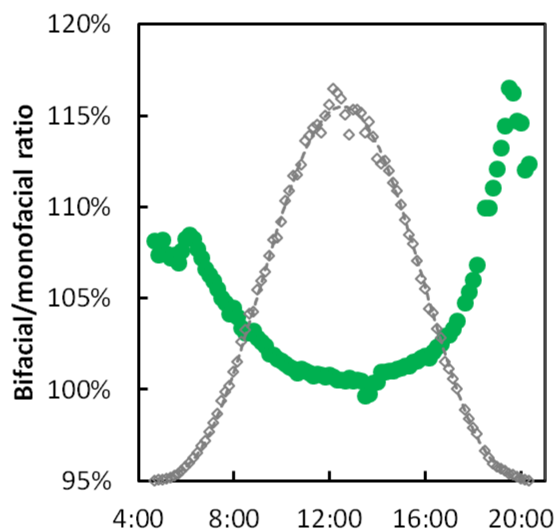

Fig. 3. Ratio between bifacial and monofacial kWh/Wp (green, filled circles) as a function of the time of day. For each 10 minute interval, the total energy production is summed and divided by the

sum of the STC power of the incorporated solar cells. Grey, open diamonds show the total illumination against the time of the day. Note: the solar noon is around 12:40pm.

The ratio is plotted against the hour of the day in Fig. 3. Around midday the ratio is 100%. With increasing distance (in time) from midday, the ratio increases in favour of the bifacial module. Before 6am and after 7pm plateaus are observed in this ratio, but the absolute values of these plateau levels differs quite a lot. As the solar noon is at 12:40pm CET winter time, most direct irradiation of the modules takes place near 1pm and thus the bifacial effect is minimal around midday. In first order approximation, the curve 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. “before East” or “after West”, almost no direct light can reach the modules and all energy is generated by diffuse light, which is more favourable for the bifacial module. Furthermore, as most of the light is indirect, the irradidation no longer depends on the relative angle of the sun and the PV system orientation. Therefore, the bifacial:monofacial ratio is constant before 6am and after 7 pm.

Because our building and set-up are 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. 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, the ratio is higher in the late afternoon plateau than in the early morning plateau. The small asymmetry in the curve, before and after “noon”, is also explain by the small orientation offset compared with due South.

Fig. 4 shows the behaviour of the same ratio but then 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 ratio is highest for the summer and lowest in January and December.

The observed minimum in the ratio in the winter months seems to contradict the hourly data, Fig. 3., where we observed the lowest ratio around midday when the irradiation is most perpendicular. In the winter, there is a minimum of 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.

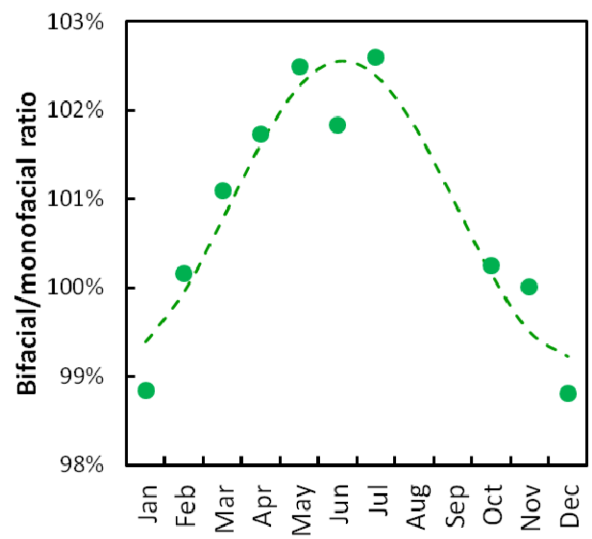

Fig. 4. Ratio between bifacial and monofacial kWh/Wp over the year. For each month the total energy production is summed and divided by the total power of the incorporated cells. Dashed line is a sinusoid to guide the eye.

IV. Conclusions and Outlook

Both AR-coated glass and transparent back sheet show a similar performance in (adapted) STC flash test measurements and perform somewhat better than float glass. 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 at a location with low albedo. The bifacial effect, i.e. the kWh/Wp 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 coincide with the daylight.

References

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