FROM BIFACIALITY TO YIELD: DIFFERENT BIFACIAL CELL TECHNOLOGIES MAY DIFFER EVEN MORE IN ANNUAL OUTDOOR PERFORMANCE

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ABSTRACT: A comparative outdoor test of different bifacial P-PERC and N-PERT PV modules was designed and operated in Freiburg, Germany. According to LG Electronic's specifications, the chosen mounting geometry and albedo deliver a high bifacial gain. While this is not comparable to typical commercial PV systems, it emphasizes differences in the bifaciality and the bifacial gain of the module samples.
A greater bifacial gain was expected already for the N-PERT modules. However, the measurements revealed more differences in annual and in high resolution performance data. Laboratory measurements do confirm the observed outdoor behavior, given they are performed under bifacial conditions as well.
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INTRODUCTION

Bifacial PV modules are able to convert solar irradiation from both surfaces. Therefore, a larger energy production—compared to standard monofacial modules—is expected. The additional energy delivered by bifacial PV modules is commonly called bifacial gain (BG). It is influenced both by PV system properties and by properties of the PV module itself, especially by the solar cell technology.

End users may distinguish different cell technologies by different conversion efficiencies and bifaciality factors, but the difference in annual energy production might be bigger than expected from these two figures. In this contribution, we compare the performance of different bifacial modules made from P-PERC and N-PERT cells. Several module properties like temperature dependency or LID are affected by the choice of cell technology. Here, we concentrate on differences in efficiency and bifaciality and their dependence on the irradiance level.

A comparative outdoor test of different PV modules was designed and operated for one full year in Freiburg, Germany. According to LG Electronic's specifications, the chosen mounting geometry and albedo deliver a high bifacial gain [1]. While this is not comparable to typical commercial systems, it emphasizes differences in the bifaciality and the bifacial gain of the module samples.

1 BIFACIAL GAIN & BIFACIALITY

The fraction of irradiance received at the rear surface of the module G_{back} may be expressed as optical bifacial gain BG_{opt} (which is a system or geometry property):

$$BG_{opt} = \frac{G_{back}}{G_{front}}$$

In opposite to the front side of the module, the availability of rear surface irradiance depends on a larger number of factors as

- the mounting geometry (module height, module tilt angle, row-to-row distance)
- the ground albedo and its homogeneity
- the mounting structure

Beside this, the rear side irradiance may vary during the day and the year in a manner quite different from the front side irradiance.

The rear side electricity production of a bifacial module is roughly proportional to the optical gain, but will be reduced by the bifaciality factor φ. This factor is a module property and usually defined as ratio of STC power or efficiency values:

$$\varphi = \frac{P_{back,stc}}{P_{front,stc}} = \frac{\eta_{back,stc}}{\eta_{front,stc}}$$

So the bifacial gain of the module may be estimated as:

$$BG_{mod} = \frac{P_{back}}{P_{front}} = \frac{G_{back}\,\eta_{back}}{G_{front}\,\eta_{front}} = BG_{opt}\,\varphi$$

Values of φ differ remarkably between p- and n-type cells and can be measured quite accurate in the laboratory. For this purpose, new standards for bifacial PV module characterization are under development. However, questions remain: Is this simple relation sufficient? Is φ a constant?

This is the main topic of our contribution, based on a full year of measured outdoor module performance data and a complementary indoor characterization, performed for different products on two different undergrounds.

From measured values of outdoor module performance, φ may be derived from values of BG_{mod} and BG_{opt}:

$$\varphi = \frac{BG_{mod}}{BG_{opt}}$$

BG_{opt} may be measured by a pair of irradiance sensors, mounted back to back in plane of array. BG_{mod} may only derived using an additional monofacial reference module:

$$BG_{mod} = \frac{P_{back}}{P_{front}} = \frac{P_{bifacial} - P_{monofacial}}{P_{monofacial}}$$

2 OUTDOOR MEASUREMENTS

The outdoor test setup with different bifacial and monofacial module samples was installed on the roof of one of Fraunhofer ISE's buildings in Freiburg, Germany, see Figure 1. The symmetrical setup was operated for one full year. IV curve and power measurements were performed on all modules in regular intervals of 5 min and 1 min. The albedo of the membrane was measured several times and reached values between 75% and 80%. For the given geometry, this lead to an average irradiation gain of 35%.

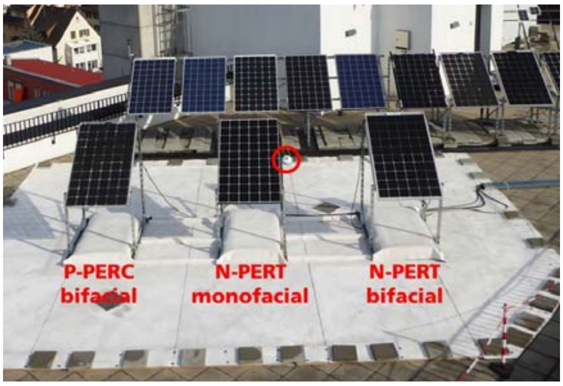

Figure 1: The 3 modules under consideration are mounted in the front row above a bright roofing membrane. For symmetry reasons, the two bifacial modules are placed on the outer positions, while the monofacial reference module is placed in the center. On the right edge of the reference module, two pyranometers are mounted back to back.

2.1 Annual outdoor results

The average annual optical gain BG_{opt} measured by the two pyranometers is close to 35%. From this optical gain and values of φ from laboratory tests, a module bifacial gain $BG_{mod,est}$ may be estimated to values of some 30% for the N-PERT module and some 20% for the P-PERC module. Table 1 compares these estimates to observed $BG_{mod,obs}$. It is seen that both modules miss the expected level of bifacial gain. The N-PERT module shows a higher bifaciality and is closer to the expected bifacial gain than the P-PERC module.

Table 1: Annual outdoor results

	BG_{opt}	Φ	BG_{mod} est.	BG_{mod} obs.	**obs. / est.**
	%	%	%	%	**%**
P-PERC	34.7	58.2	20.2	16.5	**81.7**
N-PERT	34.7	87.4	30.3	26.5	**87.2**

2.2 High resolution outdoor results

To investigate these deviations in more depth, the measured data is used in its original time step. Figures 3 and 5 depict the dependency of BG values on front side irradiance. While annual average BG_{opt} is close to 35%, instantaneous values vary from 20% to 65%. BG_{opt} clearly depends on the mounting geometry and on the actual position of the sun for a given point in time. Consequently, also BG_{mod} varies between 10% and 35% for the P-PERC module and between 15% and 45% for the N-PERT module.

According to the formulae presented in Section 1, φ may be derived from individual values of BG_{mod} and BG_{opt}. Despite φ is assumed to be a module property, it is obviously not constant. The plots in Figures 3 and 5 show values of φ in a range from 35% to 60% for the P-PERC module and from 60% to 90% for the N-PERT module.

With the P-PERC module, a clear trend is visible. Stable values of φ are seen above some 100 W/m², and a decrease in φ is observed from about 500 W/m² onwards. The situation is less clear with the N-PERT module, however, φ is on a remarkable higher level here.

3 LABORATORY MEASUREMENTS

A simple approach to determine φ in the laboratory utilizes two single sided measurements in a solar simulator. For a given irradiance level G, single sided power or efficiency values are determined while the other module surface is covered. Figures 4 and 6 present such measurements on the two bifacial modules. The upper graphs depict the efficiencies, the red curve in the lower plots gives the resulting φ(G) as ratio of both efficiencies:

$$\varphi(G) = \frac{P_{back}(G)}{P_{front}(G)} = \frac{\eta_{back}(G)}{\eta_{front}(G)}$$

Compared to the trend visible in the measured data (bifaciality decreases with irradiance), the trend seen in the single sided φ(G) curves (bifaciality increases with irradiance) follows the wrong direction. Obviously, the singled sided measurements do not represent the real operating conditions under bifacial irradiance.

This problem may be solved through measurements of φ(G) under bifacial irradiance conditions. Fraunhofer ISE operates a solar simulator which is able to measure full size bifacial modules under bifacial irradiance [2]. The light of a large pulsed solar simulator is reflected by a pair of mirrors to both sides of the test sample. The overall irradiance level may be controlled at the light source, while the back irradiance may be reduced using filter meshes. Figure 2 presents a number of combinations of front and back irradiance used for this investigation.

The results of such bifacial measurements are presented in Figures 4 and 6 as well. In contrast to the single sided measurements, now bifaciality decreases with irradiance. This is consistent with the trend seen in the outdoor data, however, deviations remain regarding the absolute level.

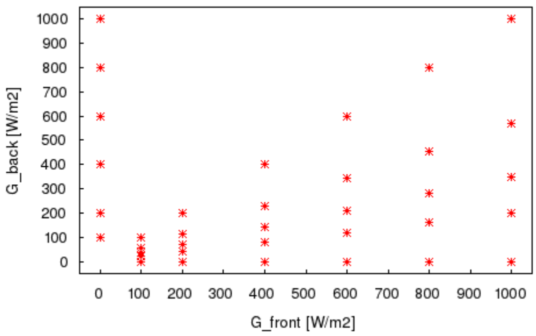

Figure 2: Possible combinations of G_{front} and G_{back} in Fraunhofer ISE's bifacial pulsed solar simulator.

P-PERC

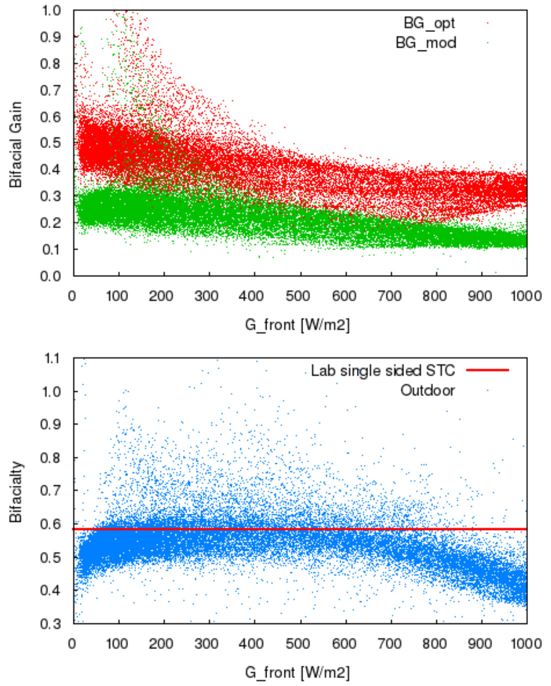

Figure 3: Top: bifacial gain values, red dots show BG_{opt}, green dots show BG_{mod}; bottom: resulting bifacialty φ for the P-PERC module.

N-PERT

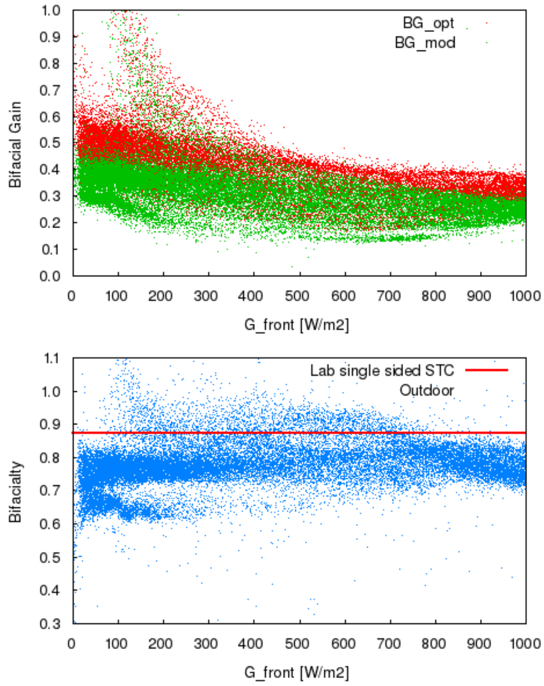

Figure 5: Top: bifacial gain values, red dots show BG_{opt}, green dots show BG_{mod}; bottom: resulting bifacialty φ for the N-PERT module.

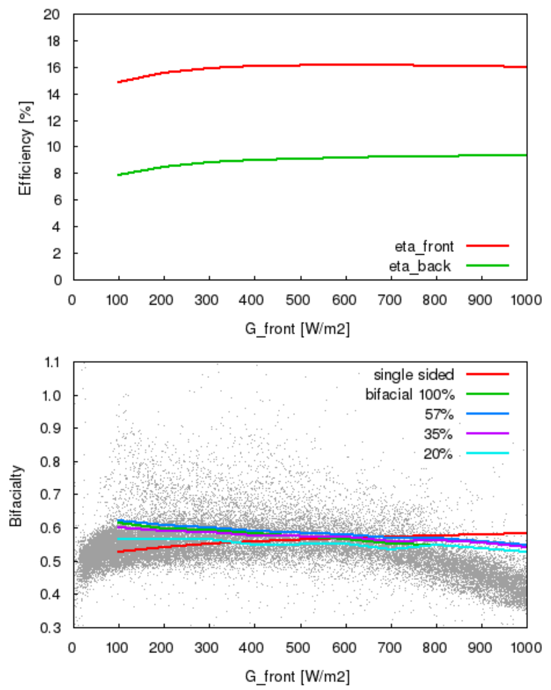

Figure 4: Top: single sided efficiencies; bottom: bifacialty φ derived from single sided efficiencies (red curve) and from measurements under bifacial irradiance conditions (all other curves) for the P-PERC module.

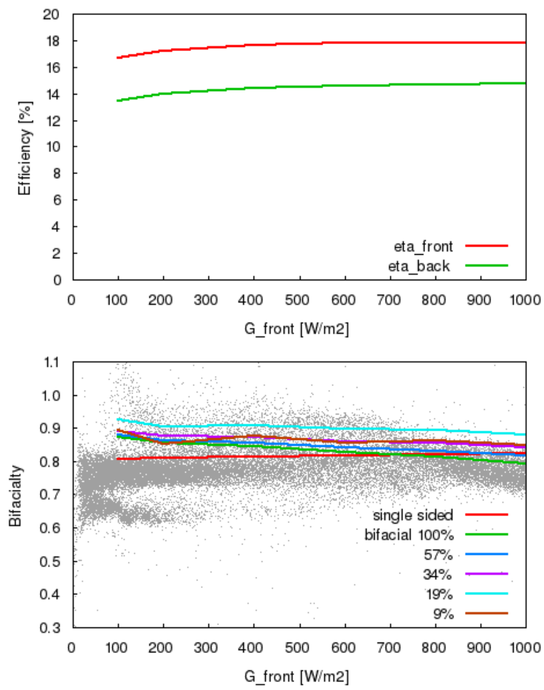

Figure 6: Top: single sided efficiencies; bottom: bifacialty φ derived from single sided efficiencies (red curve) and from measurements under bifacial irradiance conditions (all other curves) for the N-PERT module.

4 DISCUSSION

In the straight forward indoor–outdoor comparison shown in Figures 4 and 6, some differences remain between the gray dots (φ from test site) and the purple lines (φ from bifacial solar simulator measurement with the rear side irradiance set to some 35% of the front side level). There are several contributions to these deviations.

The comparison of optical bifacial gain, determined by two single spot pyranometer measurements, to module bifacial gain, determined from two full size module power measurements, does not account for inhomogeneity in rear side irradiance. This situation could be improved by multiple irradiance sensors, possibly raising additional questions on correct sensor placement and on the correct weighting of the individual sensor readings.

Also, the test setup suffered from some space restrictions and, in consequence, from the installation of only one monofacial reference module. Therefore, the bifacial output of the P-PERC module was referred to the N-PERT monofacial module. As the normalized front side efficiencies of both modules proved to be quite similar, the error induced through this kind of evaluation should be small.

A certain fraction of the deviations between outdoor and laboratory measurements is due to the different angular distribution of the incident irradiance. Especially on the rear side, the outdoor light comes in at rather large angles of incidence, while the light incidence in the simulator is close to normal – leading to lower reflection losses.

Finally, the comparison of bifacial module output power to a monofacial reference module power might need a precise correction for the module temperatures. Differing operating temperatures caused by different optical properties of the modules may distort the simple approach described in Section 1.

Despite all mentioned challenges of a bifacial indoor–outdoor comparison, the data presented in Figures 4 and 6 give some confidence in understanding the behavior of bifacial PV modules. The differences between N-PERT and P-PERC cell technology are well reproduced, and also the overall dependency of the bifaciality φ on irradiance levels appears in a consistent way.

CONCLUSION

A greater bifacial gain was expected already for the N-PERT modules. Both indoor and outdoor measurements confirmed the higher absolute efficiency and the higher bifaciality of the N-PERT product. However, the measurements revealed some issues which are of importance for future yield predictions of bifacial PV systems.

The bifaciality factor φ is not a constant value, but depends on the overall irradiance level and probably on the optical gain of the individual system design. An annual average value of φ may be determined from outdoor measurements or from accurate modelling of irradiance statistics and module behavior. Most probably, a bifaciality factor derived from single sided STC measurements (as given on some of today's module data sheets) is not the best estimator for the realistic bifacial performance of a specific module.

Laboratory measurements do confirm the observed module behavior under outdoor conditions, given they are performed under bifacial conditions as well. Such measurements provide the information necessary for state-of-the-art yield predictions for bifacial PV systems.

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