ILLUMINATION HOMOGENEITY OF BIFACIAL SYSTEMS – OUTDOOR MEASUREMENTS WITH SYSTEMATICALLY VARIED INSTALLATION CONDITIONS

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ABSTRACT: The optimum mounting condition for bifacial modules is a trade-off maximizing the performance of the front and backside output obtained for the given installation conditions. At the backside of bifacial PV modules there are more complex conditions concerning the illumination intensity and illumination homogeneity, compared to the frontside. In extended PV plants, with parallel rows of bifacial modules, there are additional factors, such as reduced ground albedo due to shading by adjacent rows, which have to be considered.
At the ZHAW, we implemented an outdoor test system to analyse the performance of bifacial arrays at differing mounting conditions by a new methodical measurement approach. The tilt angle is adjusted periodically between 0° and 90° in twelve positions within a one minute interval. In this paper we focus on outdoor measurement results concerning the illumination homogeneity at the front and backside and its impact on the total output. Not only the module data itself is analysed, but also a set of multiple small light sensors is attached at the rim of the bifacial centre module in order to reveal the illumination homogeneity in more detail. This setup enables a detailed analysis of the sensitivity at different tilt angles as well as more general yield results from long-term measurements.
Keywords: Bifacial, PV Array, Shading, System Performance, Evaluation

1 INTRODUCTION

The potential for an improved module power output of bifacial PV systems, compared to standard monofacial ones, was repeatedly demonstrated by simulations [1]–[3], measurements on single modules [4]–[8] or installations [9] with specific installation conditions. In spite of the considerable potential the installed capacity of bifacial systems is still marginal. A major obstacle for investors is the limited predictability of the bifacial PV system output. Even in the PV community there is considerable uncertainty about the real benefit due to bifaciality, as reflected by the numerous publications dealing with this issue.

For monofacial standard systems the simulation by software tools is a proven means and state-of-the-art since long. Due to the large amount of installed monofacial systems all over the world exists a huge amount of comparable data which allows an appraisal of projected arrays. Thus, for standard monofacial systems, investors can rely on a meaningful appraisal based on experience and simulations.

Because of more complicated physical conditions the predictability of bifacial PV systems is considerably less straightforward and reliable. The bifacial power gain is inherently based on the utilization of the radiation which is impinging on the modules backside. This backside illumination, reflected light from the modules surrounding, will show an inhomogeneous distribution over the backside area, dependent on multiple factors. Optimised mounting conditions for bifacial modules are a trade-off maximizing the performance of the front and backside output obtained for the given ground reflectance, the installation height, inclination and orientation. These more complex conditions concerning the illumination intensity and illumination homogeneity, compared to the frontside, hamper the development of reliable simulation software tools for bifacial modules. In real, extended systems, the arrangement of multiple modules and the specific mounting conditions will have additional effects. Shading or the reflectance caused by adjacent rows has to be taken into account. This is particularly true for some mounting conditions which are of interest for bifacial systems, such as vertical installation. Also the reduced albedo due to shading of the ground has to be considered.

A systematic analysis of a bifacial system in a real, extended array is therefore an appropriate means to improve the described obstacles, as it produces data to test and improve respective physical models and algorithms.

2 APPROACH

At the Zurich University of Applied Science (ZHAW) we currently put an array for the systematic measurements of bifacial systems with differing mounting conditions to the test. The trials are carried out at a 3x3 module array based on large, commercially available, 60-cell modules with a continuous, automated variation of the tilt angle. Other parameters like the distance between adjacent rows, the installation height or the ground reflectivity are manually adjusted. Due to the continuous variation of the tilt angle trends and interdependencies are revealed and several mounting situations are simultaneously analysed.

The basic concept of the test rig is shown in Figure 1. It offers the option to include shading and light reflection effects by adjacent rows of modules in different configurations. This is a major advantage compared to test stands with single, free standing modules. Three rows of modules, with manually adjustable distance between the rows, are mounted on vertically adjustable pillars in order to position the modules in different heights. An important feature of the measurement set-up is the automatic variation of the tilt angle in certain steps. For each step an I/V-curve of the centre module is measured in order to get the power as a function of the tilt angle of the module over a long period. All panels change their tilt angle continuously and coordinated with the central row.

By a change of the orientation of the whole measurement test array one can measure the power output of a typical flat roof or ground mounted, free field PV system, mainly oriented to the south (northern hemisphere) or a tracking system changing the orientation from east to west. In the latter case, the measurement system can be used as tracking system itself. In addition, the influence of reflective grounds with differing reflectivity can be analysed.

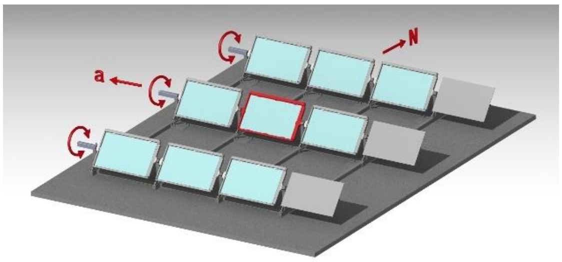

Figure 1: Measurement setup with permanently revolving modules, indicated with round arrows. Height, distance between rows and reflecting ground can be changed manually. The most relevant module in the centre, which is best suited to represent the actual conditions in real installations, is marked red.

Due to the bifaciality, the used PV modules are also sensitive to indirect shading by reason of reduced diffuse reflectance from the ground. Therefore, the panel in the centre of such an array is best suited to reflect the general conditions for a typical module in an extended bifacial power plant. By analysis of the other modules in the array the effect as a result of the limited extension and the validity of simulation tools can be tested.

An advantage of the new methodical bifacial test setup is that even small changes in yield at different tilt angels will be detected, compared to fixed mounted bifacial PV module rows at different tilt angles. This is due to the fact that measurement values of the same module at the identical position are used, which excludes drift effects of individual modules and local variations of the ambient.

3 OBJECTIVES

An important objective of the test rig, called Bifacial Outdoor Rotor Tester (BIFOROT), is the generation of data in long term measurements to test and improve existing prediction algorithms for bifacial systems. The variation of the mounting conditions allows the implementation of varying parameters (installation height, albedo, row distance) which results in an extended range of validity. The long term measurements will also reveal the energy yield and the impact of shading for specific mounting situations. For all mounting situations and lighting conditions the optimized tilt angle will be determined due to the continuous revolving of the modules.

Long term measurements are however no prerequisite to obtain meaningful results. Also at shorter time scales important conclusions about the general properties of bifacial systems can be drawn. This is especially true if certain parameters, such as the albedo from the surrounding ground, can be replaced at virtually unchanged lighting conditions. Since the adjustment of new installation conditions can be lengthy for such a large array, we additionally implemented a miniaturized version. Comparison of yield analysis from the BIFOROT and the miniaturized BIFOROT test array are subject to prior publications [10].

4 MEASUREMENT SETUP

A matrix of 3x3 modules may not be sufficient to reflect the shading effects in extended arrays for specific installation conditions, such as vertical installation. This is particularly true for small distances between rows. Therefore additional shading elements are respectively applied to one side of the rows, a further extension in the large array is not feasible due to the limited available space on the roof of the building.

Figure 2 shows the test rig, equipped with commercially available bifacial modules from the cell and module manufacturer Megacell (MBF-GG60-270). The white sheet under the test array from the manufacturer Sika (Sarnafil TS 77-20 RAL 9016) is commercially used for roof waterproofing. The measured albedo factor (measured at axis height) after a year installation and regular cleaning is 0.51, whereas the albedo factor of the surrounding concrete slabs is 0.17, also measured at axis height.

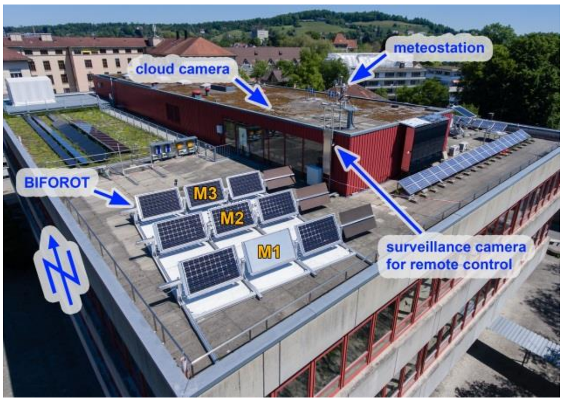

Figure 2: South orientated installation of the BIFOROT test array on the roof of the ZHAW in Winterthur. Aerial view on the roof and test array from southwest direction. The module tilt angle is changing permanently in a synchronized manner within an interval of one minute. Module 1 to module 3 (M1 –M3) are the devices under test (DUT).

The respective output versus the tilt angle is recorded for a specific set of tilt angles. The duration of a cycle is one minute, in which one cycle means the movement from the 0° horizontal position to the 90° vertical position (for south orientation of the frontside). There are 12 tilt angles / measurement positions in each cycle (0°, 10°, 15°, 18°, 21° 25°, 30°, 35°, 40°, 45°, 60°, 90°).

Multiple small light sensors are attached in vertical and horizontal positions at the centre module (M2) front (Figure 3) and backside (Figure 4). East of the centre module a rotating pyranometer and ISE reference cell is installed. Several environmental sensors are located on the north side of the test array and on top of the roof. These sensor measurements include the wind speed, wind direction, ambient temperature and the global horizontal irradiation.

Table I represents the used specifications for the BIFOROT, which were used for the measurements. All results in the following chapter are based on these specifications.

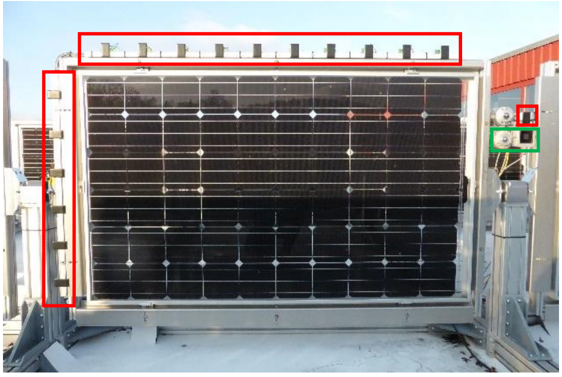

Figure 3: Small irradiance sensors - crystalline silicon cells - (red marked) enable a detailed analysis of the mapping of illumination intensity and homogeneity on the module frontside (south side). The pyranometer and silicon reference sensors ISE cell (green marked) are mounted on the east side of the module mounting frame, moving synchro with the DUT.

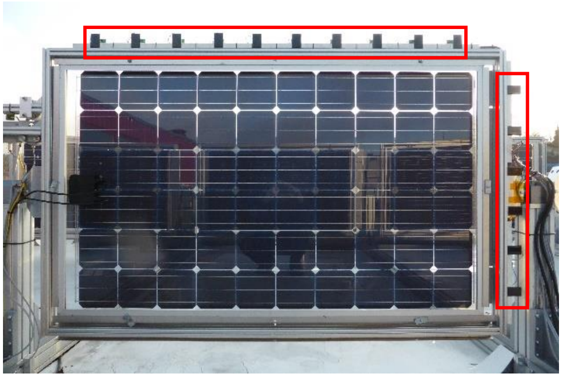

Figure 4: Small irradiance sensors - crystalline silicon cells - (red marked) on the module backside (north side).

Table I: Used specifications of the BIFOROT for the analysis in this paper

Name	Value/Description
Azimuth Angle	0° (north-south orientation)
Axis height	0.75 m (from ground to axis centre)
Axial spacing	2.86 m (from the centre of the axis to the centre of the axis)
Ground albedo	0.51 (measured at axis height)
Module height	lower edge depending on tilt angle (Figure 11), module centre always at axis height (0.75 m)
Module 1 (M1)	frontside covered for $I_{SC,back}$ measurement
Module 2 (M2)	I/V-curve measurement ($I_{SC,bifacial}$)
Module 3 (M3)	backside covered for $I_{SC,front}$ measurement

5 DATA EVALUATION

The long-time measurement started on 5th of October 2016 and was planned to continue for at least one year. Unfortunately, on 28th of March 2017, two construction cranes of a larger construction site were erected in the south of the test array. These cranes caused significant shading on the test array. Therefore, the measurement data could only be evaluated until 27th of March 2017.

In order to exclude shading from the building and reflection effects from the glass pane (Figures 2 and 5), the used data are limited to an azimuth angle range of -86.6° to +85.1° (respectively 93.4° to 265.1°), as well as to a minimum sun elevation of 0°. Figure 6 shows the sun positions during the measuring period with the corresponding angles of incidence. The white gaps correlate with the measurement outages by reason of maintenance, heavy snowfall or icing of the bearings.

Figure 5: Reflection of the sunlight in the glass pane of the roof structure.

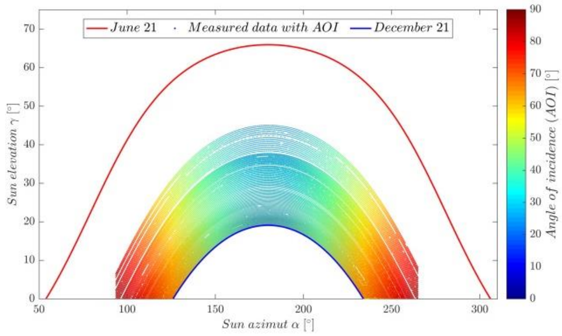

Figure 6: Solar positions at the measuring location during the measurement period with the angle of incidence (colored points), solar positions on December 21 (blue) and June 21 (red). In addition, the graph shows the interruptions (e.g. due to maintenance, heavy snowfall or frost) by the white gaps.

The used centre module (M2) has a bifaciality B of 0.694, which is calculated according to Formula (1). This value is low compared to other bifacial modules because of the shading on the modules backside, caused by the junction box. The MPP values of each side were measured with the ZHAW LED Flasher [11], whereas the not measured side was covered by a cardboard.

$$B = \frac{P_{mpp,back}}{P_{mpp,front}} = \frac{188.5\ W}{271.44\ W} = 0.694 \qquad (1)$$

5.1 Energy yield

The energy yield of the centre module (M2) is shown in Figure 7 (dark blue) for the whole measurement period (winter season). The maximal energy yield for the given setup was achieved at a 40° tilt angle. In Figure 7, the monthly energy yields from October 2016 to March 2017 are shown as well. The yield of January is low due to heavy snowfall and icing of the rotating axis.

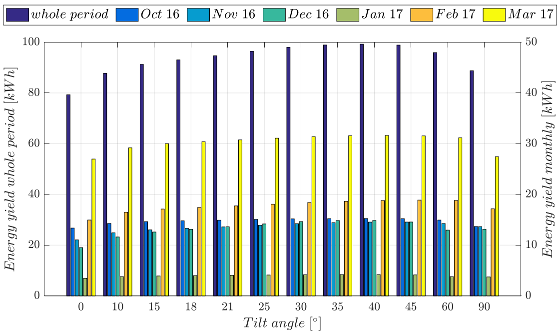

Figure 7: Energy yield (dark blue, left y-Axis) over the whole measurement period (05.10.2016 until 27.03.2017) and energy yield per month (coloured, right y-Axis) per tilt angle of module 2 (M2). The yield of January is low due to heavy snowfall and icing of the rotating axis.

5.2 Irradiance on module front and backside

Figure 8 shows the energy yield of M2 compared to the total irradiation measured with the ISE cell, which is installed in the module frontside plane. Additionally, the total irradiation on the module frontside of M3 is shown. The total irradiation is respectively obtained by integrating the I_{SC} measurement values. The courses of the total frontside irradiations (ISE and I_{SC}) are almost identical, whereas the energy yield has a different course due to the bifacial gain.

Figure 9 includes the sum of the short circuit current of the frontside (M3), backside (M1), their sum and bifacial (M2) per tilt angle. It is evident that the sum of the short circuit current on the backside of the module is nearly constant over all tilt angles. The backside contribution (Bc) is calculated according to Formula (2) and shown on the right y-axes of Figure 9.

$$Bc = \frac{\sum I_{SC,bifacial}}{\sum I_{SC,front}} - 1 \tag{2}$$

The relative contribution of the backside to the total illumination in Figure 9 is in a range between 0.15 at 45° and 0.35 at 0° dependent on the tilt angle.

The irradiation on the module backside, measured at different positions, is shown in Figure 10. The minimal irradiation on the backside of the module limits the bifacial gain. The red lines in Figure 9 (Bc) and Figure 10 (minimal value) have an identical course.

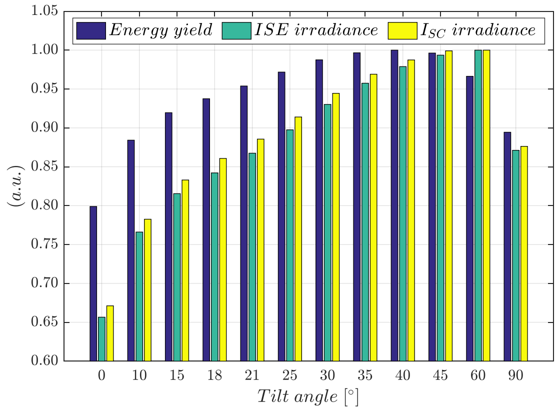

Figure 8: The course of the total irradiation on the module frontside (M2) measured with the ISE cell, as well as the total irradiation on the module frontside of M3 is shown in comparison to the energy yield per tilt angle of module 2. All values are normalized to the maximum per category.

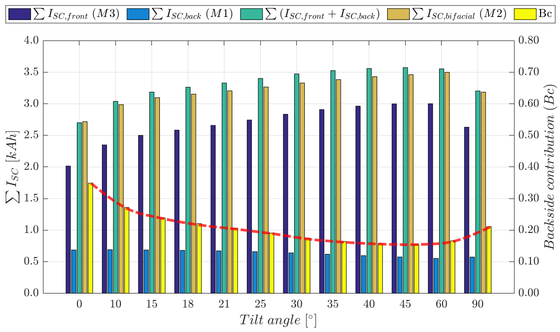

Figure 9: Total irradiation (integrated I_{SC}) over the whole measurement period for frontside (M3), backside (M1), sum of front and backside and bifacial (M2) per tilt angle. The contribution of the backside (yellow, right y-Axis) was calculated according to Formula (2).

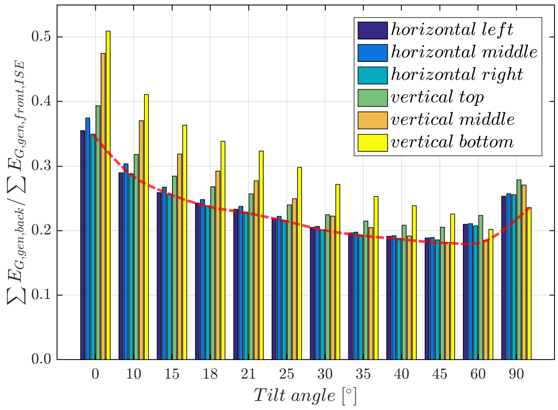

Figure 10: The irradiation over the whole measurement period on the module backside of module 2 (M2) is measured at different positions and related to the irradiation on the module frontside (ISE cell)

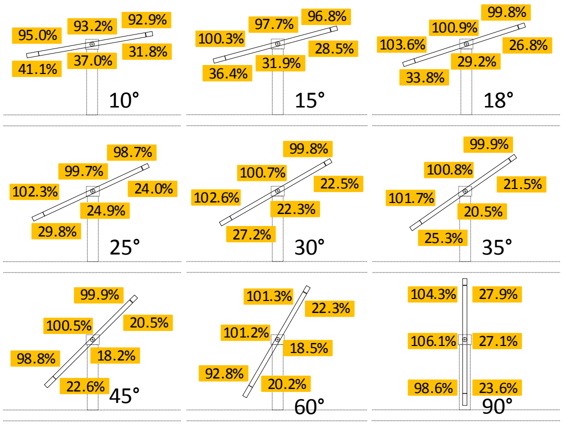

Figure 11: The vertical total irradiation for the front and backside of module 2 (M2) over the whole measurement period. The irradiation is related to the irradiation measured on the module frontside plane by the ISE cell.

The vertical irradiation distribution for three sensor heights (front and backside) and for different tilt angles is shown in Figure 11. The values are normalised to the ISE irradiation on the module frontside. The further the distance to the ground, the more diffuse irradiation reaches the backside of the module and contributes to the energy yield. The lowest value on the backside of the module limits the bifacial gain. A higher mounting height results in a higher energy yield, which has already been shown in other publications [8].

6 CONCLUSION AND OUTLOOK

The new test system was successfully operated during the first long term measurement period. The data provide valuable information about the distribution of irradiation on the module backside at different tilt angles. These data are intended to be used for the development of an energy yield simulation model.

The maximal energy yield for the measurement period (winter season) and the given setup was achieved at a tilt angle range between 35° and 45°. The total backside illumination was found to be almost constant for all tilt angles. This could indicate that the planning of bifacial systems can be performed similar to the monofacial procedures, but this has to be proved. The relative contribution of the backside to the total illumination was measured between 0.15 at 45° and 0.35 at 0° depending on the tilt angle. The minimal irradiation on the backside of the module limits the bifacial gain.

Further studies will include optimisations of the measuring device. The already obtained and future data will be used to develop and proof an energy yield simulation model in cooperation with the ISC Konstanz.

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