PERFORMANCE ANALYSIS OF VERTICALLY MOUNTED BIFACIAL PV MODULES ON GREEN ROOF SYSTEM

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ABSTRACT: A combination of PV and green roof is an ideal fusion in terms of ecology. The green roof improves the water retention in the city, whereas the PV system produces electric power at the place where it is consumed. Flat tilted modules in south or east west direction on green roofs generally require intensive maintenance to prevent them from being shaded by plants and often cover the roof area to a large extent. Because of the space requirement conflict between PV on the roof and green roofs, it is essential to combine these two systems in a smart way. Vertically mounted bifacial modules can be an option to combine PV and green roof and to also allow a cost-effective maintenance.
In this paper we report about the layout and the performance of a corresponding system, subdivided into two groups with differing albedo. Custom made bifacial modules with 20 cells were produced to reduce the wind load and to improve the general appearance. This 9.09 kWp bifacial plant achieved a specific yield of 942 kWh/kWp in one year (11.08.2017 to 10.08.2018). High quality DC power measurement systems are installed to monitor two modules in each bifacial test field and a reference south-facing module. This allows an energy yield comparison between the vertical bifacial test system with east-west orientation and the monofacial south-facing reference over four months of outdoor measurements. The use of plants with good reflective properties, which are also well suited two the ambient conditions on flat roofs, resulted in a yield increase of 17 % compared to a standard green roof planting. The vertically installed bifacial modules obtained an almost identical specific yield (-1.4 %) compared to a stand-alone monofacial south-facing reference module. Due to the increased yield in the mornings and afternoons, the vertical bifacial modules can achieve higher self-consumption depending on the load profile.
Keywords: Bifacial, PV System, System Performance, Green Roof

1 INTRODUCTION

According to the energy strategy 2050 of the Federal Council and Parliament of Switzerland, electricity originated from nuclear power has to be completely covered by electricity from new renewable energies; 16.7 % of the total electricity demand is to be covered by PV electricity by 2050 [1]. Particularly in densely populated countries such as Switzerland, the utilization of flat roofs for PV may be an important means to increase the installed capacity.

Green roofs promise a wide range of environmental, economic and social benefits. Building regulations that support the green roof concept are being implemented around the world at the moment [2]. These regulations aim to reduce rainwater runoff, to improve air quality and to reduce the need for cooling [3]. A comparison of 17 studies shows a cooling at street level between 0.03-3 C° due to green roofs [4]. Even though we could show in a previous study that the green roof cooling effect only has a negligible influence on the PV yield [5], a combined use is desirable with regard to the above considerations.

Today, PV installations on green roofs are rather rare. Because of the space requirement conflict between PV on the roof and green roofs, it is essential to identify options that allow a combination of both approaches.

Vertically mounted bifacial modules may be such an option. According to simulations, vertically mounted bifacial modules can have a higher energy yield than standard bifacial installations depending on the location and the installation conditions [6], [7].

With the presented concept for vertical mounting and corresponding outdoor measurements, we want to show that PV and green roof can be combined and that the maintenance can be done in a cost-effective way.

2 APPROACH

2.1 Project goal

This joint project of green roof experts and photovoltaic specialists [8] was set up to verify the suitability of an adapted vertical bifacial PV system on a flat green roof. One goal was to analyse how vertically east-west-facing mounted bifacial modules perform compared to a monofacial south oriented module and if the vertically mounted bifacial PV panels actually allow a cost-effective maintenance. In addition, the influence of silver-leaved plants on the specific yield should be investigated.

Figure 1 Vertically east-west mounted bifacial modules installed on the green roof in Winterthur, Switzerland with a rated output of 9.09 kWp. The east-west-facing modules have a tilt angle of 90° and an azimuth angle of -65° for the front side and 115° for the rear side. (used azimuth angle definition: east = -90°, south=0° and west = 90°)

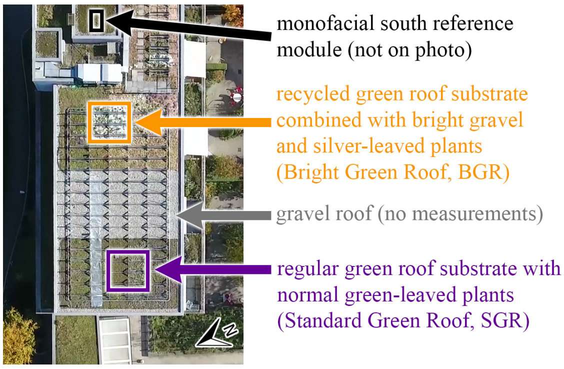

Figure 2 Aerial view of the roof. The power measurements are carried out in the marked rectangles.

Figure 3 Photos of the two green roof areas. On the left side is the standard green-leaved green roof (SGR) and on the right side the "bright" silvered-leaved green roof (BGR). The photos were taken after a long dry and heat period on 21.08.2018. It shows nicely that the silver-leaved plants survive such a period better than a green-leaved plant. The housings on the floor below the modules contain part of the measurement electronics.

Figure 4 Custom-made 20 cell bifacial module with MegaCell monocrystalline n-type silicon cells. The average STC-power of the four modules measured is 82.2 W on the front side and 71.6 W on the rear side.

Figure 5 Monofacial south facing (25° azimuth, 16° tilt angle) monocrystalline Silicon reference module of the manufacturer Hareonsolar with a measured STC power of 203.3 W.

2.2 Setup

On a flat roof (25° azimuth) located in Winterthur Switzerland, a bifacial PV plant of 9.09 kWp was installed. The modules are mounted vertically in east-west direction (90° tilt angle, -65° azimuth for the front side and 115° for the rear side) as shown in Figure 1. The green roof is divided into two test fields with different soil material. One test field consists of a standard green roof substrate and a standard mixture of green-leaved plants (standard green roof, SGR). The other consists of recycled green roof substrate combined with bright gravel and silver-leaved plants to achieve a higher albedo (bright green roof, BGR). Figure 3 shows the two test areas. The silver-leaved plants are usually found in the Mediterranean region. The bright color of the plants protects them from drying out by partially reflecting the sunlight, accordingly they also have an improved resilience in dry conditions. Plants were selected with a low growth height. Between these two test fields there is a normal gravel roof with installed PV where no detailed measurements are made. A standard monofacial module is installed in south direction (16° tilt angle, 25° azimuth) as reference. The arrangement on the roof is shown in the aerial view in Figure 2.

The bifacial modules are custom made glass/glass modules where 20 monocrystalline n-type silicon cells from the manufacturer MegaCell are embedded. A photo of such a module with the vertically mounting system from the company ZinCo is shown in Figure 4. The modules have a dimension of 36 x 170 cm, whereby the total cell area is 31.5 x 157.5 cm. The distance between the floor and the lower edge of the module is 40 cm. The row distance between the modules is 98 cm, which corresponds to a shading angle of 20.2°. The ground coverage ratio (GCR) is 36.7 %.

The south oriented (25° azimuth, 16° tilt angle) monofacial reference module is a glass/backsheet module from the manufacturer Hareonsolar (type HR-210-24/Aa) with 72 monocrystalline silicon cells as shown in Figure 5. For a fictive installation with south oriented modules on the whole roof, a row distance of 1.4 meters would have been chosen for a shading angle of 20°. The resulting GCR would then be 57.7 %, which is significantly higher compared to the solution using the vertically oriented bifacial modules. The tilt angle of 16° was chosen in order to avoid shading of the bifacial modules in a potential combination of bifacial east-west-facing and monofacial south orientated modules.

The bifacial PV plant was put into operation in March 2017 and the south-facing reference module was installed in spring 2018. The power measurement of the 5 modules (reference module plus 4 bifacial modules) was started on 19.05.2018.

2.3 Surroundings

The test roof is located in Winterthur, Switzerland (coordinates: 47°30'10.7"N 8°43'22.0"E). There is a higher building on the west side of the roof, which causes shading in the evening. Figure 6 shows a panorama photo, including the sun positions over one year. The shading causes more power loss on the bifacial modules than on the reference module. In order to be able to compare the measurements at the different locations on the roof, only the measurement data up to an azimuth angle of 86° are evaluated. In an additional evaluation, the missing data from 86° azimuth onwards were simulated as described in chapter 2.5 and added to the dataset. This allows to make conclusions for roofs that are not affected by shading.

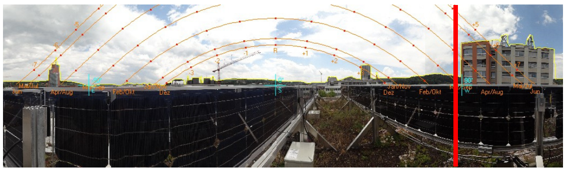

Figure 6 Panorama photo taken between the module rows with drawn sun positions (orange) and horizon line (yellow). The red line marks the 86° azimuth angle. On the left side of the red line measurement data, on the right side of the red line simulated data are used.

2.4 Measurements

High quality DC power measurement systems are installed to monitor two modules in each bifacial test field and the reference module. The measurement uncertainty for the power measurement is below 0.5 % (k=2) and the measurements are logged every 10 seconds. Each module has its own MPP tracker whereas the power measurement is installed between the PV module and the MPP tracker.

The module temperature of the reference module is measured with a Class A PT1000 sensor mounted on the module backside. The measurement uncertainty of the temperature sensor depends on the actual temperature resulting in ± 0.25 °C (k=2) at 50 °C. The used measurement electronics in the data logger add another ± 0.25 °C measurement uncertainty (k=2).

STC power measurements of the monitored modules were performed with the Portable LED Flasher [9] before the installation (each side of the bifacial module was measured separately while the other side was completely shaded).

2.5 Yield simulations

The 10 minute meteo data (global irradiance, diffuse irradiance, air temperature, wind speed and wind direction) of the nearest meteo station of MeteoSwiss (Federal Office of Meteorology and Climatology) are used for the yield simulation. The closest station is in Aadorf (13.9 km linear distance). A low-cost irradiance measurement is installed on the test roof itself, but it is also affected by the shading. Therefore, it cannot be used for the simulation. The yield simulation is structured as follows:

1. sun position (azimuth and elevation) [10]
2. angle of incidence (AOI) [11]
3. extraterrestrial irradiance [11]
4. direct normal irradiance from global and diffuse irradiance [11]
5. global tilted irradiance [12]
6. low-light performance [13]
7. module temperature [11]
8. module power considering low-light performance, module temperature, power temperature coefficient and spectral mismatch [13]

For the bifacial modules, the global tilted irradiance was calculated for both sides and then summed up considering the bifacility. In addition the mutual shading was taken into account for the calculation of the global tilted irradiance.

In order to obtain a uniform time interval with the 10 second measurement data, the 10 minute simulation data is interpolated linearly [5]. The simulated DC power is scaled according to the measurement data during the day where no shading appears. Then, the scaled data are added to the measurements after the shading occurs as shown in Figure 7.

From chapter 4.5 onwards, the results are given for the pure power measurement data up to 86° azimuth and for the combination of measurement data and simulation. In addition, the results from the combination of vertically bifacial (BGR) and south-facing monofacial systems are given. The combination of 40 % vertically bifacial and 60 % monofacial south leads to the blue colored graph shown in Figure 7. Such a combination could be interesting for industrial companies, but also for households. The combination offers a higher yield in the morning and afternoon and a more homogeneous yield at noon than the south facing plant alone. This blue graph could be optimized by rotating 180° half of the bifacial modules, regarding homogeneity over noon.

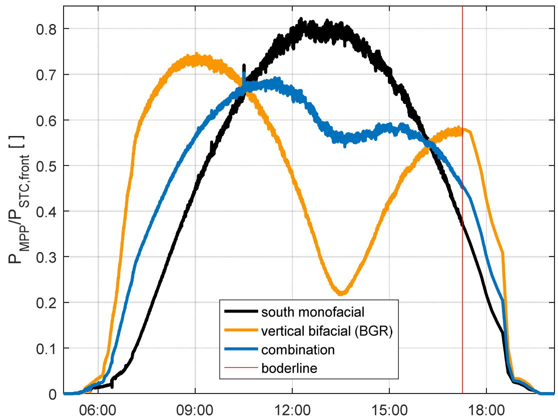

Figure 7 Graph of the measured and simulated powers of the reference south-facing module (black), a bifacial east-west-facing module (orange) and a combination of bifacial and south (blue, 40 % vertically bifacial and 60 % monofacial south). Simulated data was used on the right side of the red border line. The data from 16.08.2018 are shown, where the time is in UTC+1.

3 INNOVATION AND RELEVANCE

Sealed floor surfaces in cities, waste heat of vehicles and houses which cause heat islands enhance the warming of the air during the day and reduce the cooling of the air during night. Thus, summer nights are four to five degrees warmer in cities compared to rural regions [14]. The maximum cooling at street level due to green roofs ranges from 0.03 to 3 °C according to 17 studies that provide data on urban heat island reduction [4].

The economic and ecological advantages of green roofs are undisputed. Today, the decision between PV and green roof has to be often made for flat roofs.

The green roof has several advantages like water retention, reduction of peak water runoff, protection of the roof seal, additional insulation, cooling and air humidification of the ambient atmosphere, habitat for animals (especially insects), filtering air pollutants etc.

Typical PV installations however largely cover the flat roof area, which suppresses the green roof effect to a large extent, if not bitumen or gravel is used from the outset. Plants may also lead to considerable shading of the modules, while the green roof maintenance is hindered by the PV installation.

With vertical bifacial PV on green roofs, a symbiosis of these two approaches can be obtained. In this project, the achieved energy yield is examined for this type of module mounting, which also allows a cost-effective maintenance of the green roof.

4 MEASUREMENT RESULTS AND ANALYSIS

4.1 Data availability

The DC power measurements were started on 19.05.2018 and will be carried out for one year. Outdoor measurements up to 18.09.2018 have been taken into account for this work. Therefore, four months or 123 days of measurement data have been evaluated. Data of the electricity meter of the whole plant are available since July 2017.

4.2 STC power measurement

The STC power of the measured modules was measured in the laboratory with the Portable LED Flasher [9]. Table 1 shows the results of the measurements. Each side of the bifacial module was measured separately while the other side was shaded. The bifaciality (B) in Table 1 was calculated using Formula (1).

$$B = \frac{P_{STC,rear}}{P_{STC,front}} \quad [\,] \qquad (1)$$

Table 1 Measured STC powers of all examined modules and calculated bifaciality (SGR = test field with standard green roof with green-leaved plants, BGR = test field with bright green roof with silver-leaved plants and bright substrate)

Module	$P_{STC,front}$ [W]	$P_{STC,rear}$ [W]	B
SGR 1	76.2	56.1	0.74
SGR 2	88.8	81.1	0.91
BGR 1	88.3	81.9	0.93
BGR 2	75.5	67.1	0.89
Sum SGR	165.0	137.3	0.83
Sum BGR	163.8	149.0	0.91
Reference	203.3	-	-

4.3 Albedo measurement

The albedo measurement was performed on a clear sky day (21.08.2018) at a sun position of 25° azimuth and listed in Table 2 (the shadows of the modules were exactly under the modules). The measuring device was placed at the height of the upper edges of the monitored module in the middle of the module rows. Figure 3 and Figure 8 show the photos that were taken at the time of the albedo measurement. As a comparison, the gravel surface was also measured. In addition, the albedo was measured for the areas with more plants where no DC power measurements were performed. These two additional surfaces are shown in Figure 8. The horizontal global irradiance during the albedo measurements was 780 W/m^2.

Figure 8 Gravel (left) and standard green roof (SGR) with more plants (right) at the time of the albedo measurements.

Table 2 Results of albedo measurements carried out on 21.08.2018 of the different surfaces. Measured on the module upper edges in the middle of the module rows.

Surface	Albedo [ ]
SGR (Figure 3 left)	0.09
BGR (Figure 3 right)	0.21
Gravel (Figure 8 left)	0.14
SGR with more plants (Figure 8 right)	0.16

4.4 Specific annual AC energy yield of the entire PV system

An AC electricity meter is installed, which measures the feed-in of the entire PV system. The meter reading was read periodically and evaluated for a period of one year (11.08.2017 to 10.08.2018). The specific energy yield of the 9.09 kWp vertical bifacial PV system in this period is 942 kWh/kWp. A typical value for south-facing plants in our region is 1000 kWh/kWp.

4.5 Specific energy yield of DC power measurement

The resulting specific DC energy yields for the period 19.05.2018 to 18.09.2018 are shown in Table 3.

Table 3 Specific DC energy yields in kWh/kW for the time period of 19.05.2018 to 18.09.2018. The first row contains only the measured data up to 86° azimuth and the second line the combination of measured data and simulation beyond 86° azimuth. The combination of south and vertical bifacial corresponds to the description in chapter 2.5.

Dataset	South monofacial	East-west bifacial SGR	East-west bifacial BGR	Combination South + east-west BGR
Measurement	603.2	476.3	557.9	585.1
Measurement and simulation	658.4	556.9	649.2	654.7

For the two vertical bifacial systems, the bright green roof (BGR) provides a significant increase in yield of 17.1 % for pure measurement data and 16.6 % for measurement data combined with simulation. The lower yield of 7.5 % of the east-west bifacial BGR compared to south-oriented monofacial module for the measurement data and 1.4 % for the combined measured data and simulated data shows that the yield of the vertical bifacial modules is almost identical to that of the monofacial south-oriented module in an environment that does not cause shading by surrounding objects such as buildings.

To estimate the expected specific yield for one year, simulations were performed using PVsyst 6.74. The measured albedo according to Table 2 and the horizon according to Figure 6 (yellow line) were used for this simulation. Table 4 contains the results. The first line contains the simulation results for the measurement period (19.05.2018 to 18.09.2018). For the south oriented monofacial module (-2.2 %) and the SGR (+0.4 %) the simulation results correspond quite well. For the BGR the deviations from PVsyst are comparably higher (-8 %). The second line of Table 4 shows the expected values for one year, whereby the four months measured (Table 3, line 1) were supplemented with the PVsyst simulations for the rest of the year.

Table 4 PVsyst simulation results of specific DC energy yields in kWh/kW for the measurement period (19.05.2018 to 18.09.2018) on the first line and on the second line the combination of the measurement data (Table 3, line 1) with the PVsyst results for the rest of the year to estimate the expected specific yield for one year.

Dataset	South monofacial	East-west bifacial SGR	East-west bifacial BGR	Combination South + east-west BGR
PVsyst for measurement period	590	478	513	559
4 months measurement and 8 months PVsyst	1225	978	1090	1171

4.6 Self-consumption

A 10 second load profile [15], [16] was used to make a statement about self-consumption (SC). The load profile was generated for a single-family house (profile name HT20) with a family of two children (profile name CHR57) with an annual consumption of 8535 kWh. The amount consumed in the period under review (19.05.2018 until 18.09.2018) is 2556 kWh. The nominal power of the PV system was set at 8.5 kWp. Table 5 shows the resulting own consumption values and Figure 9 shows the daily course from 20.06.2018.

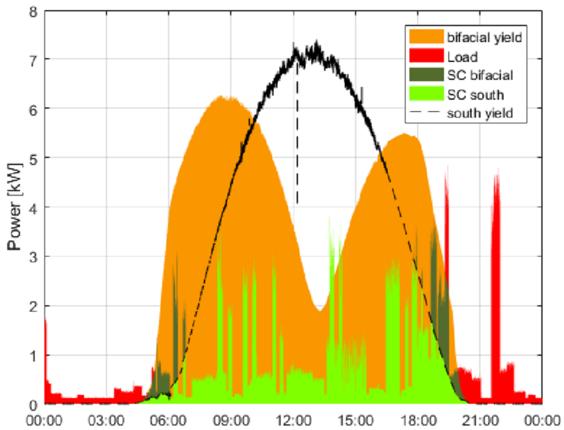

Figure 9 Vertically mounted bifacial yield curve (orange), south-oriented yield curve (black) and load profile (red) on 20.06.2018 (time in UTC+1). Light green shows the self-consumption (SC) of the south oriented system and in dark green the additional self-consumption due to the bifacial east-west orientation. The peak in the afternoon would also be covered by a combination of south and east-west. On this day, self-consumption amounts to 23 % for the south-facing plant and 26 % for the east-west-facing bifacial plant.

Table 5 Self-consumption values in percent for the period under review (19.05.2018 until 18.09.2018)

Dataset	South monofacial	East-west Bifacial SGR	East-west bifacial BGR	Combination South + east-west BGR
Measurement	24.2	28.9	26.1	25.4
Measurement and simulation	25.8	29.7	27.0	26.8

5 CONCLUSION

The combination of vertically installed bifacial modules and green roof has been proven very successful. The maintenance of the green roof can be carried out efficiently, because you can walk well between the module rows. Maintenance costs may be further reduced by using a mowing robot [5].

Due to the bright substrate with the silver-leaved plants the yield could be increased by 17 % compared to a standard green roof with green-leaved plants in summer. The additional costs of the bright surface amount to approximately 10 % [17] compared to a standard green roof. Therefore, this investment is worthwhile. The silver-leaved plants also showed very good resistance against heat and drought. The albedo of the standard green roof was further worsened by the drying-out of the plants.

The specific DC energy yield of the bright green roof with vertically mounted bifacial modules is almost identical to that of the south oriented monofacial module. The vertical bifacial installation is expected to produce a good yield in winter compared to the south module, since the vertical modules are not shaded by snow and the snow increases the albedo. The specific yield of the whole 9.09 kWp PV plant over one year was 942 kWh/kWp.

Due to the vertical installation and the associated different power distribution associated with it, there is a potential of increasing the self-consumption rate for specific consumers.

The power measurements will be continued at least until spring 2019. It is planned to install and measure a similar plant in a mountainous region to confirm the expected high yield in winter with snow.

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