YIELD AND PR ESTIMATION FOR VERTICAL AGRIVOLTAICS SYSTEMS

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ABSTRACT: Photovoltaic systems interspersed with cropland are gaining ground. Since both elements compete for radiation, determining the amount of light that reaches each of them is of great interest. Vertical agrivoltaic systems are an alternative to other systems installed in crop fields, which interfere less with tillage and machinery. When these systems consist of bifacial panels, energy capture is almost twice that of monofacial system. To determine profitability, measurements of both actual production and expected output or performance ratio (PR) must be obtained. Likewise, if the system is agrivoltaic, agricultural production must not be substantially reduced, and regulations set different limits depending on the country, with an extended objective of not assuming a reduction greater than 20%. The calculation of the PR in a vertical system is something that is still open to debate when the panels are bifacial. In addition, when the system is oriented with a north-south axis, the maximum radiation can be strongly affected by nearby shadows, both from other parallel strings and from nearby obstacles. Given the sensitivity of a vertical system to these aspects, in this work we address the elements that will affect the correct understanding and design of vertical agrivoltaic plants.
Keywords: Photovoltaic, bifacial, performance ratio, agrivoltaic

1 INTRODUCTION

Agrivoltaics (AV), the dual use of agricultural land to produce crops and photovoltaic (PV) power in the same plot, is a hot topic of research. A key aspect in AV is that both the crop and the PV plant can mutually benefit if the materials are adequately selected, and the geometry of the system is well designed. The crop can be inside a greenhouse or in open-field, what gives rise to different designs of the PV plant.

In the last years, two open-field AV geometries have been proposed: The South-facing tilted static panels arranged on a gantry-type shed structure and the static vertical East-West facing bifacial panels assembled on a fence-type structure. The research reported here is in the context of how well vertical bifacial AV will serve as the generator for electric-powered pump irrigation.

The calculation of the performance ratio (PR) in a vertical system is something that is still open to debate when the panels are bifacial. In addition, when the system is oriented with a north-south axis, the maximum radiation can be strongly affected by nearby shadows, both from other parallel strings and from nearby obstacles. Given the sensitivity of a vertical system to these aspects, in this work we address the elements that will affect the correct understanding and design of vertical agrivoltaic plants.

In this regard, the following points should be discussed:

- Is the peak power indicated by the manufacturer or should both sides be taken into account?
- If both sides are included, what bifaciality coefficient should be applied?

The objective of this work is to compare the model-based estimates of incident solar radiation on the active faces of bifacial solar panels placed vertically, with the actual radiation received by them. In this way, it will be possible to determine which parameters come into play when using radiation databases.

2 MATERIALS AND METHODS

To carry out this task, a real vertical installation (Figure 1, Figure 2) was instrumented with bifacial panels, with the intention of measuring the real radiation on both sides and at different heights. On the other hand, the electrical production on both sides was monitored.

Figure 1: Agrivoltaic system with vertical bifacial PV panels

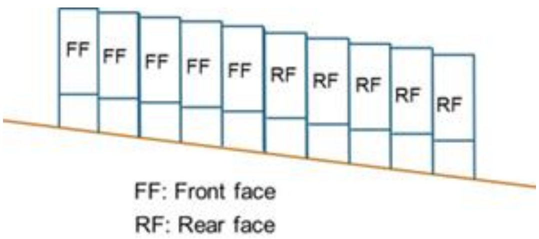

Figure 2: Vertical bifacial PV panels, where FF is the main side and RF is the rear side.

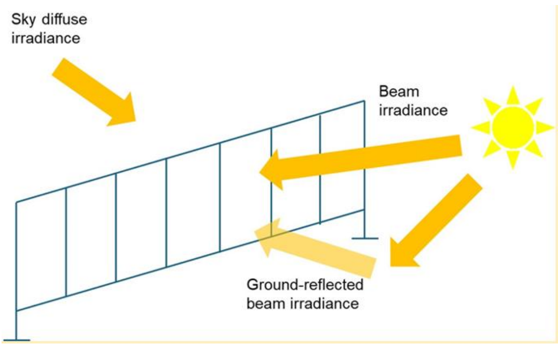

Figure 3: Main radiation sources for bifacial PV panels

Determining the quality of the data obtained from databases such as CAMS, PVGIS SARAH-2, or Solargis is of vital importance to calculate the yield of agrivoltaic plants with vertical installation.

On the other hand, the Performance Ratio (PR) would be the most commonly used parameter to determine the proper functioning of a conventional plant. However, if we look at the formula for obtaining it (Eq. 1), in a bifacial panel there would be a discussion about whether the radiation to be measured should be taken from the most exposed side, as well as whether the peak power should include both sides.

Eq. 1:

$$PR = \frac{Yield\ (kWh)}{PSH\ \left(\frac{kWh}{1\ kW}\right) \cdot P_p\ (kW)}$$

The bifaciality of a bifacial PV panel is measured with the bifaciality coefficients. The bifaciality coefficient prescribed by the technical specification IEC 60904-1-2: 2024 is the bifaciality of current, φ_{Isc} , defined as the ratio between the short-circuit current (I_{sc}) generated exclusively by the rear face of the panel and the I_{sc} generated exclusively by the front face, with the condition that both currents are measured at STC (irradiance of 1000 $W{\cdot}m^{-2}$, panel temperature of 25 °C, and with the IEC 60904-3 reference solar spectral irradiance distribution). To determine the φ_{Isc} , bifacial PV panels can be tested as showcased in Figure 4.

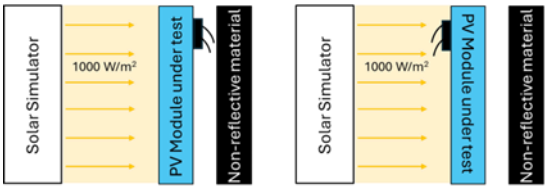

Figure 4: Single-side illumination test method for bifacial PV panels.

To qualify bifacial panels, the so-called bifacial standard test condition (BSTC) applies, characterized by a front irradiance of 1000 W/m^2, a rear irradiance of 135 W/m^2 and an equivalent irradiance G_E defined [1] in Eq.2, where $\varphi_{Isc} = I_{sc,rear} / I_{sc,front}$

Eq. 2:

$$G_E = (1000 + \varphi_{Isc} \cdot 135)\ W/m^2$$

If our solar simulator can only illuminate the tested panel from one side, then the rear irradiance is transferred to the front by using an G_E higher than 1000 $W{\cdot}m^{-2}$ (Eq. 1). The bifacial power gain or BiFi [2] is determined from solar simulator test as the slope of the linear fit that corresponds to plotting $P_{max.}$ against G_{rear}.

The conventional PR is given by Eq.1, where PSH is the Peak Solar Hours (kWh/m^2) on the generator's plane and Pp is the generator peak power.

In the case of vertical system, with main axis North-South and two parallel rows (strings), connected to independent MPPT, where one row has the main face oriented to the East and the other one to the West, we propose the PR expression of Eq.3, where the index 1 or 2 represents the Yield, PSH, Pp and bifaciality coefficient (φ_{Isc}) for each string.

Eq. 3:

$$PR = \frac{\frac{Yield_{(1)}}{PSH_{(1)} \cdot P_{p1} \cdot (1 + \varphi_{Isc(1)})} + \frac{Yield_{(2)}}{PSH_{(2)} \cdot P_{p2} \cdot (1 + \varphi_{Isc(2)})}}{2}$$

3 RESULTS AND DISCUSSION

IEC 61724-1:2021 proposes to calculate PR of a bifacial array by Eq. 4:

$$PR_{BIF} = \sum \frac{P}{\sum \frac{C \cdot P_0 \cdot G_{front} \cdot BIF}{1000\ W \cdot m^{-2}}}$$

where *P* is the system AC power output, P_0 is the system DC power rating at STC, *C* is a temperature correction factor and *BIF* , that stands for bifacial irradiance factor, is equal to $1 + \varphi{\cdot}(G_{rear} / G_{front})$

Karttunen et al. (2023) proposed a temperature-corrected PR [5].

Little information is available on the measurement of bifaciality coefficient under real operating conditions. An exception is the work by Muñoz-Cerón et al. (2024), who for outdoor conditions found that the bifaciality coefficient increases with increasing irradiance. They recommended assessing the bifaciality coefficient preferably in the central hours of sunny days. But in our case the greatest impact would be at the beginning and end of the day, so we propose a more direct method, which applies different coefficients to each string depending on its orientation (Eq.).

Starting from the estimated radiation data, both for clear and average days (Figure 5), and measuring the real radiation, it will be possible to validate the method for the real calculation and minimize the error applied in the estimation of bifacial vertical agrivoltaic systems.

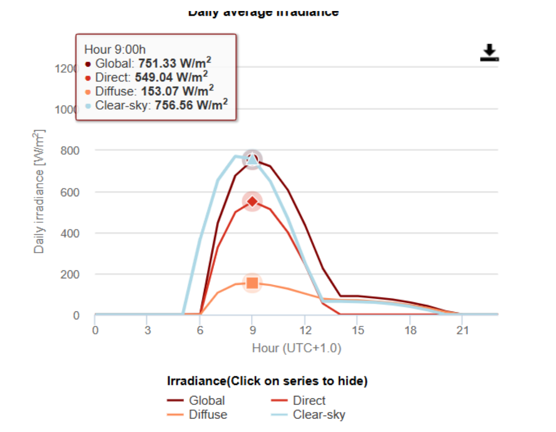

Figure 5: PVGIS estimated radiation on one side of a vertical east-oriented PV panel.

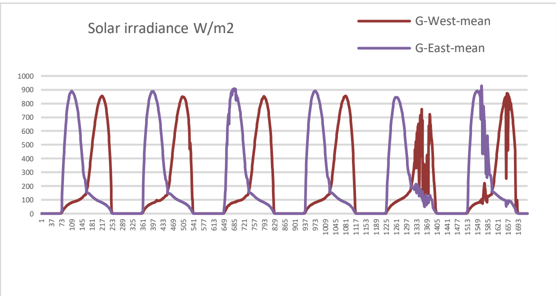

Figure 6: Radiation measured on both sides (east and west) of a vertical mounted solar panel.

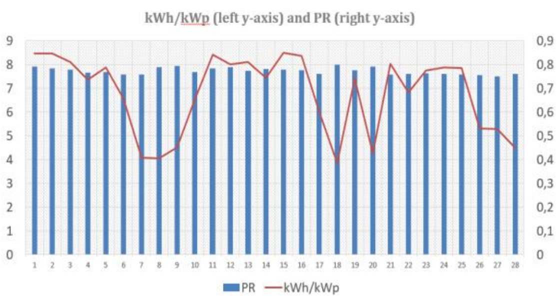

Figure 7: June 2024 daily specific yield (kWh/kWp) and Performance Ratio of vertical bifacial system.

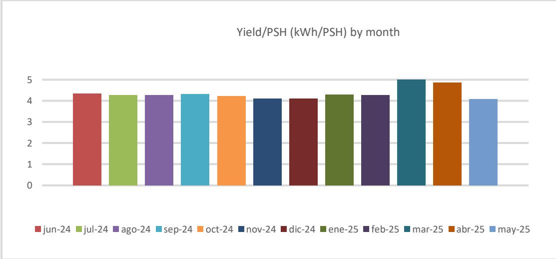

Figure 8: Yield per peak solar hour, monthly average, from June 2024 to May 2025.

For a vertical bifacial array of HJT photovoltaic panels, Badran and Dhimish [3] found that increased diffuse irradiance correlated with higher bifacial gain. Nonetheless, Muñoz-Cerón et al. [4] reported lower bifaciality coefficient for cloudy day (more diffuse irradiance) with respect to sunny day (less diffuse irradiance), although the bifacial panels in [4] were not vertical.

4 CONCLUSIONS

The following conclusions can be drawn:

- Diffuse irradiance plays a major role in vertical bifacial PV systems.
- A vertical system presents the question of radiation to be taken into account. In this work, we considered that radiation should be the sum of that captured on both sides, but applying a bifaciality coefficient.
- More research is needed on outdoor characterization of bifaciality, especially for vertical bifacial systems.

5 Acknowledgements

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