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On the Optimal Orientation of Bifacial Solar Modules

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***Abstract*—This paper presents an accurate simulation strategy to optimize the installation of bifacial photovoltaic modules in terms of orientation and tilt. The tool relies on horizontal irradiance data and ambient temperature taken from PVGIS for assigned times during the day at the selected geographical site and provides the I-V (and P-V) curves at each time. In this analysis, Naples is chosen as a case-study. It is shown that vertical bifacial modules with the front oriented either to West or to East offer energy production comparable to that of a South-oriented monofacial panel tilted by 30°, which represents the conventional optimized configuration and is thus considered as a *reference*.**

Keywords—bifacial module, monofacial module, orientation, photovoltaic (PV), tilt

I. INTRODUCTION

The market share of bifacial solar systems is expected to reach 70% in 2033 from the current 35% (Fig. 1) [1]. Along with the massive use of batteries, this is (and will be) the most impressive advancement in photovoltaic (PV) industry over the last decades. Such a growth is proceeding without substantial drawbacks. The price gap with respect to monofacial systems is expected to vanish, while it seems that there are no operating conditions under which bifacial modules (hereinafter also referred to as panels) perform worse than the monofacial counterparts. Some reliability issues might come either from the glass-to-glass structure, which is not protected by the aluminum frame, or from a potentially uneven current distribution dictated to the less controllable solar irradiance on the backside (rear) of the module; nevertheless, these issues have not been perceptibly encountered yet.

On the average, the energy gain of bifacial modules with respect to the monofacial ones is estimated to span from 5% to 10% from on-field observations, even though these values have not been confirmed yet by reliable models.

As bifacial modules are believed to produce *at least* the same energy as monofacial ones, they are currently installed even in environmental contexts where their effectiveness is questionable, like coplanar roots or vertical facades without space on the backside. However, in many cases monofacial plants still provide superior performance, as free space between cells and between modules forming the PV plant is not required. Moreover, the series resistance of bifacial modules is often higher due to the metal grid on the rear that must allow the light absorption.

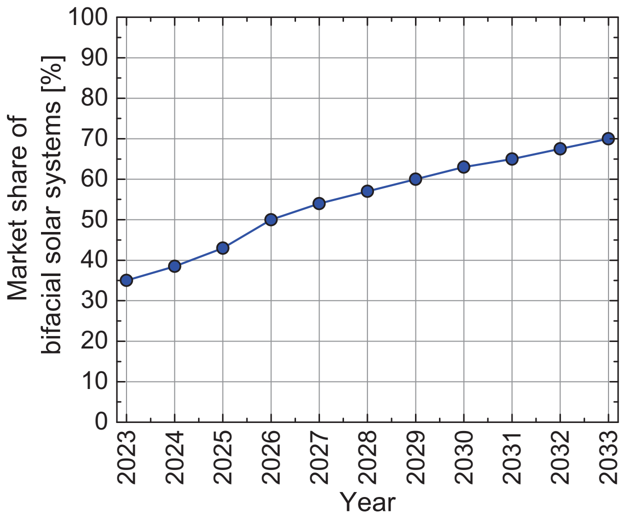

Fig. 1. Expected market share for bifacial solar systems.

Even though analytical and circuit models have been already conceived and developed for bifacial modules (examples being [2], [3]), there is still a lack of design rules providing unambiguous guidelines to determine in which circumstances bifacial modules offer distinct advantages. As is well known, the optimal orientation for fixed PV panels is the one that minimizes the angle of incidence of Sunrays θ on the module. Since the Sun continuously changes its position, the minimization of θ is done 'on the average' by maximizing the Sun energy captured over a given period, which means that the module is kept as perpendicular to the Sunrays as possible. This approach leads to the following strategy for PV plants installed in the Northern hemisphere: the panels should be South-oriented (azimuth angle γ=0°) with a tilt angle given by $\beta=\phi-15°$, ϕ being the latitude of the site. The achievable energy for every possible azimuth and tilt angles is summarized in Fig. 2 for a panel located in Naples (latitude ϕ=40°50' and longitude λ=14°15'). Here the radii indicate the azimuth directions, while concentric circles designate the tilt.

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As an example, modules with azimuth and tilt falling in the area enclosed by the red curve would achieve a yearly production between 95% and 100% of the maximum. It can be also inferred that there are conditions where a dramatic drop in the energy production arises, one being the case of a vertical (β=90°) panel, where the Sunrays are nearly vertical to the horizontal plane and therefore the incidence angle θ is high. More specifically, a South-oriented vertical panel may experience an energy loss of nearly 30%, which increases to more than 50% for West- (γ=90°) and East- (γ=-90°) oriented panels.

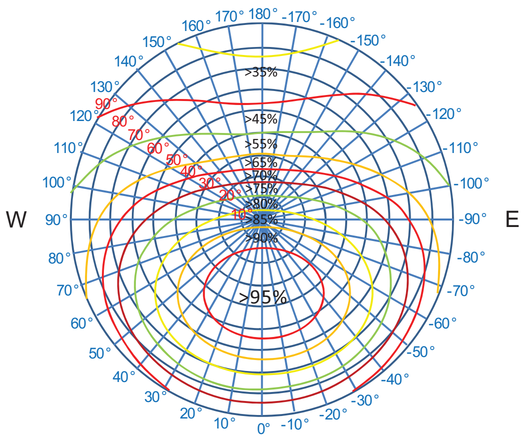

Fig. 2. Loss diagram for monofacial panels as a function of tilt and azimuth.

The relation β=ϕ-15° holds rigorously for monofacial solar panels but it is not in principle suitable for bifacial ones, as it does not account for the solar (beam and diffuse) irradiance impinging on the rear.

In this paper, a systematic and accurate analysis of the energy produced by monofacial and bifacial modules is performed with an *in-house* tool for various values of orientation (γ) and tilt (β) angles. As a main finding, it is demonstrated that bifacial modules are especially suited for vertical installations with West- and East-oriented front, where they equalize or even overcome (depending on the albedo) the performance of the monofacial counterparts.

II. The Simulation Tool

The analysis was performed with an *in-house* simulation tool developed by extending the approach presented in [4] to bifacial modules. The PV module is formed by the series-connection of N cells, each of them described by the single-diode five-parameter model shown in [5]. The panel is in turn subdivided into subpanels, each equipped with a bypass diode. As (i) the parameters of each cell can be independently assigned and (ii) the operating current, voltage drop, and temperature are independently evaluated, a *high-granularity* strategy is achieved, which allows accounting for e.g., the possible presence of shadows affecting the current generated by selected cells and the resulting hot spots, as well as the impact of cracks and other defect-related issues [4], [6]–[12]. Hence, the tool is suited to provide an accurate description of realistic I–V curves.

For bifacial panels, the increment of PV current due to photons absorbed at the rear side is included by adding another current source $I_{ph,rear}$ in parallel to that representing the front panel $I_{ph,front}$ in the cell model. As described in [4], the tool receives input data concerning the total and diffuse irradiance on the horizontal plane, as well as the ambient temperature; such data can be taken from the Photovoltaic Geographical Information System (PVGIS) website, where they are available for an average day of the month at the selected geographical site.

For the specific purpose of this study, the irradiance is kept uniform over both front and rear of the panel. The parameters of the cells were taken (or extracted) from the datasheet of a commercial PV panel. Once the geographical position of the panel is selected, the values of $I_{ph,front}$, $I_{ph,rear}$, and of the operating cell temperature are determined starting from the (preliminarily determined) Sun position and the PVGIS data concerning irradiance on the horizontal plane and ambient temperature [4]. It is assumed that the efficiency on the rear is 90% of that on the front side. As for bifacial panels the albedo is a relevant factor, the rear production is evaluated for three albedo values. Conversely, the albedo effect on the monofacial panel, as well as on the front of the bifacial panel, is disregarded.

III. Results

The panel was assumed to be located in Naples under clear-sky conditions, and the calculation of the energy produced in a month was made by multiplying the value corresponding to the 15th day (chosen as reference) by the number of days in that month. In Naples, the optimum tilt angle β amounts to ϕ-15°≈30° according to the considerations made earlier.

Fig. 3 shows the energy production along one year normalized to the peak power of the panel for South-oriented (γ=0°) panels tilted by β=30°, which is the optimum case for the monofacial module and is thus considered as a *reference*. It can be inferred that the energy increment obtained with bifacial modules (with South-oriented front) under these conditions is very small regardless of the albedo, as only diffused light is collected by the rear. More specifically, the increase in normalized energy within an entire year is about 5% and 6.5% for albedos=0.2 and 0.5, respectively.

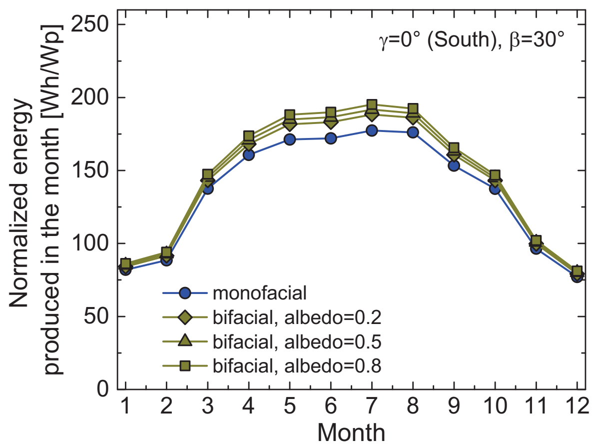

Fig. 3. Normalized energy produced in the months for South-oriented (γ=0°) modules with a tilt angle β=30° installed in Naples. The monofacial module (blue line with circles) is compared with the bifacial counterpart for various albedo values (dark yellow lines with rhombi, triangles, and squares).

Conversely, the increment of produced energy obtained with bifacial modules can be high if, during the day, the backside also receives direct light, which can happen if modules are vertical (β=90°).

The case of South-oriented vertical modules is reported in Fig. 4. The following considerations can be made: (i) this is an uncomfortable condition for monofacial modules, especially during the April-September period, when there is the maximum availability of the Sun energy; (ii) in this case, the energy production improvement ensured by a bifacial panel is significant, (iii) yet it is lower than the *reference* case (South-oriented monofacial module tilted by 30°) for low albedos, while equalizing it for albedo=0.5.

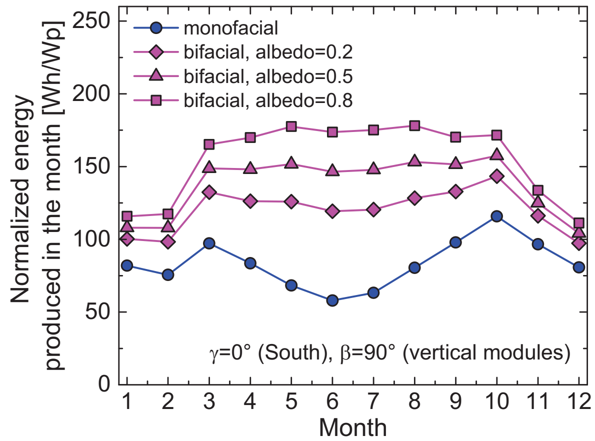

Fig. 4. Normalized energy produced in the months for South-oriented (γ=0°) vertical (β=90°) modules installed in Naples. The monofacial module (blue line with circles) is compared with the bifacial counterpart for various albedo values (magenta lines with rhombi, triangles, and squares).

Figs. 5 and 6 report the case of West- and East-oriented vertical modules. Here, the improvement achieved by a bifacial module is evident. While a monofacial panel receives beam irradiance for only half of the day, bifacial panels benefit from effective (low-θ) beam irradiance both in the morning (rear for a West-oriented panel, and front for an East-oriented one) and afternoon (the other way around). While the energy production for a West-oriented monofacial module is slightly better than that of an East-oriented counterpart (Naples faces the sea to the West and has mountains to the East), bifacial panels produce the same amount of energy. In this case, the gain with respect to the *reference* case amounts to about 2.5% and 15% for albedos=0.2 and 0.5, respectively.

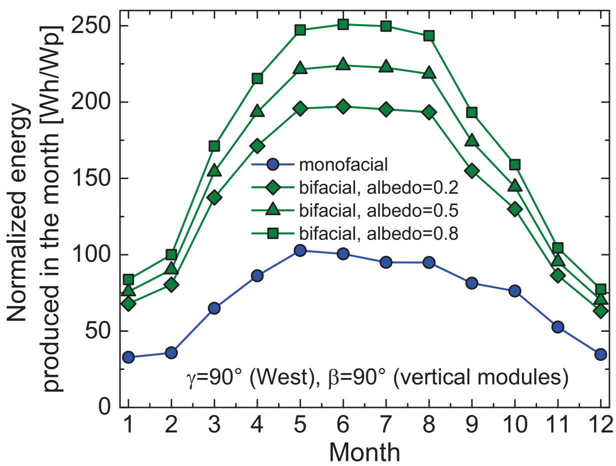

Fig. 5. Normalized energy produced in the months for West-oriented (γ=90°) vertical (β=90°) modules installed in Naples. The monofacial module (blue line with circles) is compared with the bifacial counterpart for various albedo values (green lines with rhombi, triangles, and squares).

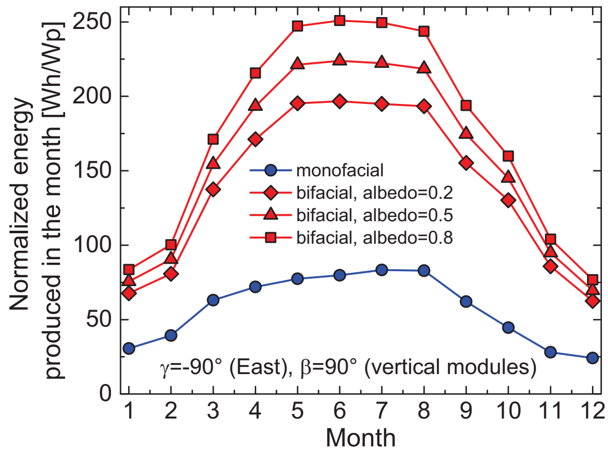

Fig. 6. Normalized energy produced vs. month for East-oriented (γ=-90°) vertical (β=90°) panels installed in Naples. The monofacial panel (blue line with circles) is compared with the bifacial counterpart for various albedo values (red lines with rhombi, triangles, and squares).

Fig. 7 summarizes the results. Here the normalized energy produced by the vertical bifacial panels for a South-, West-, and East-oriented front (the albedo being 0.2) are compared with the *reference* monofacial case. West- and East-oriented vertical modules (which lead to the same energy) offer improved performance with respect to the *reference* monofacial case, especially during the time span from April to September, in which they benefit from a low incidence angle θ of the Sunrays hitting the front and rear of the panel in the mid-morning and the mid-afternoon.

Such findings clearly indicate that bifacial modules allow the optimal exploitation of the vertical orientation, which is ineffective when using the monofacial counterparts.

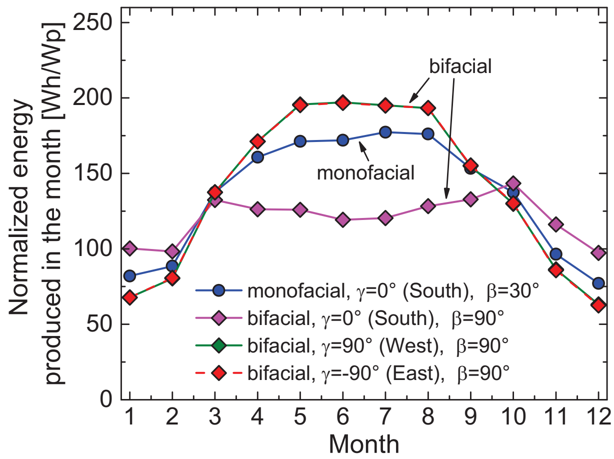

Fig. 7. Normalized energy produced in the months for the *reference* South-oriented (γ=0°) monofacial panel tilted by β=30° (blue line with circles), and various vertical (β=90°) bifacial panels, namely, with South-oriented (γ=0°, magenta line with rhombi), West-oriented (γ=90°, green line with rhombi), and East-oriented (γ=-90°, red line with rhombi) front. An albedo=0.2 was considered for all cases.

It is worth noting the improvement driven by West- and East-oriented vertical bifacial modules in comparison to the South-oriented bifacial one (about 15% regardless of the albedo) is mainly achieved during summer, while during wintertime the South-oriented panel performs better. The

TABLE I. NORMALIZED ENERGIES

Orientation (γ) and tilt (β)	Yearly-produced energy [Wh/Wp]	
	Monofacial	*Bifacial*
γ=0° (South), β=30°	1630 (*reference*)	1709 (albedo=0.2) 1736 (albedo=0.5) 1763 (albedo=0.8)
γ=0° (South), β=90°	1000	1440 (albedo=0.2) 1650 (albedo=0.5) 1860 (albedo=0.8)
γ=90° (West), β=90°	855	1670 (albedo=0.2) 1880 (albedo=0.5) 2095 (albedo=0.8)
γ=-90° (East), β=90°	685	1670 (albedo=0.2) 1880 (albedo=0.5) 2095 (albedo=0.8)

origin of this advantage can be explained by examining Fig. 8, where the normalized maximum power is reported against daytime on July 15th (Fig. 8a) and December 15th (Fig. 8b) for all cases. In July, the West and East orientation allows a better exploitation of the direct light impinging on one face (in the mid-morning) and on the other (in the mid-afternoon).

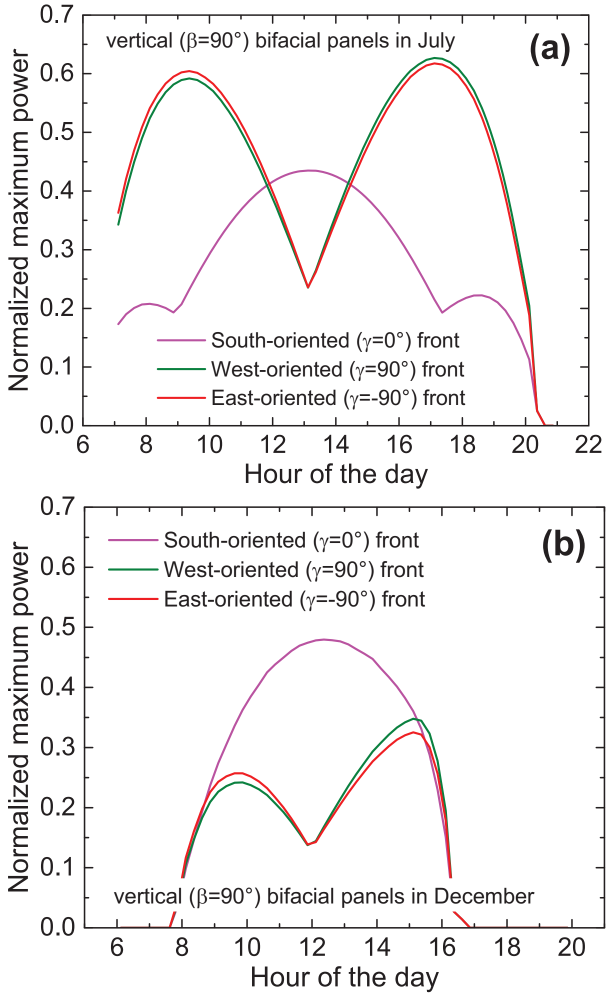

Fig. 8. Normalized maximum power vs. daytime on (a) July 15th and (b) December 15th for vertical (β=90°) bifacial panels, with South- (γ=0°, magenta line), West- (γ=90°, green), and East-oriented (γ=-90°, red line) front.

The normalized energies produced in the entire year are listed in Table I for all the considered cases.

IV. CONCLUSIONS

This paper is intended to define proper guidelines for the best installation of bifacial PV modules. A simulation campaign has been performed with an extended version of an *in-house* tool that is fed with available data on horizontal irradiances and ambient temperature in a selected geographical site. Normalized energies produced by bifacial modules during the year in Naples under clear-sky conditions have been compared with the *reference* one, i.e., that corresponding to a monofacial panel South-oriented and tilted by β=ϕ-15°≈30°. As a main finding, it was determined that either West- or East-oriented vertical modules allow improving the performance compared to the *reference* case, slightly for low albedos, and more significantly for medium/high albedos. This is mainly due to the low incidence angle θ of the Sunrays hitting the front and the rear of the module in the mid-morning and the mid-afternoon during the time span from April to September.

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