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# Technical-economic Performance Evaluation of a PV Barrier

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*Abstract* — **The increase in the deployment of photovoltaic (PV) systems has been notable, driven by the cost reductions and the need to transition to a low-carbon energy paradigm. However, with the proliferation of utility-scale photovoltaic plants, land use competition with other social and economic activities is becoming an issue. As a result, interest in implementing structure-integrated PV systems is increasing, as these are seen as a way to minimize the PV-occupied land area. This study evaluates the technical and economic performance of a photovoltaic system integrated into a vertical barrier in Sines, Portugal, and assesses its potential contribution to the decarbonization of the energy sector.**

## I. INTRODUCTION

Portugal's high photovoltaic (PV) potential [1] makes the incorporation of solar PV energy a strategic choice to promote the energy transition. The implementation of these systems faces significant constraints due to competing land use demands, notably from agriculture. Therefore, the integration of PV in built infrastructures, and the R4 (Rooftops, Roads, Railways and Reservoirs) concept have emerged as a potential solution to this problem.

In recent years, the vertical arrangement of photovoltaic systems has gained prominence. These structures have demonstrated great versatility, being widely used in various applications.

The first example in this context is vertical photovoltaic systems integrated into building facades (Fig. 1).

Fig. 1. Vertical photovoltaic systems integrated into a facade (BIPV). Source: [2].

Additionally, the use of photovoltaic fences has been seen as an efficient solution for delimiting land, combining safety with the generation of renewable energy (Fig. 2).

Fig. 2. Solar fence. Source: [3].

Finally, Fig. 3 presents a pilot project in the Netherlands where an acoustic barrier, designed to reduce noise, is simultaneously used to generate energy through the integration of PV modules [4].

Fig. 3. Acoustic photovoltaic barrier along a road. Source: [4].

According to a study by the European Commission's Joint Research Centre [5], the European Union has considerable potential for installing this type of structure along roads and railways. The recommended configuration consists of leaving the first meter above ground level empty or using it as a base for the photovoltaic system to prevent damage from flying debris, followed by three photovoltaic modules mounted horizontally in height (Fig. 4). This research showed the potential to implement 403 GWp along roads and railways, of which it would be possible to produce 391 TWh/year (16% of total final consumption in 2022) in the EU. In particular, Portugal could benefit from an estimated production of 3 to 11 TWh/year (6% to 22% of total final consumption in 2022 [6]) using this strategy.

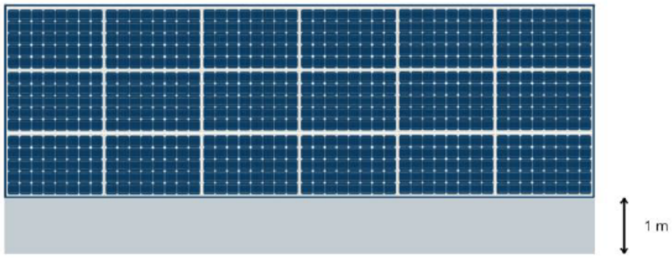

Fig. 4. Layout of a vertical photovoltaic barrier.

The use of bifacial modules in a vertical arrangement can bring another advantage when compared to traditional tilted fixed systems, found in large photovoltaic plants.

Unlike conventional fixed-tilt systems, typically south-oriented and peaking at midday — when electricity demand is relatively low — vertical systems with bifacial modules facing east-west generate two production peaks, in the early morning and late afternoon. This production profile might better align with periods of higher electricity demand and market prices. The midday peak from conventional systems increasingly coincides with the broader solar generation curve in the electricity market, often leading to lower gross market prices. By shifting production to the shoulders of the day, vertical systems may thus achieve a better economic outcome. This scenario is driven by the growing installed capacity of solar PV in the country, which reinforces this production pattern, though future dynamics may shift due to a variety of evolving factors in the energy system, such as the diversification of PV system configurations.

In this way, it becomes essential to make cost-benefit analysis of PV integrated in vertical barriers, considering monofacial and bifacial modules with different azimuths and taking into account their production profiles and profitability considering hourly fluctuations in energy prices.

## II. Technical Performance Analysis of a PV Barrier

PVSyst [7] was used in the simulations of the configuration shown in Fig. 4 located in Sines (Lat. 37.94, Long. -8.84), Portugal, for a typical meteorological year. Fig. 5 represents the annual energy production of a 69 kWp system (approximately 100 m in length), for different azimuths in the range of [-90º; 90º] — where -90º indicates east, 90º indicates west and 0º indicates south — in steps of 5º, considering bifacial (AE Solar 500W) and monofacial (EAP 500W) PV modules.

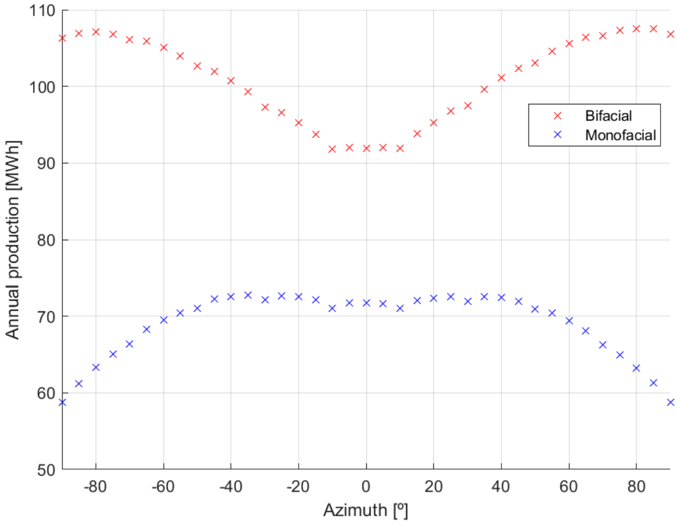

Fig. 5. Annual energy production of a 69 kWp bifacial and monofacial vertical barrier as function of the azimuth angle.

The results show that bifacial systems consistently generate more energy than monofacial ones, regardless of their orientation. Moreover, unlike monofacial systems, bifacial technology shows increased annual energy generation when facing roughly east-west. Specifically for the location under study, the maximization of annual production, approximately 107 MWh, is obtained for azimuths of -80º and 80º.

## III. Economic Viability of a PV Barrier

To identify the most economically attractive configuration and technology, a study based on the determination of the Levelized Cost of Energy (LCoE) was conducted. LCoE is an indicator that effectively estimates the average value of the electricity produced by the PV system, by dividing the total lifecycle costs (TLCC) by the energy produced by the PV system throughout its life cycle (1). For this calculation, the discounted cash flow model is used and a system lifetime of 25 years and an annual efficiency loss of 0.4% are considered, according to the module's datasheets.

$$LCoE = \frac{TLCC}{\sum_{n=0}^{n=25} Produced\ Energy_n} \quad (1)$$

Where the total lifecycle costs of the system, TLCC, are the sum of the updated cost over the lifetime of the project (2).

$$TLCC = \sum_{n=0}^{n=25} Updated\ cost_n \quad (2)$$

The updated cost is given by (3) where it was assumed a discount rate of 5%, based on [8].

$$\mathit{Updated\ cost}_n = \frac{M_n}{\left(1+\frac{\mathit{discount\ rate}}{100}\right)^n} \tag{3}$$

Furthermore, the calculation of the operation and maintenance costs (OPEX), $M_n$, are explained below.

For n=0 there are no operation and maintenance (O&M) costs, only the costs of the initial investment, so $M_n = 0$.

For the first year of energy production (n=1), the O&M costs considered are 1% of the value of the initial investment (CAPEX), $I_{n=0}$, as shown in (4).

$$M_{n=1} = I_{n=0} \times \frac{1}{100} \tag{4}$$

For the remaining years of the project (n=[2,25]), the annual O&M costs are given by (5).

$$M_{n=1} = M_{n=1} \times \left(1 + \frac{\mathit{inflation\ rate}}{100}\right)^n \tag{5}$$

The value of the inflation rate considered was 2.1%, as a result of the average recorded for Portugal over the last 10 years (between 2015 and 2024) [9].

Vertical PV barriers are still underdeveloped on the market, thus the assumed CAPEX value for these systems was based on the CAPEX of interspace agrivoltaic vertical barriers. The CAPEX values (Table I) for these typologies were taken from the Fraunhofer report [10] — 0.74 €/Wp for a monofacial system and 0.806 €/Wp for a bifacial system — considering 0,26 €/Wp for monofacial modules and 0,326 €/Wp for bifacial modules, 0,04 €/Wp for inverters, 0,132 €/Wp for mounting system, 0,03 €/Wp for electrics, 0,05 €/Wp for project planning, 0,093 €/Wp for surface preparation and installation, 0,015 €/Wp for fencing, 0,075 €/Wp for grid connection and 0,045 €/Wp related to other costs.

For the south-facing monofacial PV system, the CAPEX considered (Table I) was based on data obtained in real projects carried out by our research unit.

TABLE I

ESTIMATED CAPEX FOR MONOFACIAL AND BIFACIAL BARRIERS

| **Typology** | **CAPEX [€/Wp]** |
|---|---|
| Monofacial vertical PV barrier | 0.74 |
| Bifacial vertical PV barrier | 0.81 |
| Fixed PV | 0.68 |

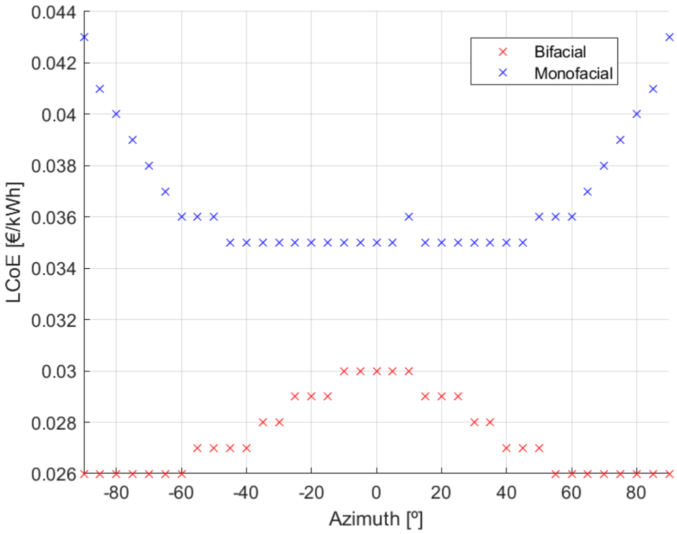

Fig. 5 Graph of LCoE as a function of azimuth for monofacial and bifacial systems.

These results indicate not only that bifacial systems prove to be more beneficial when compared to monofacial systems, but also that through a roughly east-west facing position (azimuths from -90º to -60º and from 55º to 90º) , it is possible to achieve LCoE values of €0.026/kWh (36% of the average electricity price in Portugal over the last 10 years [11]).

## IV. BIFACIAL PV BARRIER VS MONOFACIAL TILTED SYSTEM

It is important to compare these systems with the presently most commonly used configuration — monofacial tilted systems — since they are usually the most economically advantageous option for our region, especially when considering the price of bifacial modules. However, it is important to note that the ongoing decreasing trend costs of bifacial modules will probably make their integration on fixed tilted structures economically more attractive.

For this purpose, a comparison is made with a monofacial system, also with 69 kWp, tilted at 33° and south-facing (0º azimuth) — m-tilt-Sfac configuration —, which corresponds to the optimal angle for maximizing annual energy production, at the location under study, with 108 MWh/year of energy production.

Studying these systems from the perspective of their monthly energy production, as shown in Fig. 6, is essential to understand which type of system is most suitable in relation to monthly consumption patterns.

The graph below was generated considering azimuth angles ranging from -90° to 0°. For clarity, the azimuths between 0º and 90º were omitted from this graph, as their production profile, although slightly different due to the modules bifaciality factor, is similar.

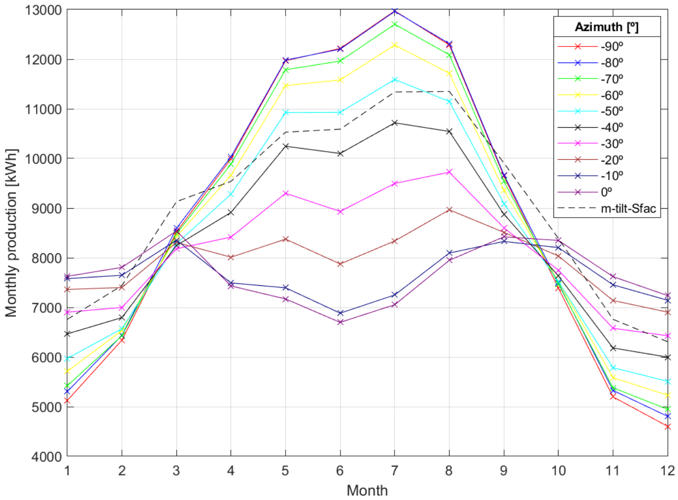

Fig. 6. Monthly production graph of the m-tilt-Sfac configuration and of a 69 kWp Bifacial PV vertical barrier for different azimuths.

Fig. 6 reveals that vertical bifacial systems facing approximately east-west, exhibit greater monthly production variability and enhance energy production during the summer months, while systems oriented closer to the south (in the range of -20º to 0º azimute) demonstrate a more consistent monthly production profile throughout the year.

Furthermore, it is shown that the south-facing monofacial tilted system, when compared to vertical bifacial systems with azimuths from -90º to -50º, presents worse performance in the summer months and better performance in the winter months.

## V. DISCUSSION

For the specific location analyzed, the results obtained show that for a vertical PV system implementation, bifacial technology shows a better technical-economic performance than the monofacial technology, especially when oriented at an azimuth angle of -80º and 80º, offering the greatest benefits in terms of both maximizing annual energy yield and achieving a lower LCoE.

To study the advantages that this type of system can bring, an analysis was made of its operation over time, for a typical meteorological year, in comparison to a tilted monofacial system (m-tilt-Sfac configuration) which is the most traditional and most economically beneficial currently.

To understand the profitability of this kind of PV typology it was conducted an analysis of electricity price fluctuations in Portugal for the year of 2024, that showed to be the most representative of the last 10 years (2015 - April 2025), since the average hourly electricity price over the last decade was not available.

Fig. 7 presents the annual hourly average of electricity prices in Portugal for the year 2024, alongside the average annual hourly production of a traditional fixed monofacial system oriented to the south with a tilt angle of 33° (m-tilt-Sfac), and of vertical bifacial barriers with the azimuth angles indicated in the legend.

The graph shows that there is a peak in electricity prices in the morning, between 8 and 9 a.m., and again at night, around 10 p.m. Furthermore, the graph shows that vertical barriers oriented approximately to east exhibit a production peak that coincides with the electricity price peak in the morning, whereas systems oriented toward the west (azimuth close to 90º) show a production peak during the period when electricity prices are at their lowest.

Based on (6) and the data in Fig. 7, it is possible to identify which orientations of vertical PV barriers are the most economically advantageous, as they generate more energy during time periods when electricity prices are higher. For each typology, the average electricity value is determined considering the time window during which the system is producing energy using (6), where $c_h$ is the average electricity cost at a given hour $h$ and $p_h$ is the energy production at that same hour.

$$\overline{Electricity\ value} = \frac{\sum_{1}^{24} c_h p_h}{\sum_{1}^{24} p_h} \qquad (6)$$

Table II shows the average electricity values during the operating hours of each system configuration, revealing that the vertical bifacial system with an azimuth of -50° generates more energy during time intervals when electricity prices are higher, compared to systems with other orientations and even to the more traditional fixed PV system, achieving an average electricity value of 0.0569 €/kWh.

With these values, it becomes possible to assess economic indicators such as payback time, which is essential in the economic viability study of a project. This is achieved through the discounted cash flow model and considering the CAPEX values on Table I and an annual increase rate of the energy tariff of 1.3 €/MWh based on the difference in cost between the year 2015 and 2024.

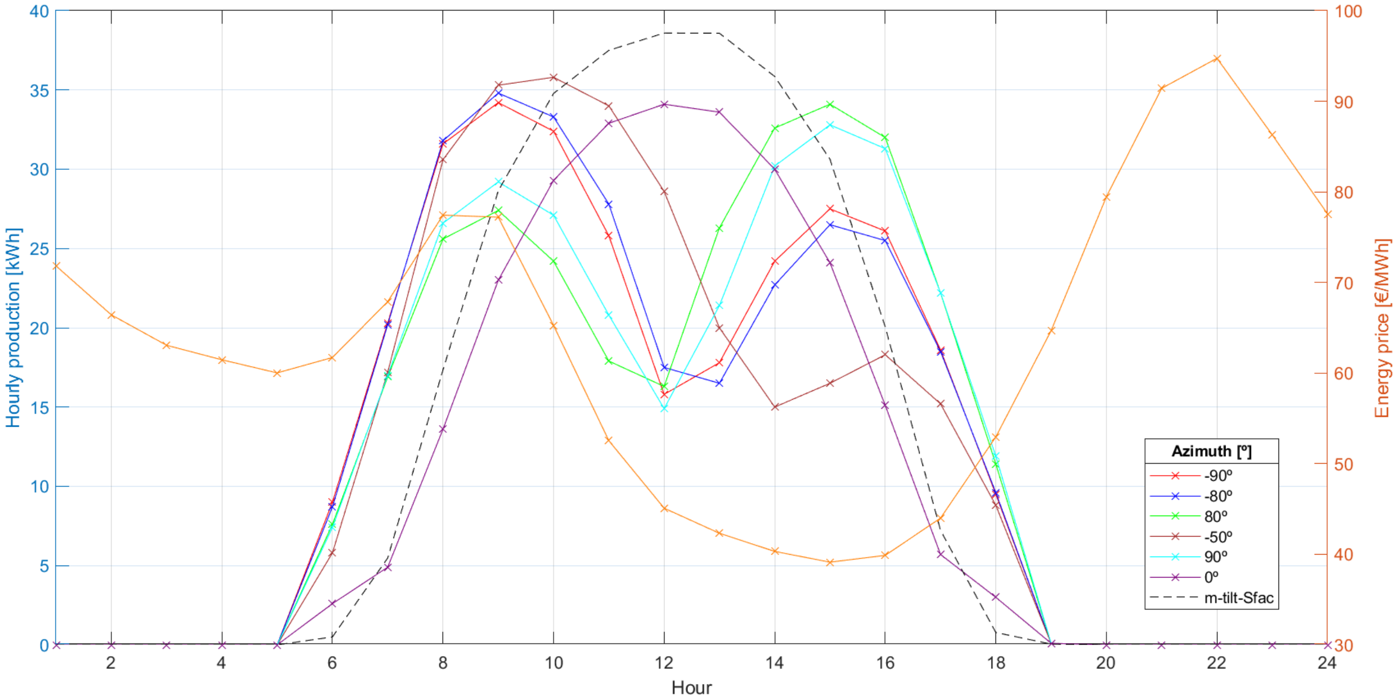

Fig. 7. Graph of annual average hourly production of the m-tilt-Sfac configuration, a bifacial vertical barrier of 69 kWp considering different azimuths and electricity price fluctuations in Portugal in 2024.

TABLE II

THE AVERAGE ELECTRICITY VALUE DURING THE OPERATING HOURS OF EACH SYSTEM, THEIR PAYBACK AND LCOE

| Typology | | $\overline{Electricity\ value}$ [€/kWh] | Payback [years] | LCoE [€/kWh] |
|---|---|---|---|---|
| Bifacial PV barrier | -90º Azimuth | 0.0559 | 11.46 | 0.026 |
| | -80º Azimuth | 0.0561 | 11.30 | 0.026 |
| | -70º Azimuth | 0.0566 | 11.32 | 0.026 |
| | -60º Azimuth | 0.0568 | 11.41 | 0.026 |
| | -50º Azimuth | 0.0569 | 11.70 | 0.027 |
| | -40º Azimuth | 0.0566 | 12.03 | 0.027 |
| | -30º Azimuth | 0.0560 | 12.66 | 0.028 |
| | -20º Azimuth | 0.0549 | 13.28 | 0.029 |
| | -10º Azimuth | 0.0534 | 14.28 | 0.030 |
| | 0º Azimuth | 0.0520 | 14.69 | 0.030 |
| Monofacial PV with 33º tilt and 0º Azimuth (m-tilt-Sfac) | | 0.0519 | 9.96 | 0.021 |

## VI. Conclusion

The need to replace fossil fuel-based energy production with renewable sources, and land use competition, has led to a significant increase in the dual land use for the installation of photovoltaic systems, and particularly the integration in human build infrastructures (IPV). Especially, the implementation of photovoltaic systems in the form of vertical barriers, have great potential in European countries, such as Portugal.

Therefore, it is important to analyze the technical and economic performance of this type of systems and compare them with the most commonly used configurations (e.g. south-facing monofacial tilted systems).

The study not only demonstrates that bifacial technology, when integrated into vertical systems, is more advantageous from a techno-economic perspective than the monofacial technology, but also that an orientation of -50° enables energy generation during time windows when electricity prices are higher than the other configurations analyzed.

Although, for the electricity price scenario considered, the south-facing optimal tilted system (m-tilt-Sfac) shows the lowest payback time, it is expected that the future evolution of electricity prices will affect this, particularly in electric grids with high PV integration. Land use costs are not considered in this work, which represent an additional disadvantage for the traditional ground-mounted tilted PV system when compared to the vertical barriers solution, thereby providing an economic advantage to the IPV approach.

In fact, the increasing share of PV systems in the energy mix is leading to challenges related to production peaks occurring during periods of low demand, which often result in zero or even negative electricity prices [12]. To address this issue, it is essential to diversify PV system deployment in terms of both technology and layout, particularly regarding tilt and orientation. The vertical bifacial configurations studied demonstrate that, depending on azimuth angle, it is possible not only to shift peak generation to periods when electricity prices are higher, but also to avoid coinciding with the current generation peak. In cases where self-consumption is favoured, the barrier orientation can even be adjusted to maximize production according to the specific need of the prosumer. The use of vertical barriers with variable azimuth angles can be an effective strategy for mitigating curtailment and maximizing self-consumption, as well as for optimizing land use.

The economic indicators presented in this work indicate that vertical bifacial systems with azimuths from -60º to -90º can be particularly promising, showing economic performance comparable to conventional, cost-effective configurations. Moreover, they offer the added benefit of generating electricity outside the typical midday peak, helping to reduce grid congestion and mitigate the risk of curtailment.

In conclusion, the integration of photovoltaic vertical systems (eg. along roads) presents a promising solution for sustainable energy generation, offering clear advantages in terms of land use efficiency, potential economic benefits, and alignment with electricity demand patterns, particularly in regions with high solar penetration.

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