Energy analysis of PV surfaces in BIPV applications

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Abstract. This paper studies the power generation performance of flexible solar panels at different radii of curvature for both concave and convex configurations. Its performance is evaluated horizontally and vertically to provide architects and designers with a reference of how power generation is impacted depending on the geometries selected for the design of facades or roofs. The study consisted of two phases, the first comprised a simulation to estimate the amount of energy a surface receives according to its geometry, orientation, location, and simulated period. The second phase corresponds to an experimental validation, in which five geometries were tested: two concave, two convex, and one flat as a baseline. The results indicate that, for horizontal configurations, curvature radii from 2.51 times the minimum radius allow adequate power generation to be maintained. In the concave configuration, 77.8% of the power generated by a flat PV module is achieved, while in the convex configuration, 80.21% is achieved. For vertical configurations, the convex geometry with minimum radius shows the best performance, exceeding the power of a flat module by 12.1%. The convex configuration with a radius of curvature of 2.51 times the minimum radius offers 81.14% of the flat reference power.

1 Introduction

Solar energy has become one of the most important renewable sources due to its great potential to reduce dependence on fossil fuels and mitigate climate change. As the energy transition progresses, the demand for electrical energy increases, so the installed capacity in different territories must gradually increase. Cities, for example, are responsible for 70% of energy consumption [1] and play a very important role in the adoption of solar technologies. The integration of solar energy into the urban environment not only promotes sustainability but also improves livability and quality of life in urban and peri-urban areas [2].

The utilization of solar energy in cities is carried out through the integration of photovoltaic (PV) and thermal solar panels in buildings and other urban elements. This integration allows cities to supply a significant part of their energy demand from renewable sources [3]. Additionally, urban design significantly influences the solar capture potential of

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buildings, making it crucial to consider orientation and architectural forms to maximize energy efficiency [4].

The use of vertical surfaces, such as building facades and walls, for the installation of solar panels is an effective strategy to increase energy generation capacity in dense urban environments. This practice not only maximizes the use of available space, but can also be aesthetically integrated into architectural design, contributing to public acceptance of these technologies [5]. Studies have shown that the integration of solar panels on facades can be especially useful in cities with a high density of low-rise buildings, where usable areas are greater [6].

The implementation of curved geometries and innovative surfaces can enhance the visual appearance of structures while optimizing solar capture [7]. Additionally, it has been shown that solar panels with curved geometries can capture more radiation than flat solar panels [8], opening up the possibility of evaluating the performance of PV surfaces at different curvature radii with a view to their harmonious integration with architectural concepts.

2 Literature review

Building-Integrated Photovoltaics (BIPV) offers great potential for distributed energy generation in dense urban areas. Freitas and Brito (2019) highlight that PV facades can complement the energy production of rooftops, optimizing generation during off-peak production hours [9]. Additionally, studies conducted in Salvador, Brazil, have shown that parameterized facade shapes can maximize incident solar radiation, significantly improving the efficiency of installed PV systems [10].

A study conducted by the Faculty of Sciences at the University of Lisbon, explored how different facade configurations can maximize PV generation. Using comparative analyses of various geometric arrangements, they found that facades with complex geometries, such as inclined surfaces and protruding modules, can significantly increase energy performance compared to standard flat facades. These results highlight the importance of geometric design in optimizing solar production [11].

Despite advancements, there are significant barriers to the integration of solar technologies in facades. Studies have identified that the lack of technical knowledge among architects and construction professionals is one of the main obstacles to the adoption of solar systems integrated into facades [12]. A study conducted by Delft University of Technology highlights that aesthetic and technical performance challenges must be addressed to promote the widespread application of these technologies [13].

Although prior research highlights the advantages of complex geometries for solar capture, experimental validation is often lacking. This study addresses that gap by experimentally testing the power generation of curved PV surfaces, providing specific data for both concave and convex configurations. Unlike previous work, our findings offer practical insights for optimizing BIPV system design, directly informing architectural applications.

3 Methodology

This study was developed in two stages. In the first stage, a simulation was carried out to identify how the energy is captured by the surface and how varies as a function of some parameters, identifying the radii of curvature with most significant variations. The second stage is an experimental validation of the behavior of the flexible solar panels for the radii defined from the simulation.

3.1 Simulation

A PV surface is a solar panel that can change its shape and adapt to various contours, introducing an important mechanical factor in its analysis. This allows geometrical studies, addressing the average curvature so that the surfaces are developable.

An energy simulation was conducted to assess the performance of different curved PV surfaces over a year and to contrast it with a reference, a PV module with flat geometry. Precisely, the amount of total incident solar energy received by semi-cylindrical, concave, and convex surfaces with dimensions of *790 x 690 mm*, is positioned horizontally, vertically and facing north, was estimated for different radii of curvature over the year 2024, in the city of Medellin, Colombia.

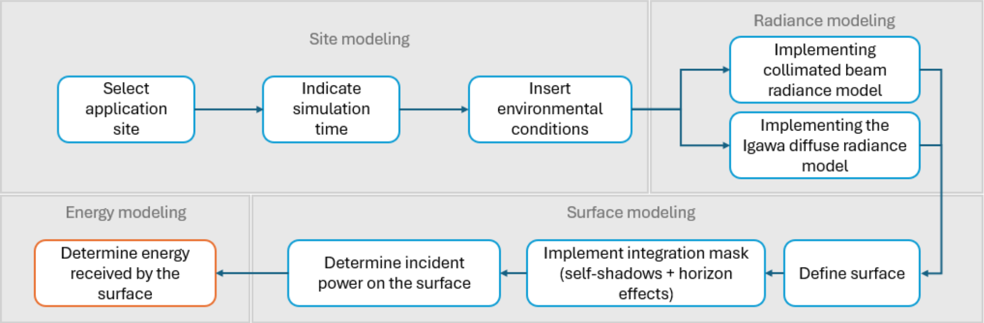

Figure 1. Simulation sequence diagram

A model of the angular distribution of the sky irradiance, also known as 'radiance,' was developed for the energy simulation. Figure 1 shows the sequence diagram of the simulation, which consists of four moments: site modeling, radiance modeling, surface modeling and energy modeling. To model the site, the first step is to select the place to be simulated and indicate the time to be simulated, which can range from days to years. Subsequently, the climatic conditions of the site are loaded for the same period and the position of the sun at each moment is obtained. Knowing the position of the sun at each moment and the climatic conditions, the radiance is modeled.

The global or total sky radiance was modelled as the sum of two components: direct and diffuse components. The direct component was mathematically modelled as an ideal beam of perfectly collimated radiation, and the diffuse radiance was modelled using Igawa's Improved All Sky model (*i-AW*), as detailed in [14]. In both cases, the effect of the local horizon was also included so that energy from parts of the sky blocked by the surrounding mountains was discounted. In both cases, the effect of the local horizon was also included so that energy from parts of the sky blocked by the surrounding mountains was discounted. It was also decided to configure the model so that the simulated radiation values coincided with those of a clear atmosphere devoid of clouds to evaluate the geometry's singular effect on energy capture and rule out the influence of other possible variables. By implementing these models, the energy emitted by the sky per unit of time, per unit of projected area and per unit of solid angle is obtained.

For surface modeling, a geometry is defined and discretized. An integration mask is implemented, which aims to identify which portion of the sky is reflected on each segment, returning a zero if it is not possible to draw a straight line that can connect that segment of the surface with a segment of the sky without being interrupted by the presence of obstacles and returning $cos\ (\theta_i)$ if it is possible to draw such a line, where θ_i is the angle of incidence on the surface. Subsequently, the amount of power incident on the surface is computed and integrated concerning time to know the energy received by the surface.

The simulation results can be seen in Figure 2. For the selection of the curvature radii, a radius of 23.4 mm was taken as the lower limit, the radius with which the solar panels form an exact half cylinder. An infinite radius was selected as the upper limit, representing the reference of the flat panel. Then, various radii were iterated to identify the points at which significant variations in the received energy began.

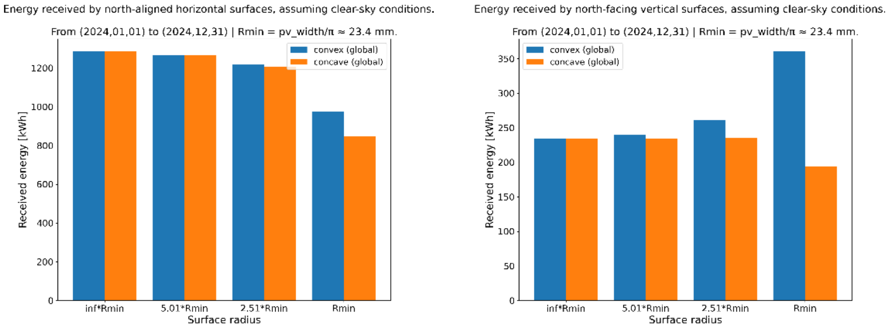

Figure 2. Results of energy simulation for different PV surfaces. Left: horizontal orientation. Right: vertical orientation.

3.2 Experimental Analysis

Experimental analysis was conducted at EAFIT University in Medellín with 100 W flexible solar panels. A PMA2144 pyrometer with, a sensitivity of 25.30 $\mu V/(W/m^2)$, was employed to measure the irradiance, while an electronic circuit was used to simultaneously measure the power output of all the panels. The circuit used a MOSFET as a variable load to take 20 measurement points from the short circuit current to the open circuit voltage, thus generating the VI curve. This process was repeated consecutively at two-minute intervals. Initially, the behavior of six flat PV modules was evaluated to identify which five devices had the most similar behavior, Figure 3 shows the results obtained, showing that solar panel 1 has the performance below the rest of the solar panels. It was decided to assess the minimum radius of curvature and the radius of curvature of 58.73 mm (2.51*Rmin) by concave and convex geometries, evaluating the PV module of flat geometry as a reference.

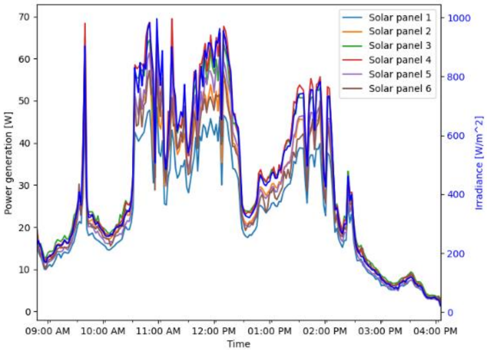

Figure 3. Power generation from flat-plate solar panels

After discarding one solar panel, the remaining five panels were assigned to concave and convex geometries with min radius (Rmin) and for radius 2.51*Rmin. Panel 6 was kept as a reference. Figure 4 shows the experimental validation performed. The image on the left shows the test performed on the six flat panels, the image in the center shows the test performed on the five selected panels in horizontal position, and the image on the right shows the test performed in vertical position and with north orientation.

Figure 4. Experimental setup. Left: Flat panels. Center: Horizontal position. Right: Vertical position

4 Results

The experimental test results for the horizontal configuration are presented in Figure 5, which show that the planar geometry performs better. The configurations with a radius of curvature of 2.51*Rmin also perform well, being only 22.20% and 19.75% lower than the reference for the concave and convex geometries, respectively. Additionally, it is observed that using small curvature radii is not recommended, as using the minimum radius resulted in decreases in power generation of 68.77% for the concave geometry and 71.09% for the convex geometry.

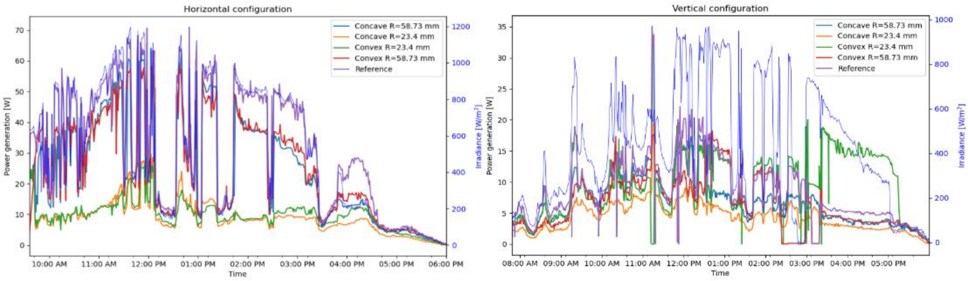

Figure 5. Results of experimental analysis in horizontal and vertical orientation, respectively

For the vertically oriented PV modules shown in Figure 5, convex geometries generally outperform concave ones. The convex geometry with the smallest radius surpasses the performance of the reference geometry by 12.1%. In contrast, the geometry with a radius of 2.51 times the minimum radius achieves 76.66% of the reference performance. On the other hand, concave geometries show a different trend: while the concave geometry with a radius of 2.51 times the minimum radius performs better than the corresponding convex geometry, whit 81.14% of the reference, the concave geometry with the minimum radius performs significantly worse, achieving only 51.17% of the reference performance.

5 Discussion and conclusions

The results of this research provide valuable guidance for architects and designers interested in incorporating curved geometries into facades and roofs. These findings allow for the exploration of innovative designs, such as the one presented in Figure 6, offering a clear reference on the potential alterations in energy generation according to the selected curvature radii.

Figure 6. Implementation of curved geometries on facades and roofs, generated by AI using Microsoft Designe.

For roof applications, architects and designers have the freedom to implement a wide variety of curvature radii, both in concave and convex geometries. In applications where a good balance between aesthetics and performance must be sought, it is recommended to work with curvature radii greater than 2.51*Rmin, if performance is not a very important factor, geometries with lower radii can be explored. For vertical applications, it is recommended to avoid concave geometries with radii close to the minimum radius due to the adverse effect of self-shading, which can reduce energy generation by up to 51.17% compared to a flat geometry. Convex geometries have the advantage of taking better advantage of the sunlight hours in the afternoon or in the morning, since there are more cells receiving the sun perpendicularly compared to the flat geometry, which makes this type of geometries more recommendable for facade applications.

6 Future work

Although the five solar panels with the most similar behavior were selected, the above research requires a more in-depth statistical study in which it can be concluded with greater certainty that the difference in power generation is purely due to geometry. Additionally, it is recommended to evaluate the effects on power generation if not only the bending radii but also their orientation and inclination are varied.

The simulation process can be extended to include an estimation of the power generation of PV surfaces. Based on the estimated incident power on the surface, it is possible to calculate the average irradiance, which allows for determining the temperature of the solar panels and, consequently, their power generation. However, it is crucial to note that the model does not account factors such as optical and electrical losses, nor is it sensitive to the type of connection used between the cells that make up the solar panel, indicating the need for a complementary analysis.

Acknowledgments

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