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BEHAVIOR ANALYSIS OF PHOTOVOLTAIC MODULES INTEGRATED INTO A BUILDING IN DIFFERENT BRAZILIAN REGIONS

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Abstract. *This paper evaluates the behavior of photovoltaic modules in distinct Brazilian regions and different arrangement positioning scenarios. The main objective is to determine the effectiveness of a photovoltaic array vertically positioned on the façades compared to those on the roof of a low-rise residential building. Irradiance and energy generation are considered. The software System Advisor Model, SAM, makes it possible to size solar panels arrangement and delimit performance aspects to obtain resulting data for each simulation performed. Five simulations are done for each of the nine cities covered. The vertical solar panels are analyzed by orienting to the north, east, south, and west. A global comparison is made among the results. As expected, the façades' modules do not generate significantly more energy than those on the rooftop. In fact, among the chosen cities, the vertical modules oriented to the north and the west presented an average of 50% of the total energy generated by the roof modules. Those oriented to the south and the east showed 26.1% and 46.7%, respectively.*

Keywords: *Photovoltaic array, irradiance, PV modules vertically positioned on the façades, building PV.*

1. INTRODUCTION

Currently, there is a growth in the use of PV modules integrated into the facades of buildings. It has been happening in different locations, with different climates and solar potential (annual average solar irradiance). According to GVR (2022), "the global building-integrated photovoltaics facade market size was valued at USD 818.2 million in 2018 and is expected to register a CAGR of 25.3% during the forecast period". The product is experiencing high demand, primarily from developed economies with well-established electricity sharing systems. The rise in government schemes and incentives regarding using BIPV as a renewable source of energy generation is expected to impact growth positively (GVR, 2022).

This work aims to analyze the electrical behavior of photovoltaic modules arranged in different places (façades and rooftops) in Brazil to recognize possible generation advantages. Two types of module positioning were established for several cities and regions in the country. The cities were Brasília, Corumbá, Curitiba, Florianópolis, Goiânia, Pelotas, Porto Alegre, Santos, and Teresina. The vertical installation consists of photovoltaic panels perpendicular to the ground placed on the building's façades. At the same time, the "horizontal" one establishes the same arrangement but for a specific inclination on the rooftop. Possible equivalencies between these two distinct methods were inspected to find better generation variability. Despite previous notions, the article does not specify a value overtaking. But the proportional idealization between the cases.

The purpose of analyzing the local irradiance of each city is because, generally speaking, when we talk about photovoltaic modules, the greater the irradiation absorbed, the greater the energy produced. We can compare the completed data through figures and tables and affirm this aspect's importance for the work's idealization.

However, there are situations where vertical panels can be even more efficient. Some researchers, such as Yu et al. (2021), Zhang and Yang (2019), and Agathokleousa and Kalogirou (2018), published articles addressing the possible advantages of this position regarding energy efficiency. The main benefit is the reduction of electrical costs from heating and air conditioning in residence, in addition to the energy production previously estimated. Therefore, despite the productivity discrepancy, the façade panels should still be seen as objects of study.

2. METHODOLOGY

Solar irradiance and energy generation data were obtained, through simulations made in the software SAM, System Advisor Model, for a specific photovoltaic modules arrangement placed in a residence submitted to different situations and regions of Brazil. The locations groups are compound by nine cities: Brasília, Corumbá, Curitiba, Florianópolis, Goiânia, Pelotas, Porto Alegre, Santos, and Teresina. For each city, were simulated five arrangement positioning scenarios: north-oriented rooftop modules with an inclination equal to each city's latitude (except for Teresina) and vertical modules placed in the north, east, south, and west façades. Due to normative parameters, Teresina has its rooftop modules inclined at 10° instead of the place latitude (5° S), which is lower than the minimum allowed for a building.

The arrangement consists of a six-module single row, totalizing an area of 9.3 m^2, and a single inverter. The chosen solar panel for the analysis is a Canadian Solar Inc. CS6P-255P, and the inverter is an SMA America SB3800TL-US-22 of 240V with 97% efficiency. As well as shadowing parameters, potential energy and irradiance losses were not estimated in each case simulation.

In this way, results about the annual irradiance and the amount of energy generated annually are obtained for each proposed circumstance. From a monthly production analysis, we can conclude about the impact of each season on the research criteria. The irradiance perspective reflects its proportionality in terms of the energy generation of each module.

To visually represent the model in question and its respective simulations, a tridimensional prototype originated in a program named Energy 3D was used. The photovoltaic arrangement on the rooftop and those on the façades are portrayed down below, Fig.1.

The building, Figure 1, initially developed by Carrilho da Graça et al. (2012), was chosen for this case study. There were made two modifications: (1) removing the horizontal *brises* in the kitchen and living room windows; (2) the building rotation by 180º - so the façade with the largest window area is now oriented to the North (Caus, 2019), Figure 1.

The windows were shifted (placed on another facade) to allow the modules to be placed in different orientations. This modification, Figure 1 (small figures on the right), changes the solar heat gain through the windows. However, as this work is just an assessment of PV generation, this change does not impact the results obtained.

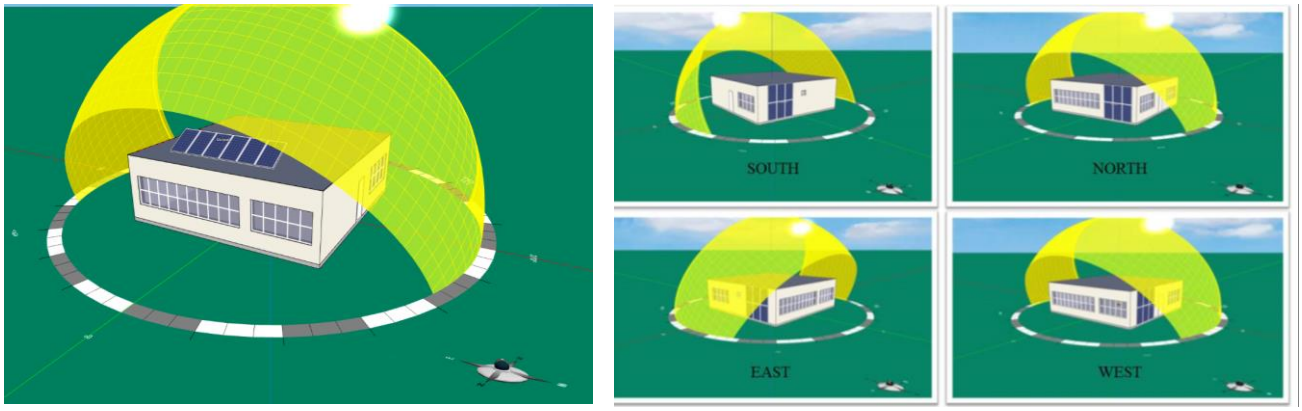


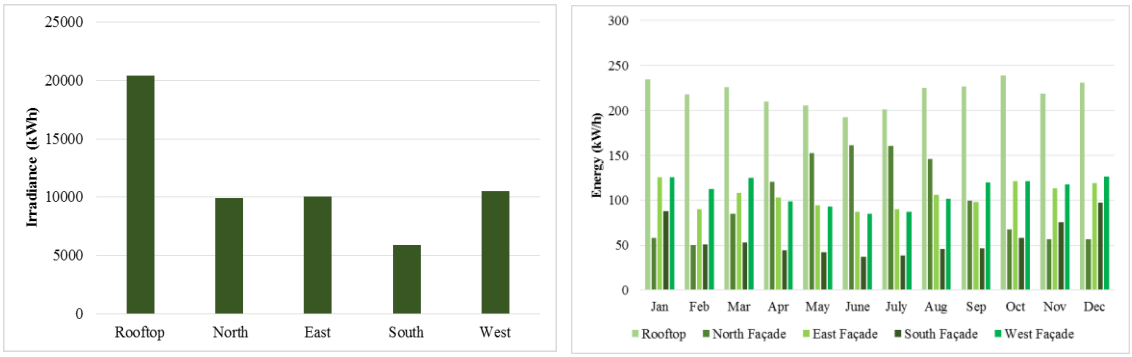
Figure 1. Rooftop inclined string and vertical modules' façades. On the left, we have the house with modifications (1) and (2). On the right, we have the facades modified to allow the installation of PV modules.

3. RESULTS

The resulting data relative to each city and its specific module arrangement positioning was obtained from a detailed analysis. Graphic representations were made to portray the data obtained in a general way. Some observations were made to succinctly conclude the typical behavior of the modules in each city. Considerations about the rooftop modules' performance were only addressed at the end of the article, emphasizing the vertical ones. Finally, the proposed cases were compared to evaluate the energy generation equivalence between rooftop and façade modules.

3.1 Brasília

The west façade is the one that receives the most irradiance and, consequently, it is the best energy generator annually in comparison to the other façades. Figure 2a shows the monthly energy generation. From April to August (Brazilian fall and winter), the north façade is the one that generates the most significant amount of energy. On the other hand, between September and March (Brazilian spring and summer), the west façade excels.

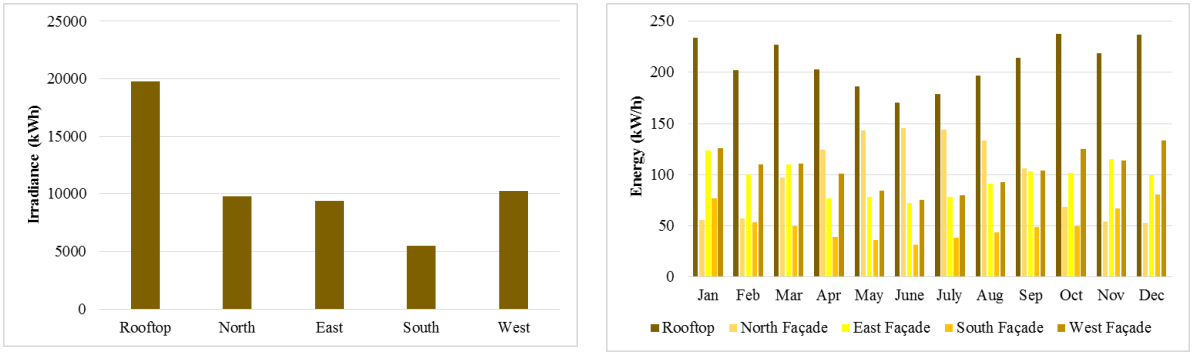


(a) Annual Irradiance (b) Month Energy Generation

Figure 2. Brasília's Annual and Monthly Energy Generation (AC) and Annual Irradiance.

3.2 Corumbá

From Figure 3, it's noticed that the west façade is the greater generator and the one that receives more solar irradiance in comparison to other guidelines. During Brazilian winter, the north façade is the best generator, but from October to March, the most significant amount of energy is produced by the west façade.

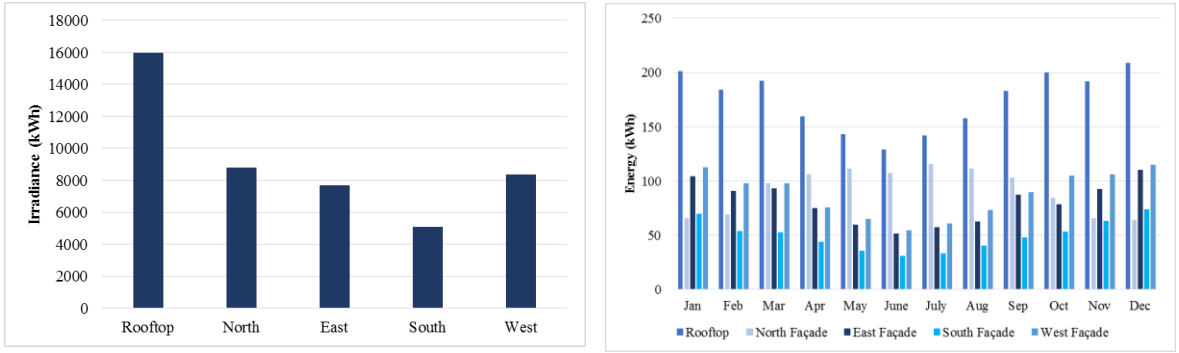


(a) Annual Irradiance (b) Annual Energy Generation

Figure 3. Corumbá's Monthly Energy Generation (AC) and Annual Irradiance.

3.3 Curitiba

North façade produces the most significant amount of energy annually and is the one that receives more irradiance. As shown in Figure 4, from April to September, the best energy producer is the arrangement of the modules vertically oriented to the north. Especially in March, the production between the north and west façades is almost identical. From October to February, the most productive module is the one on the west façade.

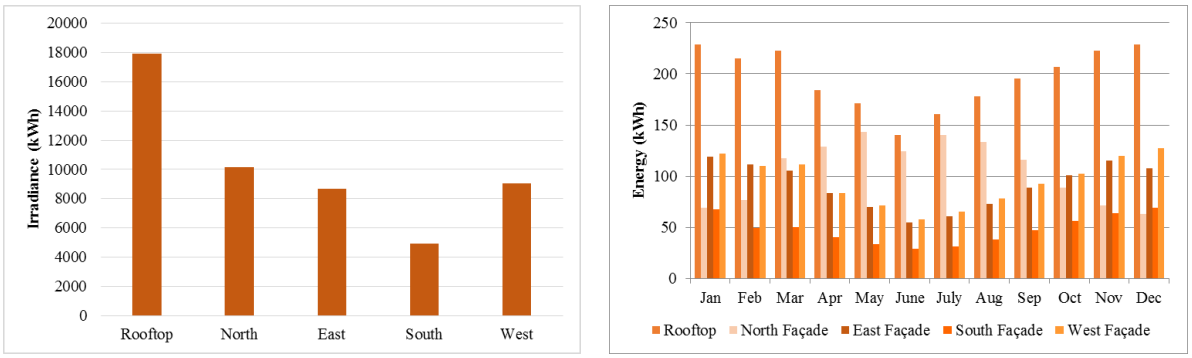


(a) Annual Irradiance (b) Annual Energy Generation

Figure 4. Curitiba's Monthly Energy Generation (AC) and Annual Irradiance.

3.4 Florianópolis

The north façade is the most profitable in energy generation and the biggest receiver of solar irradiance. Figure 5 allows us to conclude that from March to September, the north façade is the greater producer; between October and January, the west module excels; specifically, in February, the east façade is the best.

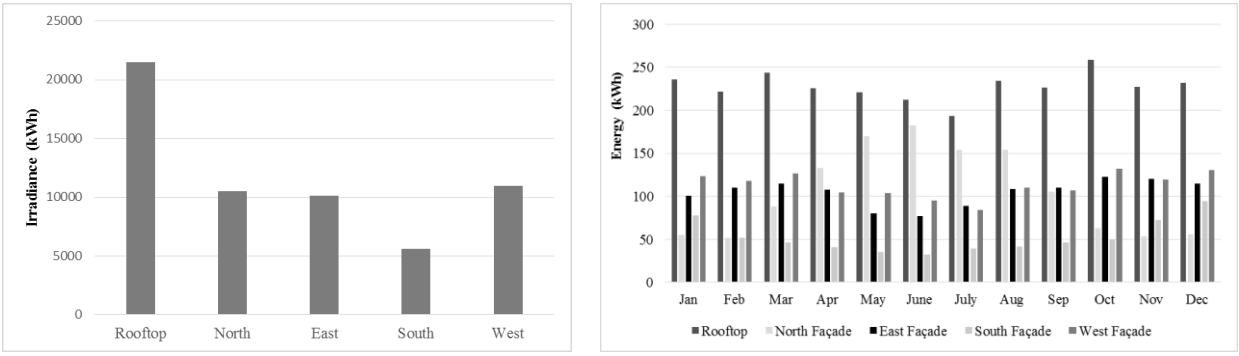


(a) Annual Irradiance (b) Annual Energy Generation

Figure 5. Florianópolis' Monthly Energy Generation (AC) and Annual Irradiance.

3.5 Goiânia

For this specific region, the west façade presented a more significant generation than the north. Consequently, this orientation was the one in which the solar irradiance had more impact. Between April and August, the north façade has a superior income. In September and November, the east façade stands out. The remaining months have as the most significant generator the west façade.

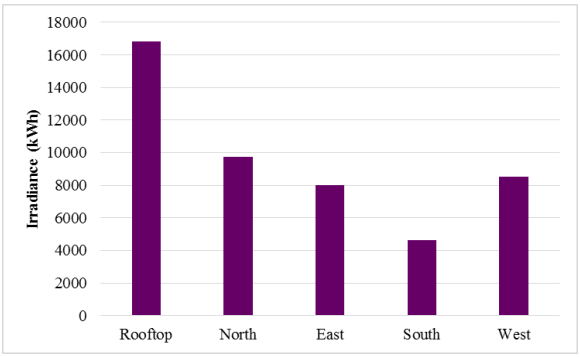


(a) Annual Irradiance (b) Annual Energy Generation

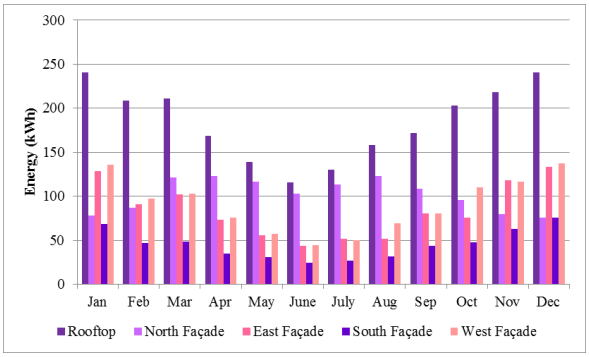
Figure 6. Goiânia's Monthly Energy Generation (AC) and Annual Irradiance.

3.6 Pelotas

It's noticeable better profitability by the north vertical modules. We can conclude from Figure 7 that from March to September, the north module is the most productive. Especially in June and July, the energy generated by the north façade approaches the amount obtained by the modules on the rooftop. Between October to February, the production is mainly maintained by the west façade, except in November when the east façade is the highlight.



(a) Annual Irradiance

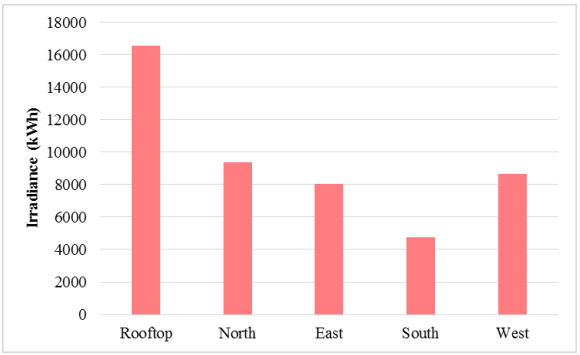


(b) Annual Energy Generation

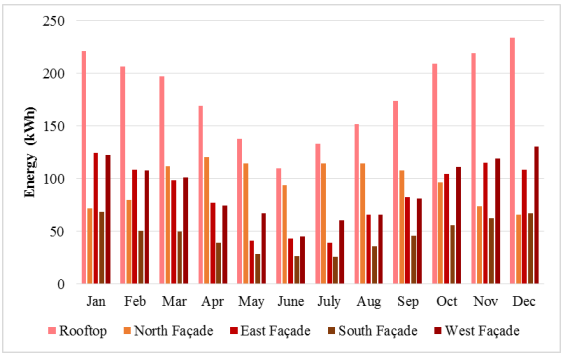
Figure 7. Pelotas' Monthly Energy Generation (AC) and Annual Irradiance.

3.7 Porto Alegre

Porto Alegre's most significant amount of energy is produced by the north façade. Following Figure 8, the north façade is the greater generator between March and September. From October to November, the west façade is the most profitable. In January and February, the west module is the one that produces more energy, although the difference with the west module is relatively small.



(a) Annual Irradiance

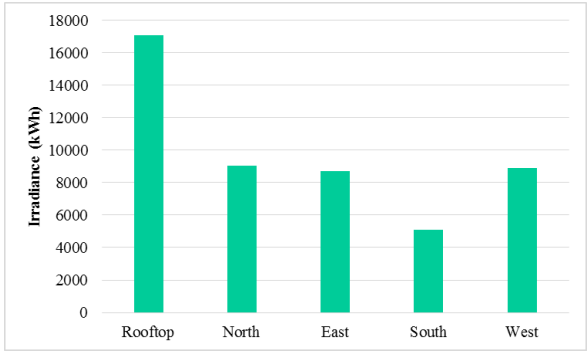


(b) Annual Energy Generation

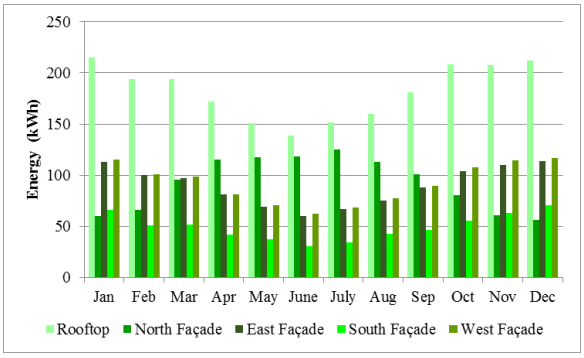
Figure 8. Porto Alegre's Monthly Energy Generation (AC) and Annual Irradiance.

3.8 Santos

The panels vertically located in the north generate the largest amount of energy annually, but the ones oriented to the west produce almost the same quantity. Consequently, the irradiance variation between these two façades is practically irrelevant. From April to September, the north façade is the most profitable. From October to March, the greatest generation comes from the west modules.



(a) Annual Irradiance

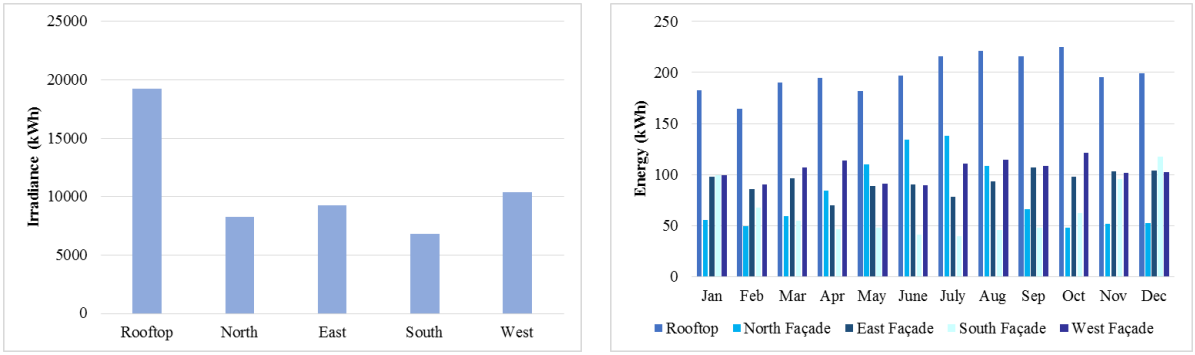


(b) Annual Energy Generation

Figure 9. Santos' Monthly Energy Generation (AC) and Annual Irradiance.

3.9 Teresina

Before showing the results, it is worth mentioning again that Teresina has its rooftop modules inclined at 10° from the horizontal surface, which is different from the other cities with an arrangement with the same latitudes.



(a) Annual Irradiance (b) Annual Energy Generation

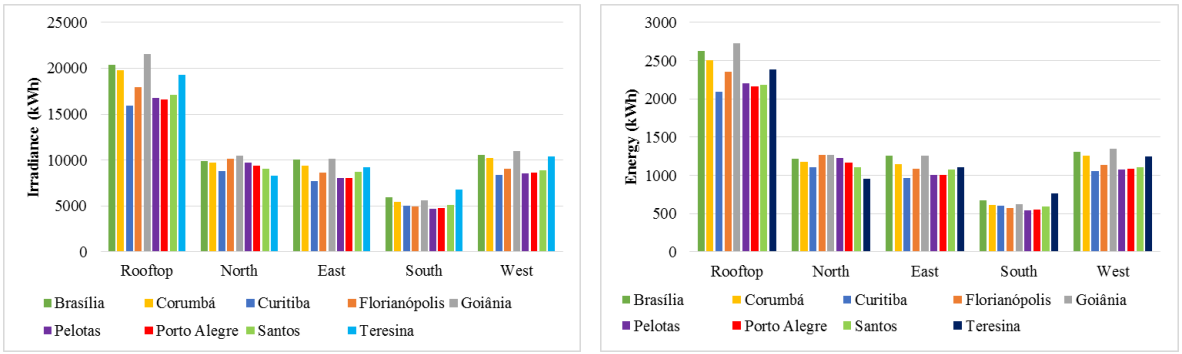
Figure 10. Teresina's Monthly Energy Generation (AC) and Annual Irradiance.

Due to the charts above, we can notice the annual energy generation superiority by the west façade, which also is the one that receives more solar irradiance.

Teresina's data are the most controversial to the standard shown until now. Fig. 10 shows us that between February to April and August to October, the principal generation comes from the west façade, while from May to July, the north stands out. Specifically, in November, the east façade generates the largest amount. The south façade gets a peak generation that surpasses the others in December and January, becoming the most profitable. Lastly, in January, the difference between the production of the south and the west is relatively tiny.

3.10 General Comparision

Now, to analyze the general context of the study addressed, it is coherent to distinguish the behavior between the façades and the cities. Through Figure 11, it is possible to conclude the annual energy generation and the solar irradiance.



(a) Annual Energy Generation (b) Annual Irradiance

Figure 11. Annual Energy Generation (AC) and Irradiance Comparison

The first remarkable relation is that Goiânia is the biggest energy producer annually through its modules turned to the west and the ones on the rooftop. It is also the biggest receiver of solar irradiance on the north, east and west sides. However, Brasília is where the most significant amount of energy is produced by the east façade. Teresina has the largest numbers by the south façade and receives the highest solar irradiation by the same orientation. For the north façade, the most productive city is Florianópolis, despite not having the greatest solar irradiance in this direction.

Annual energy yield is, in a general way, minimized when using south façade modules and maximized when using the north ones except for Brasília, Corumbá, Goiânia, and Teresina, where the most significant production comes from the façade facing west but still with a considerable generation by the north.

The following tables consist of data explicitly obtained for the energy generation and the irradiance relative to photovoltaic modules positioned on the rooftop of each respective city.

Table 1. Annual Power Generation Proportionality (kWh) - Roof x Facades.

Location	Roof AC Energy (kWh)	North (%)	East (%)	South (%)	West (%)
Brasília	2627,85	46,2	47,8	25,7	49,9
Corumbá	2507,99	47,0	45,8	24,4	50,0
Curitiba	2093,73	52,6	46,1	28,6	50,3
Florianópolis	2353,98	54,0	46,3	24,4	48,5
Goiânia	2731,35	46,3	45,9	22,9	49,5
Pelotas	2206,86	55,5	45,6	24,6	48,9
Porto Alegre	2163,23	53,8	46,6	25,7	50,3
Santos	2183,79	50,8	49,3	27,0	50,5
Teresina	2382,57	40,1	46,6	32,1	52,4
General Average	2361,26	49,3	46,7	26,1	50,0
Standard Deviation	222,541	5,044	1,193	2,777	1,131
Mean Standard Deviation	9%	10%	3%	11%	2%

Table 2. Annual Irradiance Proportionality (kWh) – Roof x Facades.

Location	Roof Irradiance (kWh)	North (%)	East (%)	South (%)	West (%)
Brasília	20399,8	49,7	50,2	29,6	52,7
Corumbá	19791	50,2	48,2	28,2	52,5
Curitiba	15942,6	55,5	48,5	32,0	52,8
Florianópolis	17939,7	56,7	48,5	27,6	50,6
Goiânia	21531,7	49,5	47,9	26,5	51,8
Pelotas	16800,6	58,0	47,7	27,7	50,7
Porto Alegre	16588,3	56,4	48,5	28,8	52,2
Santos	17070,9	53,5	51,6	30,3	52,5
Teresina	19252,6	42,9	48,0	35,3	54,1
General Average	18368,58	51,75	48,37	29,25	51,79
Standard Deviation	1946,702	4,843	1,268	2,720	1,076
Mean Standard Deviation	11%	9%	3%	9%	2%

In the table results, we can notice the activity relevance among the façades and the rooftop. The vertical west modules' predominance is remarkable in generation and irradiance proportionality towards the rooftop. It is very close to the north façade. The dispensability of the south-oriented modules is also observed since they receive the least solar irradiation, resulting in lower energy production. The tables reinforce the dependency factor between solar energy generation and irradiance.

Another relevant question to highlight is the standard deviation among the data. The annual energy generation by the modules on the rooftop varies by 9% between the cities, which means a considerable productivity difference. Although not abrupt, we can notice the significance of the territorial aspects. This behavior is reflected in the perceptual taxes of the north and the south façades. On the other hand, for vertical west and east arrangements, the standard deviation is only 3%, which means that there is not an expressive behavior change by the modules in each region of the country.

Due to Tab.3 and Fig. 12, it's possible to verify the solar irradiation predominance in the northeast Brazilian region between 1999 and 2018, although giving credit to Brasília, Goiás, Tocantins, and the northwest part of Minas Gerais state. This observation emphasizes the average irradiance values for each city previously presented.

Based on this data, it is possible to verify that the city with the greatest horizontal irradiance average is the same as the highest energy production, in that case, Goiânia. Following the same logic, we can affirm that Curitiba is the place where there is the lowest energy generation since it is also the one with the most downward irradiance. However, among these comparatives exists two exceptional cases that do not follow the rule. The Porto Alegre's Irradiance is bigger than Pelotas', although it is not the greatest generator among them. This idea rebound for Teresina and Corumbá. Nevertheless, despite the disagreement, the difference between the values of these two pairs of cities is meager, almost irrelevant.

Table 3. Average Irradiance.

Location	Average Irradiance (kWh/m²/day)
Brasília	5,81
Corumbá	5,6
Curitiba	4,5
Florianópolis	4,93
Goiânia	6,08
Pelotas	4,6
Porto Alegre	4,61
Santos	4,82
Teresina	5,64

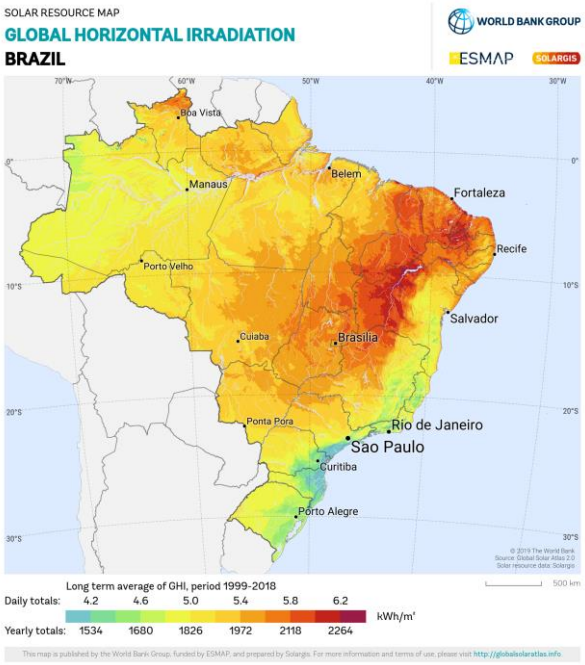


Figure 12. Brazilian Horizontal Irradiation (GSA, 2022).
Available from: https://globalsolaratlas.info/map

4. CONCLUSION

First, it's worth emphasizing that the energy generation and the solar irradiation from the roof modules are relatively higher for all situations, even presenting a 10% fluctuation. Therefore, the obtained data are based on the proportionality of production between vertical and horizontal panels. In short, the west-facing panels achieved the best performance among the other facades for energy production and irradiance, totaling an overall average of 50% and 51.8%, respectively, of the ceiling segments. The low generation of the south modules and the high performance of those oriented to the north are highlighted.

Despite showing greater instability in the results, for many cities, mainly Pelotas, the north façade obtained an even more expressive approach to the west façade. Goiânia stands out as superior to the others for the two aspects in question. The north and south façades presented a more significant variation among their results. At the same time, the west and east showed the same behavior with less difference between their results, thus emphasizing the relevance of territorial aspects in the research.

5. ACKNOWLEDGMENTS

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