Potential of solar façades for residential buildings in Brazil

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Abstract

Brazil has high solar energy harvesting potential, which has supported the growing integration of photovoltaic (PV) systems in buildings, particularly for rooftop applications. Façades typically offer lower energy performance compared to tilted roofs; however, they can serve as alternatives to meet the building's energy demand. This study investigates the potential of PV façades in residential buildings across different Brazilian states. For each State Capital a linear building with 6 typical social housing apartments were simulated in North-South and East-West orientations. Energy generation was estimated using Radiasol software to determine solar irradiation related to the maximum number of PV modules (350W) accommodated on the surface. Electricity demand was derived from Brazilian residential consumption databases considering three demand scenarios (average unit demand, and units with 2 and 4 residents). Results showed that Scenario 2, with 2 residents in corner apartments, was the most favorable: over 75% of cities met their energy demand, and about 23% exceeded 120%. In East-West orientation buildings, more than 60% of corner units achieved full demand. Scenario 3, with 4 occupants, was the least efficient, as center apartments facing south generated only 19-28% of the required energy, and those facing North produced 24-41%. The analysis demonstrates the photovoltaic potential of Brazilian façades in social housing, particularly for corner units with 2 occupants or efficient energy demand.

Keywords: building-integrated photovoltaics, zero-net energy building, residential electricity demand, urban decarbonization, solar energy potential, tropical cities

1. Introduction

Solar photovoltaic (PV) energy production in Brazil has experienced substantial growth since 2020, driven primarily by residential consumers. In 2023 alone, residential and other small-scale installations added 1.9 GW of installed capacity (REN21, 2024). Overall, the country´s solar energy production expanded from 16 GWh in 2014 to 50,632.9 GWh in 2023. According to the National Energy Balance (Brasil, 2024a), solar now accounts for 4.4% of Brazil's primary energy supply and 7% of its domestic electricity supply.

The residential sector in Brazil is responsible for 27.5% of the country's electricity consumption and recorded the highest annual growth among sectors in 2023, with an increase of 9.06% (Brasil, 2024). This rise is partly attributed to the replacement of traditional energy sources such as charcoal and liquefied petroleum gas (LPG), as well as to improvements in living standards. In 2023, residential per capita electricity consumption reached 0.782 MWh per inhabitant, reflecting a strong correlation between electricity use and Human Development Index (HDI) (PNUD, 2025). For low-income households, energy expenses can represent a significant strain on the family budget (Mpholo et al., 2020), and many are unable to afford sufficient energy to meet their basic subsistence, comfort, and leisure needs (Ray et al., 2019). Social housing plays a central role in this scenario, especially as a response to the national housing deficit, estimated at approximately 5.8 million homes (Triana et al., 2023; Fundação João Pinheiro, 2021).

Despite the positive growth in PV, rooftop systems still face limitations related to orientation, shading, shared space usage, and insufficient available area. In this context, façades emerge as a promising alternative for solar integration. Reffat and Ezzat (2023) demonstrated that, even in the Northern Hemisphere, façades facing East, West or South can generate significant amounts of electricity. Additionally, Shono et al. (2017) noted that vertical PV systems may outperform traditional installations during winter months in high-latitude locations. This insight is relevant for Brazil, where a significant portion of installed PV capacity is located in regions above 15°S. In these areas, façade-integrated PV could help compensate for seasonal decreases in rooftop generation, contributing to electric grid stability. Given

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these challenges, photovoltaic (PV) systems represent a promising strategy to reduce household energy expenditure while promoting sustainability in the residential sector.

In this context, integrating PV systems into building façades presents a promising approach to offset the increasing residential energy demand, particularly in dense urban areas and in high-latitude regions with seasonal variation in solar availability. This study aims to evaluate the energy potential of solar façades in social house multi-storey buildings across all state capitals in Brazil. The analysis is based on solar radiation potential to assess the façades' contribution to meeting a typical household electricity consumption.

2. Methodology

This study was conducted in three main stages. First, PV generation potential was assessed for building façades in 27 Brazilian state capitals, considering four orientations. Second, a linear building of social housing from literature was defined to simulate two different building orientations: North-South and East-West. Then, commercial photovoltaic modules were applied to each residential unit's external surface. Finally, electricity demand from Brazilian states was collected to assess the potential of façade-integrated PV systems to meet the residential energy needs.

In the first stage, solar irradiance was calculated using the Radiasol software (LABSOL, 2025) for four façades (North, East, West and South) in each of the 27 Brazilian state capitals. The software provides daily global radiation in the plane of array (Gpoa), which was used to calculate the electric energy generated (EEG), according to Equation 1, based on installed power (P) and assuming a Performance Ratio (PR) of 80%. The installed power was defined by selecting the most efficient module available in the catalog of the National Institute of Metrology, Standardization and Industrial Quality (Brasil, 2022). The selected module was a polycrystalline panel with a rated power of 0.35 kW, dimensions of 1.95 x 0.992m, and an efficiency of 18%. The solar capital radiation was considered representative of the average radiation of its respective state.

$$EGG\ (kWh) = P\ (kWh) x\ Gpoa\ (kwh\ per\ day) x PR \qquad \text{(eq. 1)}$$

Secondly, the façade net area was used to accommodate the largest possible number of PV modules. For this assessment, the typical floor plan proposed by Triana et al. (2015) was adopted as a standard design for a social housing linear building, as illustrated in Figure 1.

Figure 1: Typical floor plan in a linear building used in the analyses. Source: Triana et al. (2015).

The floor plan was slightly altered (Figure 2), and no roof areas were evaluated in order to consider just the directly external envelope of each residential unit. Moreover, only one floor was simulated as a representation of all floors. The following adaptations were made in the original project:: the ceiling height used was set at 2.5 m and the slab thickness was not considered to maintain a conservative approach; the window openings were redefined to comply with the minimum ratio of 1/6 of the net floor area, as required by several Brazilian municipal building codes, such as Florianópolis, Belo Horizonte, Natal, Palmas, Porto Alegre (PBH, 2009; PEREIRA; SCHMITT; MORAES, 2015; Florianópolis, 2000); and the parapet wall height was established at 1.0 m to allow the installation of PV modules. Typical sill heights in Brazil range from 0.9 to 1.2 m; therefore, the minimum value of 1.0 m was adopted to ensure proper module placement since many PV modules are 1.0 m wide. The arrangement of PV modules on the façades was designed to maximize the installed area within architectural constraints, ensuring that only modules fully contained within the apartment façade were considered. Recessed wall sections more than 0.6 m behind the main façade were excluded from the analysis due to the shading effect on PV modules.

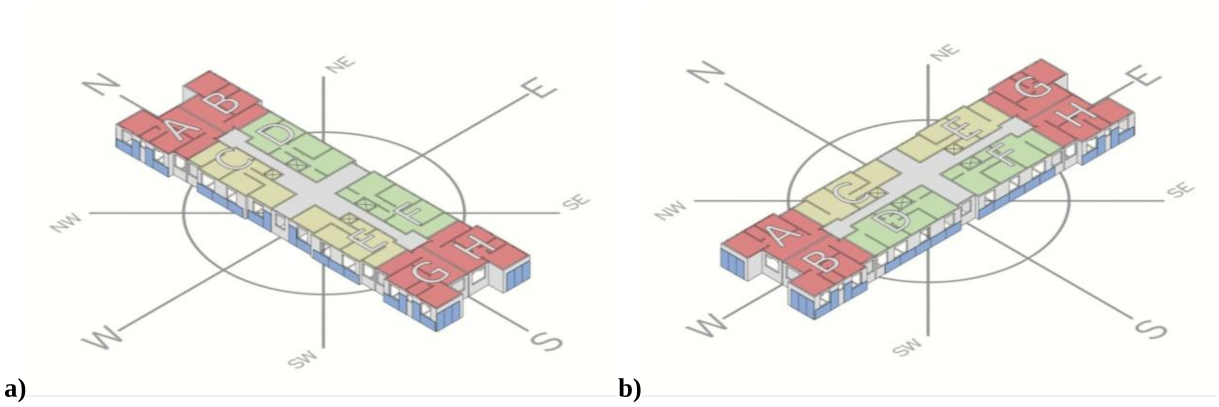

Figure 2: Building orientation (a) North-South (a) and (b) East-West, adapted from Triana et al. (2015). Corner apartments are shown in red, center apartment facing one direction in yellow, and center apartments facing the opposite direction in green. Photovoltaic (PV) modules attached to the façades are represented in blue.

The adopted typical floor plan consisted of eight apartments, with four corner apartments facing two perpendicular orientations (A, B, G and H, in Figure 2) and four apartments in the center (C, D, E, F), facing just one orientation each. Center apartments were considered equivalent, as they share identical façade areas and accommodated five modules each, in the same orientation, but two opposed orientations in the building floor plan. Corner apartments also have identical façade areas, accommodating seven modules (four in one façade and three in the adjacent one), and were modeled for all four building corners. Consequently, for the two linear orientations: North-South and East-West, twelve types of apartment façades were simulated to obtain photovoltaic generation (Figure 2).

In the final stage, residential electricity consumption data for each state were obtained from the Brazilian Energy Research Office (Brasil, 2024a). This analysis adapted the methodology proposed by Brito et al. (2017), which considered multiple scenarios based on the "consumption unit" in Brazilian datasets and compared them with per capita energy demand. While irradiation data used the capital city as the average value for the state, electricity consumption data were based on state-level information to consider regional and demographic aspects. This approach resulted in twelve apartment orientations simulated across the 27 Brazilian states, yielding an estimated 324 PV system generations.

Subsequently, three scenarios were defined to represent different family profiles commonly associated with social housing projects. Scenario 1 represents the energy demand of a single consumer unit (total residential consumption divided by the number of consumer units). Scenario 2 uses per capita energy demand (total residential consumption divided by total population) and assumes two residents per household. Scenario 3 is similar to Scenario 2 but assumes four residents per household. These were then compared against the 324 PV generation, resulting in 972 compositions.

The final results were expressed as the percentage of residential demand that could be supplied by façade-photovoltaics systems. Five levels were established to categorize the results, ranging from low to high generation potential: below 29,99%, 30-49,99%, 50-69,99%, 70-89,99% and above 90%. The threshold of 90% was selected to represent a near net-zero balance, considering Brazil's mandatory Grid Disposal Cost, which generates a 30kWh credit (Brazil, 2022). Consequently, this margin results in the smallest energy account possible for a PV system that only generates 90% of the total demand.

The main limitations of this study are that the effects of shading from surrounding buildings and the electrical configurations were not considered.

3. Results

3.1 Brazil Irradiance and Electric Demand

In the first phase, Radiasol software was used to estimate solar irradiation. Table 1 shows that the highest tilt irradiation values (above 5.5 kWh/m².day) were found in the Northeast states of Paraíba, Pernambuco, Rondônia, Alagoas, Tocantins and Sergipe. Contrary, the highest vertical irradiation (above 3 kWh/m²day) was observed at the North façade in Minas Gerais (latitude 19.94ºS), and on the West and East façades in Rio Grande do Norte (latitude 5.80oS). These cities, within different latitudes, illustrated how specific regional climatic conditions can significantly influence solar irradiation, beyond the effect of latitude alone.

Regarding façades irradiation, most states presented North-oriented façades that receive 2.5 kWh/m²day, while East and West façades gain around 2.75 kWh/m²day and South façades receive an average of 1.7 kWh/m²day (Table 1). Overall, the East and West oriented façades presented higher potential due to Brazil's predominant low latitudes. At small latitudes, the zenith angle between the sun and vertical surfaces diminished the solar radiation received by the PV module in summer. However, this condition increases the generation in winter (where the zenith angle is close to perpendicular to vertical surfaces). Moreover, mid-latitude cities experience lower irradiation available and larger zenith angles, which can result in irradiation values similar to or even greater than those on North façades, as noted by Shono et al. (2017). Therefore, Brazil demonstrates significant potential for photovoltaic façade integration all over the country, particularly for those North, East and West-orientated. These façades can generate more than 50% of tilted photovoltaic roofs at their locations.

Table 1: Solar irradiation on buildings façades and residential demand in Brazilian capitals, organized by latitude

Brazilian States	State capital	Capital Gpoa irradiation	Capital Latitud	Façades irradiation				State monthly per capita demand	State unit consumer demand
				North Façade (azimuth 0°)	East Façade (azimuth 90°)	West Façade (azimuth 270°)	South façade (azimuth 180°)		
		kWh/W²		kWh/W²	kWh/W²	kWh/W²	kWh/W²	kWh	kWh
Roraima	Boa Vista	4,90	2.89°N	1,89	2,52	2,51	1,60	81,06	369,48
Amapa	Macapá	4,94	0.02°N	1,71	2,44	2,41	1,71	71,45	340,38
Pará	Belém	4,87	1.41°S	2,16	2,75	2,78	1,98	50,33	175,75
Maranhão	São Luis	5,21	2.47°S	2,19	2,69	2,77	1,90	56,75	167,54
Amazonas	Manaus	4,33	3.21°S	2,19	2,65	2,70	1,86	51,43	259,80
Ceará	Fortaleza	5,78	3.81°S	2,29	2,93	2,98	2,00	50,81	132,97
Piauí	Teresina	5,58	4.94°S	2,44	2,93	2,98	1,88	60,29	157,74
Rio Grande do Norte	Natal	5,68	5.80°S	2,33	3,00	3,01	1,99	56,79	146,93
Paraíba	João Pessoa	5,53	7.16°S	2,44	2,92	2,97	1,92	55,13	150,00
Pernambuco	Recife	5,45	8.20°S	2,35	2,89	2,95	1,91	50,01	135,18
Rondônia	Porto Velho	4,52	8.89°S	2,47	2,80	2,10	1,74	74,11	285,93
Alagoas	Maceió	5,53	9.61°S	2,40	2,87	2,92	1,88	48,64	136,98
Acre	Rio Branco	4,61	9.82°S	2,37	2,52	2,57	1,67	59,60	224,72
Tocantins	Palmas	5,29	10.06°S	2,71	2,92	2,99	1,72	71,56	210,80
Sergipe	Aracaju	5,51	11.07°S	2,53	2,96	2,96	1,82	53,93	142,87
Bahia	Salvador	5,40	12.89°S	2,49	2,85	2,87	1,73	44,77	113,19
Mato Grosso	Cuiabá	5,24	15.51°S	2,75	2,87	2,88	1,60	89,89	247,93
Distrito Federal	Brasília	5,43	15.80°S	2,88	2,85	2,87	1,59	67,63	208,97
Goiás	Goiânia	5,44	16.55°S	2,84	2,71	2,74	1,51	79,27	203,33
Minas Gerais	Belo Horizonte	5,35	19.94°S	3,01	2,77	2,83	1,47	57,55	152,36
Espírito Santo	Vitória	5,13	20.42°S	2,81	2,69	2,71	1,49	67,67	200,69
Mato Grosso do Sul	Campo Grande	5,24	20.58°S	2,96	2,80	2,85	1,50	71,73	209,65
Rio de Janeiro	Rio de Janeiro	4,93	22.76°S	2,72	2,57	2,58	1,42	62,94	160,32
São Paulo	São Paulo	4,67	23.65°S	2,79	2,54	2,59	1,45	83,00	205,59

Paraná	Curitiba	4,41	25.56°S	2,67	2,47	2,44	1,43	69,59	192,92
Santa Catarina	Florianópolis	4,49	27.70°S	2,89	2,57	2,61	1,39	86,53	243,82
Rio Grande do Sul	Porto Alegre	4,67	29.94°S	2,92	2,55	2,58	1,38	77,19	212,46

Regarding energy consumption, Brazil presents a wide variation in residential electricity demand, ranging from 113kWh to 370kWh per housing unit. This variation is primarily influenced by climatic conditions and user habits across the country. The highest consumption levels occur in the Northern States, where high temperatures and humidity lead to frequent use of air conditioning for thermal comfort and increased demand for refrigerators. Conversely, lower demands were present in Northeast states, which, despite having high temperatures, also experienced low humidity and constant winds that mitigate thermal discomfort and reduce the need for air conditioning. In these regions, electricity use is mainly associated with refrigerators and fans (Teixeira et al., 2022).

The relation between horizontal global tilt radiation and residential energy consumption is illustrated in Figure 3. This figure shows the lower irradiation values in Southern states, due to their higher latitudes, and in Northeast states, where regional climatic conditions include cloudy skies and frequent rainfall. Nevertheless, average energy consumption tends to be higher in states with lower radiation, indicating that solar irradiation does not have a linear relation with energy demand. Instead, electricity consumption is more closely related to air temperature, humidity and user behavior.

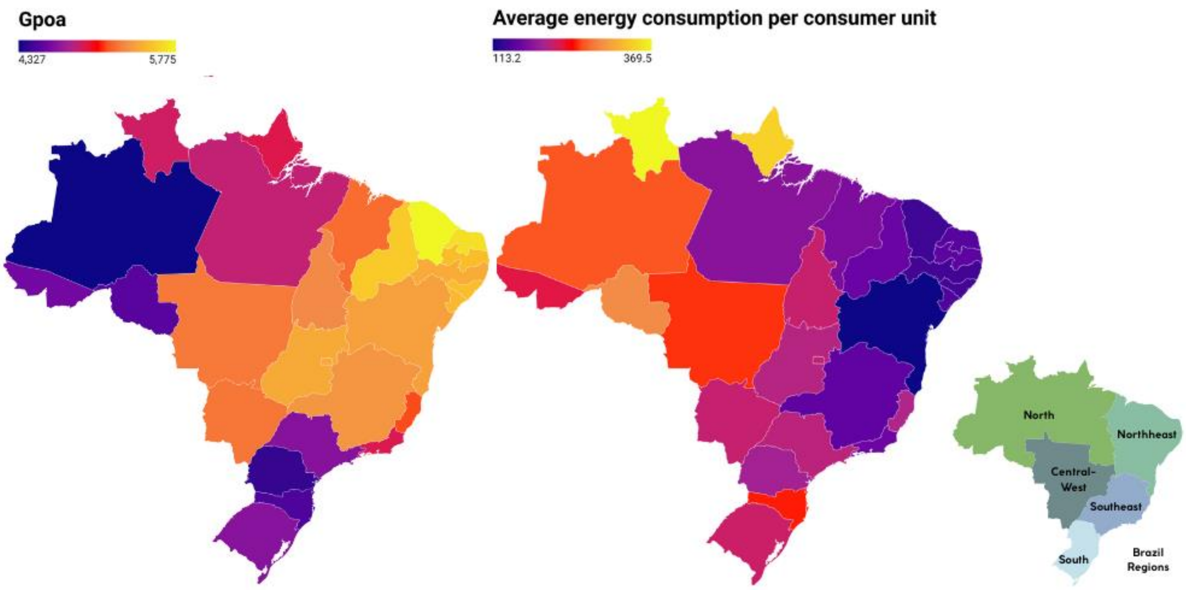

Figure 3: Average tilt radiation and energy consumption across Brazilian States

Scenario 1 illustrates the relationship between photovoltaic façade generation and residential unit electricity consumption (Table 2). The results indicate that façade orientation has a stronger influence on performance than regional latitude. Overall, 48% of simulated façades generated more than 70% of the residential demand, and 25% of simulations achieved full coverage of household consumption. These findings demonstrate a favorable relationship between PV façade generation potential and residential energy requirements across Brazilian states.

Table 2: Scenario 1 –Contribution of apartment photovoltaic façade to the residential unit energy demand

Brazilian States	State unit consu-mer demand (kWh)	Building North-South orientated						Building East-West orientated					
		Corner N-E	Corner E-S	Corner S-W	Corner W-N	Center East	Center West	Corner N-E	Corner E-S	Corner S-W	Corner W-N	Center North	Center South
Roraima	369,48	36%	34%	34%	47%	29%	29%	34%	32%	32%	34%	21%	18%
Amapa	340,38	37%	37%	36%	49%	30%	30%	35%	35%	35%	35%	21%	21%
Pará	175,75	84%	81%	82%	104%	66%	66%	81%	77%	78%	81%	52%	47%
Maranhão	167,54	87%	83%	84%	110%	67%	69%	84%	79%	80%	86%	55%	48%

Amazonas	259,80	56%	52%	53%	70%	43%	44%	54%	50%	50%	55%	35%	30%
Ceará	132,97	117%	112%	113%	144%	93%	94%	113%	106%	107%	114%	72%	63%
Piauí	157,74	101%	92%	94%	122%	78%	79%	99%	87%	88%	100%	65%	50%
Rio Grande do Norte	146,93	109%	103%	103%	131%	86%	86%	105%	97%	97%	105%	67%	57%
Paraíba	150,00	106%	98%	99%	128%	82%	83%	104%	92%	93%	105%	68%	54%
Pernambuc o	135,18	116%	107%	109%	141%	90%	92%	112%	101%	102%	113%	73%	59%
Rondônia	285,93	55%	48%	40%	57%	41%	31%	54%	45%	39%	48%	36%	26%
Alagoas	136,98	115%	105%	106%	139%	88%	90%	112%	99%	100%	113%	74%	58%
Acre	224,72	64%	56%	57%	79%	47%	48%	64%	53%	54%	64%	44%	31%
Tocantins	210,80	79%	67%	68%	93%	58%	60%	78%	62%	63%	79%	54%	34%
Sergipe	142,87	114%	102%	102%	135%	87%	87%	112%	95%	95%	112%	74%	54%
Bahia	113,19	140%	123%	124%	167%	106%	106%	137%	115%	115%	138%	92%	64%
Mato Grosso	247,93	67%	55%	55%	77%	49%	49%	66%	51%	51%	67%	47%	27%
Distrito Federal	208,97	81%	65%	65%	92%	57%	58%	81%	60%	60%	81%	58%	32%
Goiás	203,33	80%	63%	64%	92%	56%	57%	81%	59%	59%	81%	59%	31%
Minas Gerais	152,36	111%	85%	87%	126%	76%	78%	112%	78%	79%	113%	83%	41%
Espírito Santo	200,69	80%	64%	64%	93%	56%	57%	81%	59%	59%	81%	59%	31%
Mato Grosso do Sul	209,65	80%	63%	64%	92%	56%	57%	81%	58%	58%	82%	59%	30%
Rio de Janeiro	160,32	97%	76%	76%	113%	67%	68%	97%	70%	70%	98%	71%	37%
São Paulo	205,59	76%	59%	60%	89%	52%	53%	77%	55%	55%	77%	57%	30%
Paraná	192,92	78%	62%	61%	91%	54%	53%	79%	57%	57%	78%	58%	31%
Santa Catarina	243,82	65%	50%	50%	75%	44%	45%	66%	46%	46%	67%	50%	24%
Rio Grande do Sul	212,46	75%	57%	57%	86%	50%	51%	76%	52%	52%	77%	58%	27%

Corner apartments exhibited higher generation performance than center units because they accommodate more PV modules and span two façade orientations. This configuration compensates for seasonal variations in solar incidence, as East and West façades perform better in summer, while North façades perform better in winter. The best results occurred at corner apartments with façades oriented to the West and North, which supplied more than 70% of the demand in 24 of the 27 states. West-facing façades generally receive higher solar irradiation than East-facing ones, since morning fog in several locations reduces early-hour irradiance on the East façades.

Regarding building orientation, the North-South model presented better results since it provides greater East- and West-façade areas, which receive higher radiation than the North ones, in all cities located up to 15oS latitude. Therefore, East-West-oriented buildings presented lower generation in all states, including those situated South of 15oS, due to both to lower solar availability and slightly higher energy consumption. In general, electricity demand was the main aspect determining the extent to which PV systems can supply household needs. In states where average consumption per unit is below 200kWh/month, corner apartments can supply at least 70% of demand in all cases, provided that one façade faces North. Corner apartments with a South-facing façade can also achieve this level of contribution in Northern and Northeastern states when consumption remains below 200kWh/month. In Central and Southern states, the same units typically met around 60% of energy demand.

Center apartments achieve the best performance when they have East and West-façades in the building-oriented North-South. In these cases, larger zenith angles between the sun and PV modules during morning and afternoon hours enhance energy generation. Although solar radiation peaks at midday, the smaller incidence angle reduces module performance, and even the lower winter sun does not compensate for the advantage of East and West façades. South-facing center apartments showed the lowest performance but still contribute between 18% to 64% of the energy demand, which is an important supplementary share that complements the generation of better-oriented PV systems within the same building.

Scenario 2 (Table 3) further reinforces the favorable relation between photovoltaic façade generation and residential consumption, as it assumes two occupants per apartment. The simulations indicated that not only could 90% of apartments generate more than 70% of their electricity demand, but also that 62% of the cases could fully meet household consumption. All states presented at least one apartment configuration capable of achieving net-zero or surplus generation. In several states, such as Pará, Ceará, Paraíba, Pernambuco, Alagoas, Sergipe, Bahia, and Minas Gerais, any apartment orientation could meet the demand, except for central units facing South.

Table 3: Scenario 2 – Contribution of apartment photovoltaic façade to the energy demand of two occupants per unit, considering per capita demand

Brazilian States	Two occupants demand (kWh)	Building North-South orientated						Building East-West orientated					
		Corner N-E	Corner E-S	Corner S-W	Corner W-N	Center East	Center West	Corner N-E	Corner E-S	Corner S-W	Corner W-N	Center North	Center South
Roraima	162,12	82%	77%	77%	106%	65%	65%	78%	72%	72%	78%	49%	41%
Amapa	142,90	88%	88%	87%	117%	72%	71%	83%	83%	83%	83%	50%	50%
Pará	100,65	146%	141%	142%	182%	115%	116%	141%	135%	136%	142%	90%	83%
Maranhão	113,50	128%	122%	124%	162%	100%	103%	125%	116%	118%	126%	81%	70%
Amazonas	102,87	140%	132%	134%	176%	108%	110%	136%	126%	127%	138%	89%	76%
Ceará	101,62	154%	146%	148%	188%	121%	123%	148%	139%	140%	150%	95%	83%
Piauí	120,58	133%	121%	122%	160%	102%	104%	129%	114%	115%	130%	85%	65%
Rio Grande do Norte	113,58	140%	133%	133%	170%	111%	111%	135%	125%	126%	136%	86%	74%
Paraíba	110,25	145%	133%	134%	174%	111%	113%	141%	125%	126%	142%	93%	73%
Pernambuco	100,02	156%	145%	147%	191%	121%	124%	152%	137%	138%	153%	99%	80%
Rondônia	148,22	105%	93%	77%	110%	79%	60%	104%	87%	75%	92%	70%	49%
Alagoas	97,28	161%	148%	150%	196%	124%	126%	157%	139%	141%	159%	104%	81%
Acre	119,20	121%	106%	108%	150%	89%	91%	120%	100%	101%	121%	84%	59%
Tocantins	143,12	116%	99%	100%	136%	86%	88%	115%	92%	93%	116%	80%	50%
Sergipe	107,87	151%	135%	135%	179%	115%	115%	148%	126%	126%	148%	99%	71%
Bahia	89,53	177%	156%	156%	211%	134%	135%	174%	145%	146%	174%	117%	81%
Mato Grosso	179,78	92%	76%	76%	107%	67%	67%	92%	70%	70%	92%	64%	37%
Distrito Federal	135,25	124%	100%	101%	142%	89%	89%	125%	93%	93%	125%	89%	49%
Goiás	158,53	103%	81%	82%	119%	72%	73%	103%	75%	76%	104%	75%	40%
Minas Gerais	115,10	147%	113%	115%	167%	101%	103%	149%	104%	105%	150%	110%	54%
Espírito Santo	135,33	119%	95%	95%	138%	83%	84%	120%	87%	87%	120%	87%	46%
Mato Grosso do Sul	143,47	118%	92%	93%	134%	82%	83%	119%	84%	85%	119%	87%	44%
Rio de Janeiro	125,88	123%	97%	97%	144%	86%	86%	124%	89%	90%	124%	91%	47%
São Paulo	166,00	94%	73%	74%	110%	64%	66%	95%	68%	69%	96%	71%	37%
Paraná	139,18	108%	86%	85%	127%	75%	74%	109%	79%	79%	109%	81%	43%
Santa Catarina	173,07	92%	70%	71%	106%	62%	63%	94%	64%	65%	94%	70%	34%
Rio Grande do Sul	154,38	103%	78%	79%	119%	69%	70%	105%	72%	72%	106%	79%	38%

In the North-South-oriented building model, corner apartments with North and West façade achieved the highest generation levels, surpassing 105% of the energy demand in all locations and reaching up to 211% at Bahia. Among Northern and Northeastern states, only Roraima, Amapá and Rondônia showed limitations, where net-zero energy demand was attained exclusively by North-West-orientated corner units. In the East-West-oriented model, all states met or exceeded the household demand except Roraima and Amapá, which still achieved approximately 80% coverage.

Center apartments also showed notable improvements under this lower-consumption scenario, regardless of building orientation. These results demonstrated that households with fewer occupants, or with higher energy efficiency, present highly favorable performance when using BIPV at façades. In 23 states, a North-oriented façade could supply more than 70% of residential demand. In contrast, Roraima and Amapá achieved around 50%, while Rondônia and Mato Grosso reached slightly above 60%, all corresponding to average consumption levels exceeding 154 kWh/month.

South-facing façades presented more variable contributions, ranging from 33% to 82%. Contributions below 50% were found in states with higher energy demand and in the Central and Southern regions, where solar irradiation levels are lower. Nevertheless, South façades achieved contributions above 70% in Northern states with monthly energy demands below 120kWh and tilt irradiance levels above 5.3 kWh/m²day. In East-West orientated buildings, center apartments with East or West-facing façades also reached more than 70% of demand in 22 states, except in those with higher consumption rates or lower irradiation values typical of Southern Brazil.

Scenario 3 (Table 4) considers the per capita electricity demand to simulate an apartment occupied by four residents. The results are similar to those of Scenario 1, but more restrictive. In this scenario, 70% of demand was met in only 17% of all cases, and full demand was achieved in just five out of 324 simulations. These five apartments correspond to corner units with West-North façades in the states of Pará, Ceará, Pernambuco, Alagoas and Bahia.

Table 4: Scenario 3 - Contribution of apartment photovoltaic façade to the energy demand of four occupants per unit, considering per capita demand

Brazilian States	Four occupants demand (kWh)	Building North-South orientated						Building East-West orientated					
		Corner N-E	Corner E-S	Corner S-W	Corner W-N	Center East	Center West	Corner N-E	Corner E-S	Corner S-W	Corner W-N	Center North	Center South
Roraima	324,2	41%	39%	38%	53%	33%	33%	39%	36%	36%	39%	24%	21%
Amapa	285,8	44%	44%	43%	59%	36%	35%	42%	42%	41%	41%	25%	25%
Pará	201,3	73%	71%	71%	91%	57%	58%	70%	67%	68%	71%	45%	41%
Maranhão	227,0	64%	61%	62%	81%	50%	51%	62%	58%	59%	63%	41%	35%
Amazonas	205,7	70%	66%	67%	88%	54%	55%	68%	63%	63%	69%	45%	38%
Ceará	203,2	77%	73%	74%	94%	61%	62%	74%	69%	70%	75%	47%	41%
Piauí	241,2	66%	60%	61%	80%	51%	52%	65%	57%	57%	65%	42%	33%
Rio Grande do Norte	227,2	70%	66%	67%	85%	55%	56%	68%	63%	63%	68%	43%	37%
Paraíba	220,5	72%	66%	67%	87%	56%	57%	71%	63%	63%	71%	46%	37%
Pernambuco	200,0	78%	73%	74%	95%	61%	62%	76%	68%	69%	77%	49%	40%
Rondônia	296,4	53%	47%	39%	55%	40%	30%	52%	44%	38%	46%	35%	25%
Alagoas	194,6	81%	74%	75%	98%	62%	63%	79%	70%	70%	79%	52%	41%
Acre	238,4	61%	53%	54%	75%	44%	45%	60%	50%	51%	61%	42%	29%
Tocantins	286,2	58%	49%	50%	68%	43%	44%	58%	46%	47%	58%	40%	25%
Sergipe	215,7	76%	67%	67%	89%	58%	58%	74%	63%	63%	74%	49%	35%
Bahia	179,1	89%	78%	78%	106%	67%	67%	87%	73%	73%	87%	58%	41%
Mato Grosso	359,6	46%	38%	38%	53%	34%	34%	46%	35%	35%	46%	32%	19%
Distrito Federal	270,5	62%	50%	50%	71%	44%	45%	62%	46%	46%	63%	45%	25%
Goiás	317,1	51%	41%	41%	59%	36%	36%	52%	38%	38%	52%	38%	20%
Minas Gerais	230,2	73%	57%	57%	84%	51%	52%	74%	52%	52%	75%	55%	27%
Espírito Santo	270,7	60%	47%	48%	69%	42%	42%	60%	44%	44%	60%	44%	23%

Mato Grosso do Sul	286,9	59%	46%	47%	67%	41%	42%	59%	42%	43%	60%	43%	22%
Rio de Janeiro	251,8	62%	49%	49%	72%	43%	43%	62%	45%	45%	62%	45%	24%
São Paulo	332,0	47%	37%	37%	55%	32%	33%	48%	34%	34%	48%	35%	18%
Paraná	278,4	54%	43%	42%	63%	37%	37%	55%	40%	39%	54%	40%	22%
Santa Catarina	346,1	46%	35%	35%	53%	31%	32%	47%	32%	32%	47%	35%	17%
Rio Grande do Sul	308,8	52%	39%	39%	59%	35%	35%	53%	36%	36%	53%	40%	19%

This scenario represents the highest energy consumption level, exceeding that of Scenario 1, which was based on unit consumer data. These findings highlight that the typical four-person, two-bedroom configuration may not fully reflect actual households demand in Brazil. This study adopted the two-bedroom layout as an average reference; moreover, Brazilian dwellings vary considerably in size, number of bedrooms, and occupancy rates, which is another limitation of this work.

It was noticed that the states of Rondônia, Amapá and Amazonas presented lower average consumption when limited to four residents, suggesting that households in these regions might include large family configurations. States such as Pará, Maranhão, Rondônia, Acre and Distrito Federal showed consumption patterns similar to Scenario 1, with values from Scenario 3 only up to 30% higher than the per-unit average. Other states exhibited even greater differences, ranging from 30% to 60% higher than Scenario 1. This discrepancy may reflect demographic differences, with smaller household sizes in many Brazilian states: such as Ceará, Piauí, Rio Grande do Norte, Paraíba, Pernambuco, Alagoas, Tocantins, Sergipe, Bahia, Mato Grosso, Goiás, Minas Gerais, Espírito Santo, Mato Grosso do Sul, Rio de Janeiro, São Paulo, Paraná, Santa Catarina and Rio Grande do Sul. Socioeconomic disparities also can cause these differences since high-income families have elevated energy consumption, while some low-income households still lack access to electricity.

For the North-South oriented building, corner apartments facing North-West (55% to 105%) performed best, followed by North-East corner units (40% to 88%). South-facing corners units performed slightly worse: East-south façades generated 35% to 77% and West-South façades, 38% to 78%. Center apartment units with East or West façades achieved intermediate results, ranging from 30 to 60%.

Regarding the East-West oriented building, apartments’ performance was comparable but slightly overall. Corner units facing North-West and North-East achieved between 39% and 87% of demand, while South-West and South-East corners reached 32% to 72%. Center apartments with North-facing façades performed better (24% to 58%) than those facing South (16% to 41%).

As a result of the three scenarios, façade orientation, the number of installed PV modules, and residential energy consumption are the key factors to determine the contribution of façade-integrated photovoltaic systems. Brazil solar irradiation showed minor impact, as it is fairly consistent across the country, ranging from 4.41 to 5.77kWh/m2day. Apartments with two external façades, corner units case, demonstrated the best performance, indicating that tower buildings, with four apartments per floor and semi-detached houses, would exhibit similar behavior. Detached houses, with three external façades, are expected to perform even better. This suggests that social housing projects designed with these configurations could enhance the technical and economic viability of façade-integrated PV systems.

Furthermore, this study focused on two-bedroom apartments, with Scenario 3 representing the average occupancy condition. However, it can be assumed that residential units with more bedrooms would also have greater façade area available. As illustrated in Figure 2, each additional bedroom increases the façade surface sufficiently to accommodate one or two extra PV modules. This additional area could be integrated into the available façade space considered in the two-bedroom configuration, further improving the system´s generation potential.

4. Conclusions

This study evaluated the potential of photovoltaic façades to meet residential electricity demand in Brazil, using multi-family social housing buildings. The simulations used a standardized linear social housing building model, considering its length aligned with North-South and East-West orientations. The study simulated just the floor typology with two-bedroom apartments; four at the corners and four at the center of the building. As the two center units were equal, the simulation considered only six apartment configurations. These six configurations were simulated in two building orientations and for all the 27 Brazilian States. Besides that, each state had its solar irradiation estimated for each façade orientation. The energy demand data was collected for each state and considered three scenarios: average consumption of a household unit; per capita consumption for two occupants, and per capita consumption for four occupants.

The solar irradiation data for each of the 27 Brazilian states demonstrated that it does not vary significantly, at an average of 5.1 kWh/m² day, besides its latitude range from 2.89oN to 29.94oS. The façades also presented regular performance with an average of 2.6 kWh/m²day at North, East and West. South façades presented the minor number with an average of 1.7kWh/m² per day. It demonstrates the valuable potential of Brazilian façades across the country, with 3 orientations, and every angle between them producing half the energy produced by the best orientation in each location. Although 50% could be seen as a conservative value, façades do not compromise any roof maintenance and could be a complementary element to reach the net-energy goals. In addition, electricity consumption per unit presented higher variation, around 200kWh/month, with some states consuming more than three times the others. The higher values were found in very Northern states, with more prevalence of heat and humidity, and lower wind rates.

In Scenario 1, which considered average residential consumption, 48% of façades generated more than 70% of the required electricity, and 25% could fully meet the demand. Corner apartments showed the best performance, particularly those facing North and West, with generation exceeding 70% of consumption in 24 of the 27 states. Buildings oriented North–South had superior results due to larger East and West façades, which receive higher radiation in cities up to 15° S latitude.

Scenario 2, with reduced demand equivalent to two occupants per apartment, presented the most favorable results. Ninety percent of apartments could supply more than 70% of the energy demand, and 62% could meet it entirely. In this scenario, almost all states had at least one apartment orientation capable of satisfying full demand, and North–West corner units could even generate up to 211% of consumption in Bahia. Only Roraima, Amapá, and Rondônia showed limitations. These results highlight that more efficient households can easily reach self-sufficiency with PV façades.

In Scenario 3, which simulated higher consumption from four residents, only 17% of apartments achieved 70% of their demand, and just five of the 324 simulations reached full coverage—all in North–West-oriented corner units located in Pará, Ceará, Pernambuco, Alagoas, and Bahia. This scenario confirms that higher occupancy and energy demand considerably reduce the photovoltaic contribution, though façades still represent a significant complementary source.

Comparative analysis of the three scenarios emphasizes that façade orientation, the number of installed PV modules, and residential energy demand are the key determinants of system performance. While solar irradiation is relatively uniform across Brazil, architectural configuration strongly guides the photovoltaic contribution. Corner apartments achieved the highest generation, followed by center units with East or West orientations. These results suggest that semi-detached and detached houses could yield proportionally higher energy generation, as they have greater façade area.

In summary, this study focused on the application of PV in Brazilian building façades and demonstrated that residential units with less than two residents generated sufficient energy to meet the demand. In addition, in some cities the PV-façades can meet demand even for four residents. Residential energy consumption varies across Brazilian regions, showing no direct correlation to latitude or climate, even if solar radiation levels are generally higher in the North and Northeast regions. Cities near the Equator tend to experience greater irradiation losses on vertical surfaces compared to those at higher latitudes, presenting higher electricity consumption. These findings reinforce the photovoltaic potential of Brazilian façades as reported by Shono et. al (2023) in other countries.

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