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ENERGY PERFORMANCE OF RESIDENTIAL BUILDINGS ADJACENT TO HIGH-RISE BUILDINGS: SHADING EFFECTS ON EXTREME TEMPERATURE DAYS

DESEMPENHO ENERGÉTICO DE EDIFÍCIOS RESIDENCIAIS ADJACENTES A EDIFICAÇÕES ALTAS: EFEITOS DO SOMBREAMENTO EM DIAS DE TEMPERATURAS EXTREMAS

DESEMPEÑO ENERGÉTICO DE EDIFICIOS RESIDENCIALES ADYACENTES A EDIFICIOS ALTOS: EFECTOS DEL SOMBREADO EN DÍAS DE TEMPERATURAS EXTREMAS

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ABSTRACT

This study investigates how the insertion of a high-rise building modifies the electricity consumption of adjacent buildings under different thermal conditions. The research was conducted in a consolidated urban area of Santos-SP, Brazil, considering a 112-meter-high reference building and six adjacent residential buildings. Three urban scenarios were simulated using EnergyPlus. The analysis focused on the hottest and the coldest days identified in the climate file used. Daily electricity consumption was analyzed for cooling, heating, and artificial lighting, together with the duration of additional shading caused by the reference building. The results showed that, on the hottest day, total electricity consumption was lower with the reference building than in the scenario without it, with reductions ranging from 7.90% to 28.88%. On the coldest day, the response was heterogeneous, with both reductions and increases in electricity consumption. Additional shading varied among buildings and did not show a consistent relationship with changes in electricity consumption.

KEYWORDS: *High-rise buildings. Urban shading. Electricity consumption. Extreme temperatures. Adjacent buildings.*

RESUMO

Este estudo investiga como a inserção de um edifício alto modifica o consumo de eletricidade de edifícios residenciais adjacentes em diferentes condições térmicas. A pesquisa foi realizada em uma área urbana consolidada de Santos-SP, Brasil, considerando um edifício de referência de 112 metros de altura e seis edifícios adjacentes. Foram simulados três cenários urbanos no EnergyPlus. A análise concentrou-se no dia mais quente e no dia mais frio identificados no arquivo climático utilizado. O consumo diário de eletricidade foi analisado para resfriamento, aquecimento e iluminação artificial, em conjunto com a duração do sombreamento adicional causado pelo edifício de referência. Os resultados indicaram que, no dia mais quente, o consumo total de eletricidade dos seis edifícios adjacentes foi inferior no cenário com a presença do edifício de referência, com reduções entre 7,90% e 28,88% em comparação ao cenário sem essa edificação. No dia mais frio, a resposta foi heterogênea, com reduções e acréscimos no consumo

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de eletricidade. O sombreamento adicional variou entre os edifícios e não apresentou relação consistente com as alterações no consumo de eletricidade.

PALAVRAS-CHAVE: Edifícios altos. Sombreamento urbano. Consumo de eletricidade. Temperaturas extremas. Edifícios adjacentes.

RESUMEN
Este estudio investiga cómo la inserción de un edificio alto modifica el consumo de electricidad de los edificios residenciales adyacentes en diferentes condiciones térmicas. La investigación se llevó a cabo en una zona urbana consolidada de Santos-SP, Brasil, considerando un edificio de referencia de 112 metros de altura y seis edificios adyacentes. Se simularon tres escenarios urbanos en EnergyPlus. El análisis se centró en el día más cálido y el día más frío identificados en el archivo climático utilizado. Se analizó el consumo eléctrico diario para refrigeración, calefacción e iluminación artificial, junto con la duración adicional del sombreado causado por el edificio de referencia. Los resultados indicaron que, en el día más caluroso, el consumo total de electricidad de los seis edificios adyacentes fue menor en el escenario con el edificio de referencia presente, con reducciones entre el 7,90% y el 28,88% en comparación con el escenario sin este edificio. En el día más frío, la respuesta fue heterogénea, con reducciones y aumentos en el consumo eléctrico. El sombreado adicional varió entre edificios y no mostró una relación consistente con los cambios en el consumo eléctrico.

PALABRAS CLAVE*: Edificios altos. Sombreado urbano. Consumo eléctrico. Temperaturas extremas. Edificios adyacentes.*

1. INTRODUCTION

Shading caused by a high-rise building may lead to different energy responses in adjacent buildings. This response may vary according to climatic conditions. During hot periods, the reduction in solar gains may contribute to lower cooling consumption, whereas under cold conditions, it may reduce the solar gains available for heating. At the same time, reduced daylight availability may increase electricity consumption for lighting.

The insertion of a high-rise building in urban areas can be evaluated in several ways. The study aims to understand how such an intervention in a consolidated urban area modifies the energy response of adjacent buildings under different climatic conditions.

The study was conducted in a neighborhood in the city of Santos, Brazil. The area is part of a consolidated coastal urban area characterized by multifamily residential buildings of different heights, orientations, and spatial configurations. Before 1998, the Santos Zoning Code allowed buildings up to 15 floors, equivalent to approximately 45 meters. After that year, building height was no longer limited, making it possible to construct buildings taller than 100 meters (Santos, 1998). This heterogeneous urban context was selected to investigate how the insertion of a high-

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rise building can modify the electricity consumption of other buildings already present in the urban area.

Santos is a city located in a hot and humid climate at 23°S latitude, characterized by high relative humidity throughout the year and seasonal variations in air temperature. According to CIIAGRO (2026), average temperatures reach approximately 26°C in summer and drop to 19°C in winter. The obstruction of direct solar radiation caused by high-rise buildings can modify solar radiation conditions on building facades, potentially affecting cooling, heating and artificial lighting of adjacent buildings. These effects also depend on facade orientation, as well as geometry and relative positions of adjacent buildings.

The research seeks to answer the following question: How does the insertion of a high-rise building affect the electricity consumption of adjacent buildings on the hottest and coldest days? The objectives are: a) to compare the electricity consumption of the adjacent buildings with and without the presence of the high-rise building in the urban context, and b) to analyze the contributions of cooling, heating, and artificial lighting to the observed energy response.

Although previous studies have investigated inter-building effects on building energy performance, further investigation is needed into how the presence of a high-rise building affects the energy consumption of adjacent residential buildings under different thermal conditions. This study investigates the additional effect of inserting a 112-meter-high building into an existing urban context on the electricity consumption of six adjacent residential buildings. Using comparative EnergyPlus simulations under selected hot and cold conditions, the study examines changes in total electricity consumption, energy end uses, and equivalent shading duration.

This analysis is relevant because the effects of inserting high-rise buildings into consolidated urban contexts are not restricted to the buildings themselves. A new building can modify the environmental conditions and energy consumption of existing buildings in its surroundings. Understanding these variations can contribute to a more comprehensive assessment of the energy effects associated with the insertion of high-rise buildings in consolidated urban areas.

Solar radiation is one of the main environmental factors affecting the thermal and luminous performance of buildings. The amount of solar radiation received by a surface varies according to solar position, atmospheric conditions, surface orientation and inclination, and the presence of surrounding obstructions. Direct, diffuse, and reflected radiation contribute to the total radiation incident on building surfaces and influence thermal and daylight conditions.

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The relationship between solar radiation and buildings is also influenced by latitude. Latitude influences the Sun's apparent trajectory and solar altitude, affecting the amount of solar radiation received by building surfaces. At lower latitudes, the higher solar altitude produces shorter projected shadows. At middle and high latitudes, the solar apparent trajectory is more inclined, producing longer shadows, especially during the winter. The effect of an obstruction depends not only on the geometry of the buildings but also on the solar conditions of the location.

In urban areas, the geometry and the arrangement of buildings create different patterns of solar obstruction and shadow projection. Shading occurs when one building obstructs part of the solar radiation that would reach the surfaces and openings of another building. The extent of this obstruction depends on the relative position, height, orientation, and distance between buildings, as well as the solar position, latitude, and climatic conditions. Urban shading is not a constant condition, but a spatial and temporal phenomenon resulting from the interaction between solar geometry and the built environment.

The energy implications of shading are not unidirectional. Shading may decrease the cooling demand in hot climates by reducing direct solar gains. In cold climates, the reduction in solar exposure may limit the availability of daylight and solar gains, potentially increasing the demand for artificial lighting and heating.

In their study conducted at latitude 55°N, Strømann-Andersen and Sattrup (2011) demonstrated through thermal and daylighting simulations that changes in urban density and in the relationship between building height and street width affect both heat losses and access to daylight. Higher density reduced heat losses but also restricted daylight availability, increasing the demand for artificial lighting and heating. Their findings demonstrate that changes in urban configuration can produce different effects on different energy uses rather than a single uniform response.

Pisello *et al.* (2014) investigated the influence of surrounding buildings on primary energy consumption for heating, cooling and artificial lighting in a real urban context at latitude 43°N. The study gave particular attention to shading and showed that the effect of surrounding buildings differed according to building orientation and energy end use. The authors concluded that adjacent buildings should be considered when evaluating building energy performance, because urban context can modify the energy response of the building under analysis.

Han *et al.* (2017) highlighted the relationship between daylighting conditions and building energy consumption in their study conducted at latitudes of 25°N, 38°N, and 45°N. Among the

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mechanisms of the interaction between buildings, shading is particularly important for energy performance. The authors concluded that excluding shading from building energy simulations may overestimate or underestimate electricity consumption. In their simulations, total energy consumption increased up to 30% when shading from the adjacent buildings was not considered in the energy consumption analysis.

Nugroho *et al.* (2022) demonstrated that the presence of a high-rise building alters shadow patterns and conditions in its surroundings. These effects are not uniform throughout urban space and may also depend on climatic conditions. The influence of the surrounding urban context is not limited to urban density. The relative position of buildings, their orientation, and their geometric characteristics determine different solar exposure conditions. Rostami *et al.* (2024) identified relationships between morphological parameters, solar radiation, energy consumption, and daylight availability, reinforcing the need to consider these variables in an integrated manner.

2. MATERIALS AND METHODS

A district in the city of Santos, Brazil, was chosen for the study. This district features a heterogeneous mix of building uses and heights, and has been undergoing a massive verticalization process. A 112-meter-high building, identified as the Reference Building (RB), was selected to investigate the effects of its insertion into the urban context. Six residential buildings around the RB were selected as adjacent buildings. They occupy different positions relative to the RB and consequently present different solar exposure and shading relationships. The selected buildings differ in height, floor area, and orientation. This configuration makes it possible to analyze the response to the insertion of the same high-rise building in receptors with different characteristics, while keeping the RB and the surrounding urban context constant. The urban configuration was represented using cadastral data provided by Santos Mapeada (2025). The site plan, available in DWG format, was used as the geometric basis for representing the existing buildings and their spatial relationships, as shown in Figure 1. The characteristics of adjacent buildings are described in Table 1.

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Table 1. Adjacent building characteristics.

Adjacent building	Position	Number of floors	Floor area (m²)	Orientation	Building height (m)
Building 1	East	11	387.79	E-W	36
Building 2	East	4	333.23	E-W	14
Building 3	Southeast	4	207.03	N-S	14
Building 4	South	5	375.80	N-S	16
Building 5	Southwest	12	584.32	N-S	36
Building 6	West	26	684.00	E-W	80

Source: Authors, 2026.

Figure 1. Site plan



Source: Adapted by the authors from Santos Mapeada (2025).

The floor area reported in Table 1 corresponds to the area of a single floor of each adjacent building. The total built floor area of each building can be obtained by multiplying this area by the number of floors. The total built floor area was used to normalize daily electricity consumption, expressed in kWh/m²·day.

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Buildings were modeled using SketchUp and EnergyPlus 9.6. The site plan was imported into SketchUp, preserving the original spatial coordinates. The models reproduced the building geometries and the spatial relationships relevant to solar exposure and shading. The geometry was simplified while preserving the characteristics relevant to the analysis, including position, external volume, height, and openings. Each floor was represented as an independent thermal zone, with a floor-to-ceiling height of 3.0 m. Architectural elements considered irrelevant to the shading analysis, such as small balconies, were not included in the models.

In order to isolate the effect of shading, the same construction, material, climatic, and operational parameters were applied to all simulation scenarios. The external walls were represented by concrete blocks with mortar, with a thickness of 0.19 m, thermal conductivity of 1.75 W/m·K, specific heat of 1,000 J/kg·K, density of 2,200 kg/m³, and solar absorptance of 0.58. The roof was represented as a concrete slab with thermal conductivity of 1.75 W/m·K, specific heat of 1,000 J/kg·K, density of 2,200 kg/m³, and solar absorptance of 0.58. Window areas were defined according to actual dimensions of each building. Clear glazing was used with a thermal transmittance of 5.7 W/m²·K and a solar heat gain coefficient of 0.87. Cooling and heating setpoints were defined as 26°C and 18°C, respectively, and the air conditioning system was represented by a coefficient of performance (COP) of 3.24. Internal heat gains from occupants and equipment were excluded. Air change rate was kept constant at 1 air change per hour in all scenarios. These constitute methodological simplifications and do not reproduce the full variability of actual occupancy and operation.

Daylighting control was modeled using sensors positioned 1.0 meter above the floor and 3.0 meters from the openings. Artificial lighting was available between sunrise and sunset and was activated when the illuminance measured at the control sensor fell below 200 lux, with on/off control. The installed lighting power density was set to 3 W/m². This choice was adopted to focus the analysis on the effects of shading and avoid the introduction of occupancy and equipment-use patterns that could not be standardized across the buildings. The influence of occupant and equipment internal gains on actual residential scenarios is a limitation of the study. The simulations were not calibrated or validated against measured building consumption. Therefore, the simulated results are used for comparative analysis among the modeled scenarios under the assumptions and boundary conditions adopted in this study.

Santos is classified as having an *Af* climate according to the Köppen-Geiger classification (Peel, Finlayson and McMahon, 2007). This climate is characterized by high temperatures, high

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relative humidity, and high precipitation throughout the year, with no defined dry season. The mean annual temperature is 23°C. The climate file used in the simulations was BRAS_SP_Santos.AB.838180_TMYx.2009-2023 provided by Climate.OneBuilding Organization (2025). Although the weather file is derived from official meteorological data, it represents a typical meteorological year rather than the actual chronological sequence of weather conditions observed during a specific year. Therefore, the selected dates represent the hottest and coldest days identified within the weather file used in simulations. They should not be interpreted as the most extreme meteorological events historically recorded in Santos.

Three climatic conditions were selected: hottest day, coldest day, and a typical day. The typical condition corresponds to April 29th, which belongs to the period identified in the file metadata as “Typical – week near average annual” from April 23rd to 29th. The coldest day corresponds to July 12th, which belongs to the period identified in the file metadata as “extreme – week near annual minimum”, from July 9th to 15th. July 12th was selected as the coldest day because it represented the lowest daily minimum and maximum outdoor air temperatures in the weather file. The hottest condition corresponds to September 20th, which represents the hottest day in the climate file. It was selected as the hottest day based on the highest daily minimum and maximum outdoor temperatures in the weather file. Although the weather file metadata points to December 25th to 31st as the hottest week, the highest temperatures were recorded on September 20th. These conditions were selected to represent different thermal states in the climate file and to determine whether the effect of the insertion of the high-rise building varies according to external conditions. The selected conditions are characterized in Table 2. The shadows cast by the RB are shown in Figure 2.

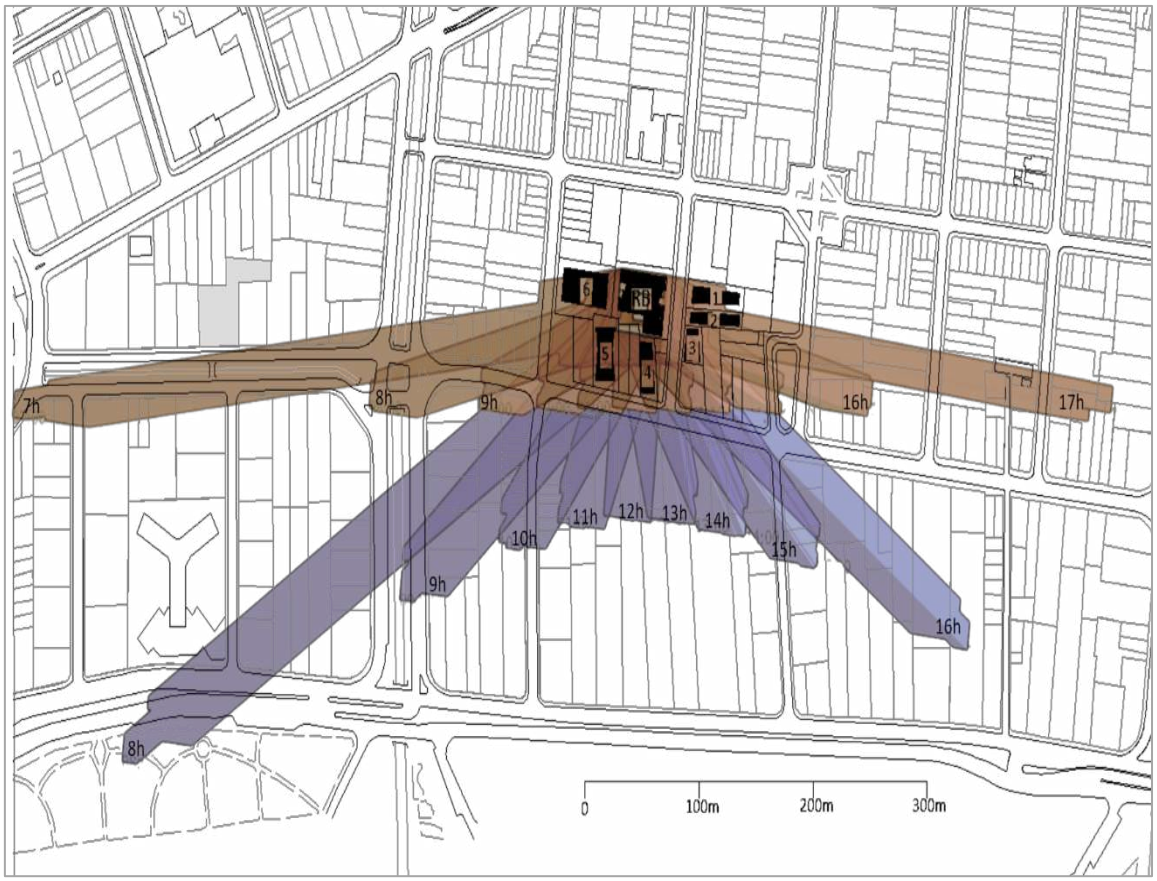
Table 2. Climatic data for selected days.

Condition	Date	Minimum temperature °C	Maximum temperature °C	Mean temperature °C	Daily global horizontal solar radiation Wh/m²
Hottest	Sep 20th	24	39	29.09	6,334
Typical	Apr 29th	19	25	21.65	3,767
Coldest	Jul 12th	12	18	14.99	3,584

Source: prepared by authors based on the climate file BRAS_SP_Santos.AB.838180_TMYx.2009-2023.

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Figure 2. Shadows cast by the Reference Building over neighboring buildings on July 12th (blue) and September 20th (yellow)



Source: Authors, 2026.

Three urban scenarios were simulated for each of the six adjacent buildings:

SC1 – Isolated: the adjacent building is isolated, as if none of the buildings were constructed. It is the control condition.

SC2 – Urban context with the high-rise building: the receptor building was simulated within the existing urban context, including RB at its full height of 112 m.

SC3 – Urban context without the high-rise building: the receptor building was simulated within the same urban context as SC2, but without the presence of RB.

All construction, material, climatic, and operational parameters were kept constant between scenarios. Thus, the SC3–SC2 comparison isolates the change associated with the

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presence of RB in the existing urban context. This study investigates the effect of inserting a high-rise building into an existing urban context, rather than quantifying the overall energy effect of surrounding buildings. The RB is substantially taller than the existing buildings considered in the study, making its additional effect on the adjacent buildings the central focus of analysis.

The EnergyPlus results were analyzed in terms of electricity consumption associated with cooling, heating, and artificial lighting. The analysis was performed for each of the six adjacent buildings, under the two urban scenarios and the three selected climatic conditions.

For each building and simulation scenario, the hourly electricity consumption associated with cooling, heating, and artificial lighting was aggregated over the 24 hours of each selected day. The resulting daily consumption was normalized by the floor area of the respective building and expressed in kWh/m²·day. This normalization allowed comparisons between buildings with different floor areas.

The main comparison was performed between SC3 and SC2, representing the urban context without and with the RB, respectively. This comparison was used to quantify the change in electricity consumption associated with the insertion of the 112-meter-high building into the existing urban context.

For each building and climatic condition, the relative variation in daily electricity consumption associated with the insertion of the high-rise building was calculated as follows:

$$\Delta E(SC3,SC2)\ (\%) = [(E_SC2 - E_SC3) / E_SC3] \times 100$$

where E_SC2 and E_SC3 correspond to the daily electricity consumption, expressed in kWh/m²·day, under scenarios SC2 and SC3, respectively. Negative values indicate a reduction in consumption following the insertion of the high-rise building, whereas positive values indicate an increase in electricity consumption. Total daily consumption was analyzed together with its energy end uses (cooling, heating, and artificial lighting) to identify the mechanisms contributing to the response of adjacent buildings to the insertion of the high-rise building. Energy consumption values are presented rounded to three decimal places. Percentage changes were calculated using the original unrounded values to avoid discrepancies arising from rounding.

To quantify the shading duration on each adjacent building, a new simulation was run using the Surface Outside Face Sunlit Fraction output available in EnergyPlus. The shading duration was calculated by summing, over all timesteps, the differences between the sunlit

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fraction in SC1 and that in either SC2 or SC3. The results represent the solar radiation that the wall ceases to receive due to the surroundings, expressed in equivalent hours of full shade. For example, a wall that has 30% of partial shading over a 10-hour period is equivalent to 3 hours of full shade.

Night steps and those facades facing away from the sun do not contribute, as the sunlit fraction is zero in SC1 and in the chosen scenario. Self-shading was also excluded from the results. Only direct radiation was considered. The facade walls were grouped by orientation (north, east, south and west). For each facade, the values were then summed for each building, without accounting for differences in facade area. The indicator represents the total equivalent shading hours across all facades, not an area-weighted average.

3. RESULTS

3.1. Shading associated with the Reference Building

Table 3 and Table 4 present the shading associated with the RB on the coldest day and the hottest day, considering the scenarios SC2 and SC3. The difference between SC2 and SC3 represents the additional shading associated with the presence of the RB.

Table 3. Equivalent full-shading hours on the coldest day - July 12th

Building	SC1 Direct solar radiation (hours)	SC2 Direct solar radiation (hours)	SC3 Direct solar radiation (hours)	SC2 Shading (hours)	SC3 Shading (hours)	Δ SC2 − SC3
Building 1	5h14min	3h46min	3h47min	1h28min	1h27min	0h01min
Building 2	5h15min	0h36min	0h58min	4h39min	4h17min	0h22min
Building 3	5h15min	2h02min	3h49min	3h13min	1h26min	1h47min
Building 4	5h10min	1h38min	3h35min	3h32min	1h35min	1h57min
Building 5	5h15min	0h29min	2h39min	4h46min	2h36min	2h10min
Building 6	5h13min	3h44min	4h10min	1h29min	1h03min	0h26min

Note: Shading duration is expressed as equivalent full-shading hours; it does not represent the duration of a continuous shading event. Source: Authors, 2026.

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Table 4. Equivalent full-shading hours on the hottest day - September 20th

Building	SC1 Direct solar radiation (hours)	SC2 Direct solar radiation (hours)	SC3 Direct solar radiation (hours)	SC2 Shading (hours)	SC3 Shading (hours)	Δ SC2 − SC3
Building 1	5h42min	4h41min	5h15min	1h01min	0h27min	0h34min
Building 2	5h56min	0h53min	2h16min	5h03min	3h40min	1h23min
Building 3	5h53min	2h44min	4h32min	3h09min	1h21min	1h48min
Building 4	5h44min	2h51min	3h53min	2h53min	1h51min	1h02min
Building 5	5h52min	1h56min	3h42min	3h56min	2h10min	1h46min
Building 6	5h52min	3h49min	4h50min	2h03min	1h02min	1h01min

Note: Shading duration is expressed as equivalent full-shading hours; it does not represent the duration of a continuous shading event.

Source: Authors, 2026.

On the coldest day, the additional shading varied from 1 minute in Building 1 to 2h10min in Building 5. Buildings 3, 4, and 5 showed the largest increases in shading duration, whereas Buildings 1, 2, and 6 showed smaller differences.

On the hottest day, the additional shading ranged from 34 minutes in Building 1 to 1h48min in Building 3. Buildings 3 and 5 showed greater additional shading.

The comparison between the two days shows that the additional shading associated with the Reference Building varied both among adjacent buildings and between the analyzed days. Buildings 3 and 5 showed relatively high additional shading on both days, while Buildings 1 and 2 showed comparatively smaller increases.

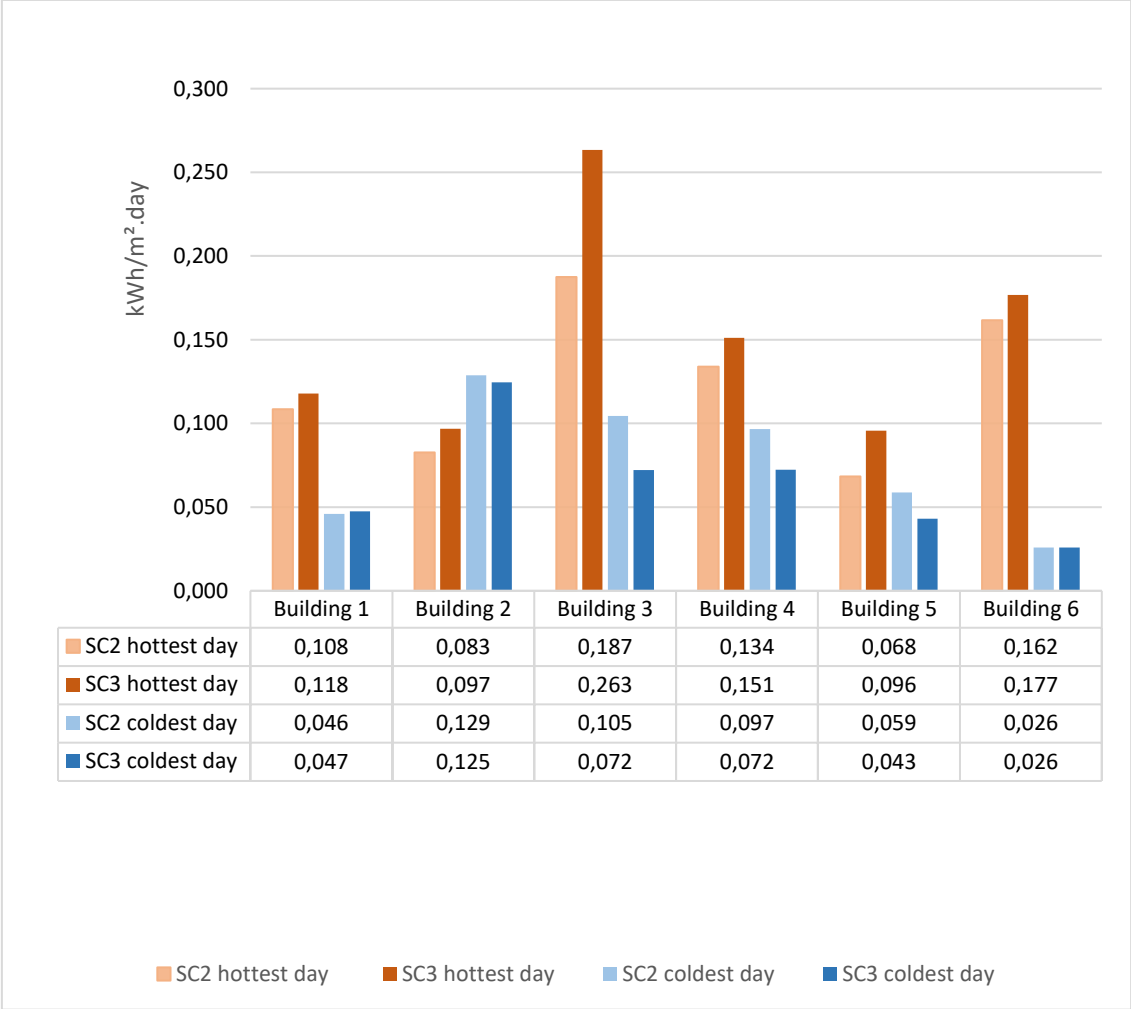
3.2. Total electricity consumption on the hottest and the coldest days

Figure 3 shows the total daily electricity consumption for SC2 and SC3 scenarios for six adjacent buildings on the hottest and the coldest day.

On the hottest day, total daily consumption was lower in SC2 than in SC3 across all six adjacent buildings, as shown in Figure 3, with reductions ranging from 7.90% to 28.88% (Table 5). This variation differed among the adjacent buildings.

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Figure 3. Total daily electricity consumption on peak days in different scenarios, in kWh/m²·day



	Building 1	Building 2	Building 3	Building 4	Building 5	Building 6
SC2 hottest day	0,108	0,083	0,187	0,134	0,068	0,162
SC3 hottest day	0,118	0,097	0,263	0,151	0,096	0,177
SC2 coldest day	0,046	0,129	0,105	0,097	0,059	0,026
SC3 coldest day	0,047	0,125	0,072	0,072	0,043	0,026

Source: Authors, 2026.

Under the coldest day condition, total daily consumption was slightly lower in SC2 than in SC3 in Building 1. It was higher in SC2 than in SC3 for Buildings 2, 3, 4, and 5. In Building 6, the consumption in SC2 and SC3 was almost the same.

Total electricity consumption on this day decreased in Building 1. In contrast, consumption increased in Buildings 2, 3, 4, and 5, with increases from 3.34% to 45.00%. In Building 6, consumption remained almost unchanged (Table 5).

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Table 5. Variation in total electricity consumption

Building	Hottest day	Coldest day
	Δ%	Δ%
Building 1	-7.90	-3.16
Building 2	-14.68	3.34
Building 3	-28.88	45.00
Building 4	-11.42	33.52
Building 5	-28.51	36.45
Building 6	-8.57	0.12

Note: percentages were calculated using original unrounded energy consumption values.
Source: Authors, 2026.

The presence of the RB was associated with a reduction in total daily electricity consumption on the hottest day for all adjacent buildings. On the coldest day, the response was mixed, with a reduction in Building 1 and increases in Buildings 2, 3, 4, and 5. Building 6 showed a negligible increase of 0.12%. The response also varied considerably among the buildings. These differences indicate that the change in total consumption was not uniform across adjacent buildings. The contribution of cooling, heating, and artificial lighting to these variations will be examined in the following section.

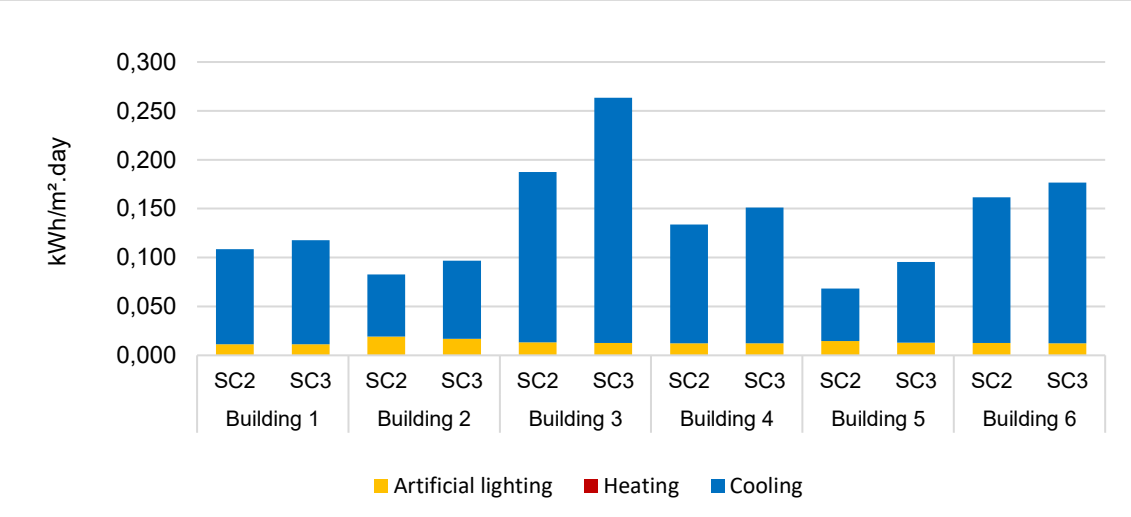
3.3. Energy end uses consumption

The different energy end uses contributed differently to total electricity consumption under the hottest and the coldest day conditions.

On the hottest day (Figure 4), cooling was the main end use in all six adjacent buildings, while heating consumption was zero. Artificial lighting represented a smaller part of the total consumption. Under SC2, cooling consumption ranged from 0.054 kWh/m²·day in Building 5 to 0.174 kWh/m²·day in Building 3. Under SC3, it ranged from 0.080 kWh/m²·day in Building 2 to 0.251 kWh/m²·day in Building 3. In all six buildings, cooling consumption was lower in SC2 than in SC3. Artificial lighting also differed between the scenarios, but the changes were smaller. Lighting consumption was slightly higher in SC2 for Buildings 2, 5, and 6, while it was the same in Buildings 1, 3 and 4 under both scenarios. Table 6 shows detailed results for consumption on the hottest day.

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Figure 4. Energy end use consumption on the hottest day



Source: Authors, 2026.

Table 6. Electricity consumption by end use on the hottest day, in kWh/m²·day.

		Lighting	Cooling	Heating	Total		Lighting	Cooling	Heating	Total
Building 1	SC2	0.011	0.097	0.000	0.108	SC3	0.011	0.107	0.000	0.118
Building 2	SC2	0.019	0.063	0.000	0.082	SC3	0.017	0.080	0.000	0.097
Building 3	SC2	0.013	0.174	0.000	0.187	SC3	0.013	0.251	0.000	0.264
Building 4	SC2	0.012	0.121	0.000	0.133	SC3	0.012	0.139	0.000	0.151
Building 5	SC2	0.014	0.054	0.000	0.068	SC3	0.013	0.083	0.000	0.096
Building 6	SC2	0.013	0.149	0.000	0.162	SC3	0.012	0.165	0.000	0.177

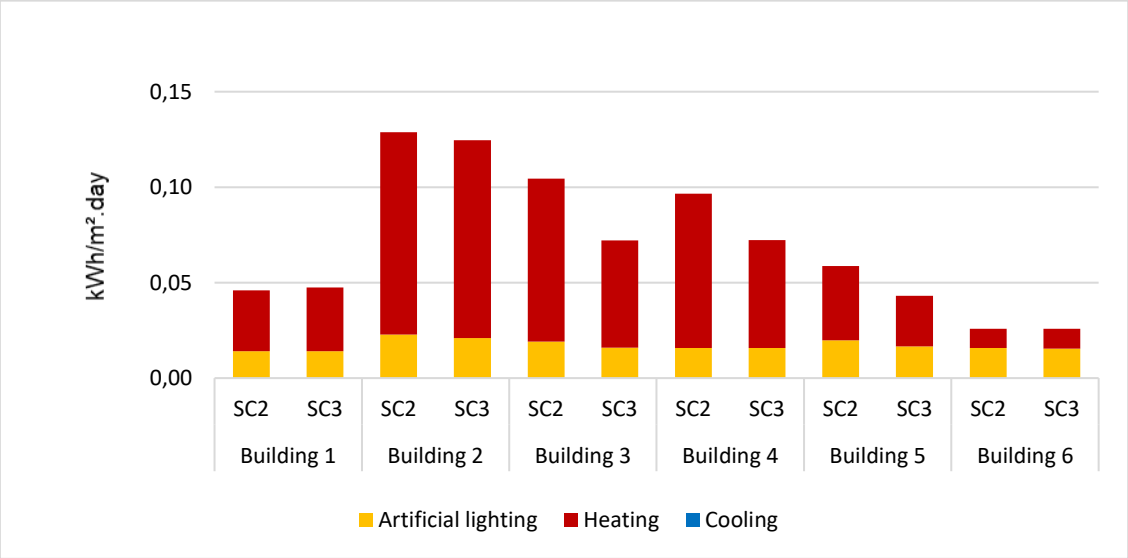
Source: Authors, 2026.

On the coldest day (Figure 5), cooling consumption was zero for all six buildings in both scenarios. Heating was the main use in Buildings 1, 2, 3, 4, and 5. Heating consumption ranged from 0.010 kWh/m²·day in Building 6 to 0.106 kWh/m²·day in Building 2 under SC2. Under SC3, it ranged from 0.010 kWh/m²·day in Building 6 to 0.104 kWh/m²·day in Building 2. The difference between the scenarios was not the same for all buildings. Heating consumption was lower in SC2 for Building 1, while it was higher in Buildings 2, 3, 4, and 5. Building 6 showed no difference among scenarios. Artificial lighting was the main end use for Building 6. Artificial lighting also varied between scenarios, with SC2 values higher than SC3 for Buildings 2, 3, and 5, while the

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values were the same for Buildings 1 and 4. Table 7 shows detailed results for consumption on the coldest day.

Figure 5. Energy end use consumption on the coldest day



Source: Authors, 2026.

Table 7. Electricity consumption by end use on the coldest day, in kWh/m²·day.

		Lighting	Cooling	Heating	Total		Lighting	Cooling	Heating	Total
Building 1	SC2	0.014	0.000	0.032	0.046	SC3	0.014	0.000	0.033	0.047
Building 2	SC2	0.023	0.000	0.106	0.129	SC3	0.021	0.000	0.104	0.125
Building 3	SC2	0.019	0.000	0.085	0.104	SC3	0.016	0.000	0.056	0.072
Building 4	SC2	0.016	0.000	0.081	0.097	SC3	0.016	0.000	0.057	0.073
Building 5	SC2	0.020	0.000	0.039	0.059	SC3	0.017	0.000	0.026	0.043
Building 6	SC2	0.016	0.000	0.010	0.026	SC3	0.016	0.000	0.010	0.026

Source: Authors, 2026.

The energy end use results help explain the differences observed in total electricity consumption under the two extreme temperature conditions. On the hottest day, cooling accounted for the largest share of electricity consumption, whereas heating was the main end

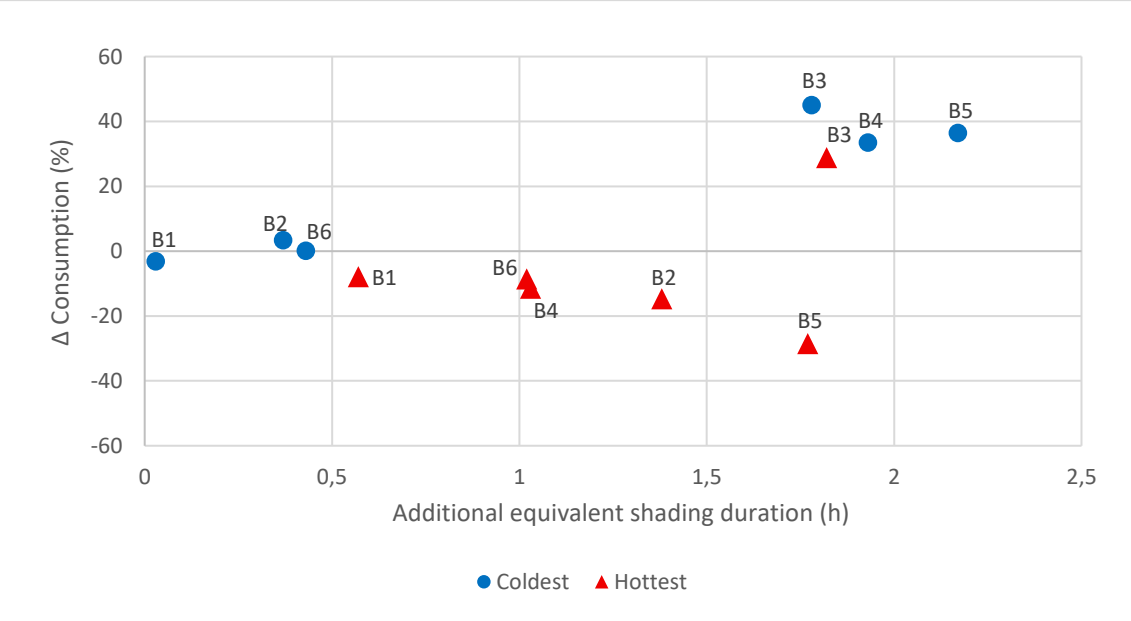
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use on the coldest day. Artificial lighting consumption showed smaller differences between SC2 and SC3.

3.4. Relationship between additional shading and electricity consumption

Figure 6 compares the additional shading duration associated with the RB with the percentage change in total electricity consumption for the six adjacent buildings under the two extreme-day conditions. The results show that additional shading duration was not associated with the direction of the change in electricity consumption. On the coldest day, Buildings 3, 4, and 5 received similar equivalent shading durations, ranging from 1h47min to 2h10min, but showed different variations in total consumption. On the hottest day, all buildings showed reductions in consumption despite differences in equivalent shading duration.

Figure 6. Relationship between additional equivalent shading duration and change in total electricity consumption



Source: Authors, 2026.

The comparison between additional shading duration and electricity consumption indicates that shading alone did not explain the direction or magnitude of the observed energy

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consumption changes. Buildings with similar equivalent shading hours showed different changes in electricity consumption. These findings indicate that the energy response cannot be interpreted from shading duration alone.

4. DISCUSSION

The results demonstrated that the presence of the Reference Building can modify the electricity consumption of adjacent buildings, and that this effect is not uniform. On the hottest day, the presence of the Reference Building was associated with lower total electricity consumption in all six adjacent buildings, while on the coldest day the response varied among the buildings. This result is consistent with previous studies showing that inter-building effects can modify building energy performance by changing solar exposure and, consequently, heating and cooling demands. Studies have shown that the effect of surrounding buildings varies with urban configuration and climatic conditions, indicating that inter-building effects cannot be interpreted independently of the context in which they occur.

The different responses observed between the hottest and the coldest days are related to the predominance of different energy end uses under thermal conditions. On the hottest day, cooling was the main electricity use in all six adjacent buildings. The finding is consistent with the interpretation that reduced solar exposure associated with RB contributed to lower cooling consumption under modeled conditions. However, the shading duration indicator does not quantify the total reduction in incident solar energy, and the individual contribution of shading to the observed changes in electricity consumption cannot be isolated using this indicator alone. On the coldest day, heating became the main electricity end use in five of the six buildings, whereas artificial lighting exceeded heating consumption in Building 6. The reduction in solar exposure associated with the RB occurred under a different thermal demand condition, and the resulting changes in total electricity consumption were not uniform. Heating consumption was higher in Buildings 2, 3, 4, and 5. Artificial lighting also increased in Buildings 2, 3, and 5, but its contribution to total electricity consumption was smaller. These results indicate that the response of total electricity consumption under the modeled cold condition was mainly associated with differences in heating use, particularly in Buildings 3, 4, and 5.

The comparison between additional shading duration and changes in total electricity consumption shows that shading duration alone did not consistently explain the direction of the

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observed changes. On the coldest day, Buildings 3 and 4 had similar additional shading durations, but their total electricity consumption varied differently. Similar additional shading durations did not correspond to proportional changes in total electricity consumption. On the hottest day, all six buildings showed reductions in electricity consumption despite differences in shading duration. The results indicate that equivalent additional shading duration, as defined in this study, was not sufficient to explain changes in total electricity consumption. This does not imply that shading is irrelevant to energy performance; rather, its effects cannot be characterized by shading duration alone.

The results of this study are consistent with previous research. In the simulations for the hottest day, the results showed reductions of 7.90% to 28.88% in total electricity consumption after the insertion of RB. This finding is in line with Strømann-Andersen and Sattrup (2011), whose simulations showed that increased urban density and the resulting obstruction of solar radiation can reduce cooling demand through shading, although the effect on heating and artificial lighting may differ. In the same way, Han *et al.* (2017) found that the energy impact of inter-building shading was greater than that of inter-building reflection and varied across climatic contexts analyzed. It was also shown that shading can increase some energy demands while reducing others. These findings caution against assuming that reduced solar exposure necessarily leads to a uniform effect on total energy consumption. This study similarly demonstrates that the insertion of a high-rise building can modify electricity consumption in adjacent buildings. However, the comparison between additional equivalent shading duration and changes in electricity consumption revealed no consistent relationship.

In this study, the results for the coldest day also illustrate this context dependence. Unlike the hottest day, the six adjacent buildings had different energy responses on the coldest day. Pisello *et al.* (2014) demonstrated that the surrounding urban configuration can modify the energy performance predicted for adjacent buildings. By incorporating lighting energy use into their analysis of inter-building effects, Pisello *et al.* (2014) also demonstrated that these effects cannot be neglected. In this study, it was observed that the contribution of artificial lighting may also influence the total energy response to urban shading, as observed in Building 6 on the coldest day.

In this study, six adjacent buildings differed in their relative positions, orientations, and geometric characteristics with respect to the Reference Building. Accordingly, they showed distinct energy responses to the insertion of the high-rise building. This finding is consistent with

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Nugroho *et al.* (2022), who provided complementary evidence that the geometry and orientation of high-rise buildings influence the thermal conditions of their surroundings.

These results provide quantitative evidence of how the insertion of a high-rise building can affect existing buildings under different thermal conditions in a hot and humid coastal context. The results also demonstrated the importance of evaluating the energy effects of high-rise buildings within the specific urban context in which they are inserted, rather than assuming a uniform response among adjacent buildings. This is particularly relevant in consolidated urban areas, where buildings with different configurations and orientations are exposed to the same high-rise building.

5. CONCLUSIONS

This study investigated the effects of shading caused by a 112-meter-high building on the electricity consumption of six adjacent residential buildings under the hottest and the coldest day conditions in Santos-SP, Brazil. The results showed that the presence of the Reference Building did not produce a uniform response among the adjacent buildings. Furthermore, the relationship between additional shading and electricity consumption varied for the two extreme thermal conditions. Additional shading alone was not sufficient to explain the change in total electricity consumption.

The results are comparative and limited by methodological simplifications adopted in this study. They should not be interpreted as representing annual performance or actual energy consumption. Furthermore, the findings refer to six adjacent buildings within a specific urban configuration in Santos and should not be directly generalized to other urban contexts or climatic conditions.

The study contributes quantitative evidence from an urban context characterized by a hot and humid climate and highlights the importance of considering inter-building effects when assessing the energy implications of high-rise buildings in consolidated urban areas. Further studies considering other climatic regions, longer simulation periods, and different urban configurations are suggested as future works.

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