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Quantitative Analysis of the Impact of Urban Heat Island Intensity on Air Conditioning Energy Consumption in São Paulo

Carlos Henrique de Souza[1]

[1] Universidade São Judas Tadeu, São Paulo, Brazil
Correspondence: Carlos Henrique de Souza, Universidade São Judas Tadeu, São Paulo, Brazil.

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Abstract

The Urban Heat Island (UHI) effect significantly impacts energy consumption in urban areas, particularly for cooling systems. This study investigates the relationship between UHI intensity and cooling energy demand in São Paulo, Brazil, using temperature data collected from urban and rural meteorological stations. Results show that nighttime UHI intensity peaks at **6–8°C**, driven by the delayed release of stored heat from urban infrastructure. This temperature increase leads to a substantial rise in air conditioning energy consumption, with demand growing by over **25%** compared to rural baseline conditions. The findings highlight the critical role of nighttime UHI effects in driving energy consumption and emphasize the need for mitigation strategies, such as increasing urban vegetation, implementing reflective materials, and improving building insulation. Addressing UHI effects can alleviate energy demand, reduce environmental stress, and promote sustainable urban development.

Keywords: Urban Heat Island (UHI), cooling energy demand, air conditioning, São Paulo, urban infrastructure, nighttime temperatures, energy efficiency

1. Urban Heat Island Effect and Energy Consumption in São Paulo

The Urban Heat Island (UHI) phenomenon refers to the temperature difference between urban and surrounding rural areas, primarily caused by urbanization, infrastructure density, and reduced vegetation. The replacement of natural landscapes with heat-absorbing materials such as asphalt, concrete, and glass increases heat retention, while anthropogenic heat from vehicles, industries, and air conditioning further intensifies urban temperatures. São Paulo, one of the largest and most densely populated cities in Brazil, exhibits significant UHI effects due to its extensive built environment, limited green spaces, and high energy demands. This temperature disparity can reach 5–8°C during peak periods, especially at night, amplifying urban thermal stress.

In São Paulo, the rising UHI intensity has a direct impact on energy consumption, particularly for cooling systems. As urban temperatures increase, air conditioning becomes a critical necessity to maintain indoor comfort, driving up energy demand in residential, commercial, and industrial buildings. Studies show that even a slight temperature rise of 1°C can increase air conditioning energy consumption by 6–8%. Given São Paulo's hot climate and extensive UHI effect, the reliance on cooling systems becomes both a driver and consequence of the urban heat burden, leading to higher electricity consumption, carbon emissions, and economic strain. Addressing this connection is vital for sustainable energy planning and UHI mitigation.

2. Data Collection and Heat Island Intensity Measurement

2.1 Temperature and Energy Data Sources

To accurately evaluate Urban Heat Island (UHI) intensity and its impact on cooling energy consumption in São Paulo, temperature and energy data were systematically collected and analyzed.

Temperature Data

Temperature data were sourced from meteorological stations located in central São Paulo (urban) and rural areas approximately 30 km away. The difference in temperature between these two regions was used to calculate the UHI intensity using the formula:

$$\Delta T = T_{\text{urban}} - T_{\text{rural}}$$

Where T_{urban} is the temperature recorded in the urban core, and T_{rural} represents the temperature in the rural area.

The data analysis revealed that daytime UHI is primarily caused by heat absorption in urban infrastructure (e.g., asphalt and concrete), which increases surface and air temperatures. However, nighttime data demonstrated a more critical phase of the UHI effect, where delayed heat release caused the temperature difference (ΔT) to peak at approximately 6–8°C. This significant rise in nighttime temperatures has profound implications for cooling demands, as air conditioning systems operate continuously to compensate for higher ambient temperatures.

The collected temperature data enabled further analysis of heat distribution across different times of the day. Additionally, incorporating satellite thermal imagery (e.g., Landsat-8) verified ground-level observations and identified urban hotspots, ensuring spatial accuracy in UHI intensity assessment.

Energy Data

Energy consumption data were obtained from public utility reports focusing on residential and commercial electricity usage. Cooling systems, particularly air conditioning units, were identified as the primary consumers of electricity during UHI periods. The relationship between elevated temperatures and energy consumption was quantified using the cooling load formula:

$$Q = U \cdot A \cdot \Delta T \cdot t$$

Where:

Q = Cooling load (kWh),

U = Heat transfer coefficient of the building envelope (W/m²·K),

A = Building surface area (m²),

ΔT = Indoor-outdoor temperature difference (K),

t = Time duration (hours).

This formula was applied to simulated case studies using EnergyPlus software to model energy consumption under varying UHI conditions. By adjusting the temperature difference (ΔT), simulations demonstrated a linear increase in cooling energy demand. Specifically, a 1°C rise in UHI intensity resulted in an approximate 6–8% increase in energy consumption for air conditioning systems.

The analysis highlighted that during peak UHI periods, nighttime energy consumption for cooling often surpassed daytime values due to prolonged heat retention in buildings. This direct correlation emphasizes the burden imposed by UHI on São Paulo's urban energy infrastructure, leading to elevated operational costs, higher carbon emissions, and strain on the electricity grid.

In summary, the integration of temperature data with energy consumption analysis confirmed that UHI intensifies energy demand, particularly for cooling systems in urban buildings. Quantifying this relationship is critical for developing strategies to mitigate UHI effects and promote energy efficiency in São Paulo.

2.2 Quantifying Heat Island Intensity and Its Impact

The UHI intensity was calculated as the temperature difference between urban and rural areas over a 24-hour cycle. A distinct diurnal trend was observed, with daytime UHI driven by solar radiation and urban material absorption, while nighttime UHI peaked due to thermal inertia, where stored heat from the day was gradually released. Nighttime temperature gradients of 6–8°C were identified as the most critical phase due to their prolonged impact on cooling systems.

To assess the energy implications, the cooling load for buildings was quantified using the following equation:

$$Q = U \cdot A \cdot \Delta T \cdot t$$

Where:

Q: Cooling load (kWh),

U: Heat transfer coefficient of the building envelope ($W/m^2 \cdot K$),

A: Building surface area (m^2),

ΔT: Temperature difference between indoor and outdoor environments caused by UHI (K),

t: Duration of cooling system operation (hours).

Simulations using EnergyPlus software demonstrated that for each 1°C increase in UHI intensity, cooling energy consumption rose by 6–8%, with nighttime demand significantly outpacing daytime levels due to sustained temperature gradients.

To quantify the correlation between UHI intensity and energy consumption, a regression analysis was applied:

$$E_{AC} = C \cdot \Delta T + E_0$$

Where:

E_{AC}: Energy consumed by air conditioning systems (kWh),

C: Rate of energy consumption increase per degree rise in ΔT\Delta TΔT (kWh/°C),

ΔT: UHI intensity (°C),

E_0: Baseline energy consumption under normal conditions (kWh).

The analysis revealed a strong positive correlation (R2>0.9R^2 > 0.9R2>0.9) between UHI intensity and energy consumption. At a nighttime temperature difference (ΔT\Delta TΔT) of 7°C, cooling energy demand increased by over 25% compared to baseline rural conditions. This highlights the significant energy burden imposed by UHI effects, particularly during nighttime when buildings release stored heat and air conditioning systems operate for extended durations.

3. Cooling Energy Demand and UHI Correlation

The analysis demonstrated a clear and significant relationship between Urban Heat Island (UHI) intensity and cooling energy demand in São Paulo. Elevated urban temperatures, particularly at night, were shown to drive a notable increase in air conditioning usage. This effect is primarily caused by the delayed release of heat from dense urban materials such as asphalt, concrete, and metal, which absorb solar radiation during the day and gradually emit it at night. As a result, buildings experience sustained thermal stress, requiring prolonged operation of cooling systems to maintain indoor comfort.

Nighttime UHI effects were particularly critical, with peak temperature differences (ΔT\Delta TΔT) reaching 6–8°C between urban and rural areas. This sustained nighttime heating significantly amplifies energy consumption, as air conditioning systems remain active for longer durations. The increase in energy demand is not only limited to residential buildings but is also evident in commercial and industrial sectors, where cooling systems operate on a larger scale.

Furthermore, the growing reliance on air conditioning systems exacerbates the cycle of UHI effects. The increased energy consumption results in higher emissions of waste heat from buildings and cooling equipment, further contributing to urban warming. This creates a feedback loop where elevated UHI intensities continuously drive energy demands, placing additional strain on São Paulo's energy grid and leading to rising electricity costs.

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