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BUILDING ENVELOPE DESIGN AND COOLING DEMAND IN HIGH-RISE RESIDENTIAL BUILDINGS: A COMPOSITE CLIMATE CASE FROM THE GLOBAL SOUTH

Summary

Rapid urbanization in cities of the Global South is increasing the construction of high-rise residential buildings, leading to rising cooling-driven electricity demand. In composite climates, building envelope design strongly influences indoor thermal conditions and cooling loads. This study analyzes field data from 128 residential buildings in Jaipur, India, examining energy consumption patterns, Energy Performance Index (EPI), façade glazing distribution, and appliance-level electricity use. Results show that cooling accounts for approximately 40% of total electricity consumption, while window-to-wall ratio and façade orientation significantly influence cooling demand. The study highlights passive envelope optimization and solar-assisted cooling as key strategies to reduce cooling loads. These findings provide empirical insights for climate-responsive design and support the development of low-energy and net-zero residential buildings in rapidly urbanizing regions.

Keywords: Building envelopes, cooling demand, window-to-wall ratio, composite climate, passive cooling, solar cooling, high-rise residential buildings

Field of application for the findings: Energy-efficient building design, solar cooling systems, urban housing

Addressed audience: B*uilding engineers, architects, urban planners, and policymakers*

1. Introduction

The building sector accounts for around 36% of global final energy consumption and nearly 37% of energy-related carbon emissions, making it a critical focus for energy efficiency and climate mitigation. In rapidly urbanizing cities of the Global South, high-rise residential buildings are increasingly common due to land constraints and population growth. However, these buildings often exhibit higher energy intensity because of extensive façade exposure, larger glazing areas, and increased reliance on air-conditioning systems. Cities located in composite climates experience high solar radiation and extreme summer temperatures, which significantly increase cooling demand in residential buildings. Jaipur, India, represents a typical composite climate where summer temperatures frequently exceed 40°C. In such conditions, building envelope characteristics strongly influence indoor thermal conditions and cooling energy consumption. Among various envelope parameters, the window-to-wall ratio (WWR) plays an important role in regulating solar heat gain and indoor temperatures. In high-rise buildings with large façade areas, excessive glazing can substantially increase cooling loads. Despite its importance, empirical studies linking façade design and cooling demand in residential buildings in composite climates remain limited. This study investigates the relationship between building envelope design and cooling-driven electricity consumption in high-rise residential buildings using field survey data from Jaipur. The analysis evaluates electricity consumption patterns, Energy Performance Index (EPI), façade glazing distribution, and appliance-level energy use, while discussing passive design and solar-assisted cooling strategies for reducing cooling demand.

2. Methodology

The analysis is based on a field dataset collected from 128 high-rise residential buildings located in Jaipur. The dataset includes building characteristics and operational parameters such as annual electricity consumption, built-up area, building height, façade orientation, window-to-wall ratio, and appliance-level electricity usage. These variables were used to analyze the relationship between building envelope design and cooling-related electricity consumption. The first step of the analysis involved calculating the Energy Performance Index (EPI) for each building, defined as annual electricity consumption divided by the built-up floor area. The EPI provides a normalized metric for comparing energy performance across buildings of different sizes and allows identification of energy-efficient and energy-intensive buildings within the sample. Statistical analysis was then conducted to examine the distribution of annual electricity consumption and EPI values across the dataset. Histograms were used to identify consumption patterns and variability within the building stock. Scatter plot analysis was further applied to investigate the relationship between built-up area and electricity consumption, enabling assessment of whether building size directly influences energy intensity. To evaluate the influence of building envelope design, the window-to-wall ratio was analyzed across the building sample. Distribution analysis was conducted to identify typical glazing ratios, while additional scatter plots were used to examine relationships between WWR, building height, and built-up area. Orientation-based analysis was also performed to determine how glazing distribution varies across different façade directions. Finally, appliance-level electricity consumption data were analyzed to determine the contribution of major end uses such as air conditioning, fans, lighting, refrigerators, pumps, and water heating systems. This analysis enabled identification of the dominant drivers of electricity consumption and provided insights into the role of cooling demand within the overall building energy profile.

3. Key Results and Framework

The selected results are presented in Fig 1. The analysis of annual electricity consumption reveals considerable variability in energy use across the surveyed buildings. Electricity consumption ranges from approximately 1,000 kWh to over 13,000 kWh per year, with the majority of buildings consuming between 2,000 and 5,000 kWh annually. The distribution is right-skewed, indicating that while most buildings operate within moderate energy consumption levels, a smaller group of buildings exhibits significantly higher electricity demand. The Energy Performance Index distribution provides further insight into building energy efficiency. Most buildings demonstrate EPI values between 20 and 50 kWh/m² per year, with a median value of approximately 35–40 kWh/m² per year. However, several buildings exhibit EPI values exceeding 70–100 kWh/m² per year, indicating relatively poor energy performance. Approximately 25% of buildings achieve EPI values below 28 kWh/m² per year, representing the most energy-efficient segment of the sample. The relationship between built-up area and electricity consumption shows a positive but relatively weak correlation. Larger buildings tend to consume more electricity overall due to greater conditioned floor area, but buildings with similar sizes often display significant differences in energy consumption. This variability suggests that building envelope design, operational patterns, and occupant behavior strongly influence energy demand beyond simple building size. Appliance-level energy analysis shows that air-conditioning systems account for approximately 40% of total electricity consumption, making cooling the dominant energy end-use in residential buildings. Ceiling fans represent the second largest share, followed by lighting and refrigeration. The dominance of cooling demand reflects the climatic conditions of Jaipur, where prolonged periods of high temperatures require significant mechanical cooling to maintain indoor comfort. The distribution of window-to-wall ratios across the building sample indicates that most buildings maintain glazing ratios between 6% and 12%, with an average around 8–10%. While this range helps limit excessive solar heat gain, several buildings exhibit glazing ratios approaching 15–18%, which may significantly increase cooling loads in hot climates. Orientation analysis further reveals that glazing distribution varies across façades, with north-facing façades generally exhibiting higher glazing ratios due to their lower exposure to direct solar radiation.

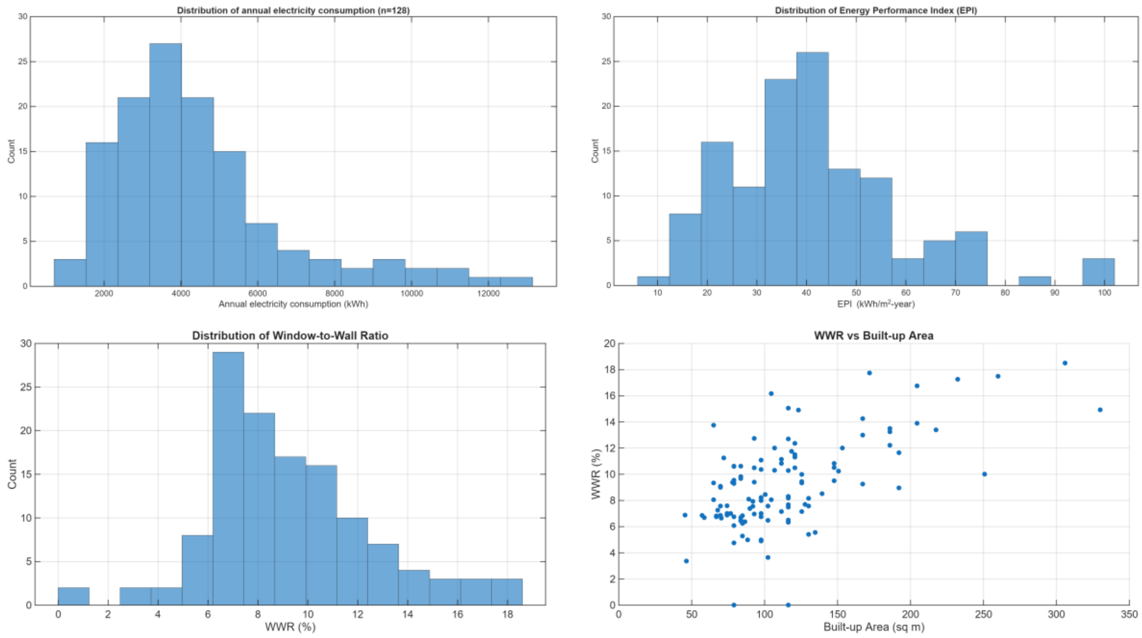

Fig. 1: Building envelope as well as electricity consumption pattern from the survey data

These findings highlight the strong influence of building envelope characteristics on cooling demand. Buildings with higher glazing ratios and unfavorable façade orientation tend to experience greater solar heat gains and higher electricity consumption associated with air conditioning. From a design perspective, the results suggest that passive cooling strategies can play a significant role in reducing cooling demand in high-rise residential buildings. Limiting glazing ratios on solar-exposed façades, incorporating external shading devices, and optimizing building orientation can substantially reduce solar heat gains and indoor temperatures. Such passive strategies can significantly lower cooling loads before mechanical systems are considered. In addition to passive envelope optimization, solar-assisted cooling technologies offer promising opportunities for addressing cooling demand in composite climates. High solar radiation levels during summer months coincide with peak cooling demand, making solar thermal cooling and photovoltaic-powered air-conditioning systems particularly suitable for residential buildings in this region. Integrating passive design measures with solar cooling technologies can therefore support the development of low-energy and net-zero residential buildings. This study demonstrates that building envelope design plays a critical role in determining cooling-driven electricity consumption in high-rise residential buildings located in composite climate regions. The empirical analysis shows that cooling systems account for approximately 40% of total residential electricity consumption, highlighting the importance of reducing cooling loads through climate-responsive building design. Window-to-wall ratio and façade orientation emerge as key design parameters influencing solar heat gain and cooling demand. Buildings with higher glazing ratios and unfavorable orientation tend to experience greater cooling loads and higher electricity consumption. Optimizing envelope design through controlled glazing ratios, orientation-sensitive façade design, and external shading strategies can therefore significantly reduce cooling demand. Furthermore, the findings suggest that combining passive cooling strategies with solar-assisted cooling technologies offers a promising pathway for reducing electricity consumption in high-rise residential buildings (Fig. 2). Such integrated approaches can support the development of energy-efficient and net-zero residential buildings in rapidly urbanizing cities across the Global South.

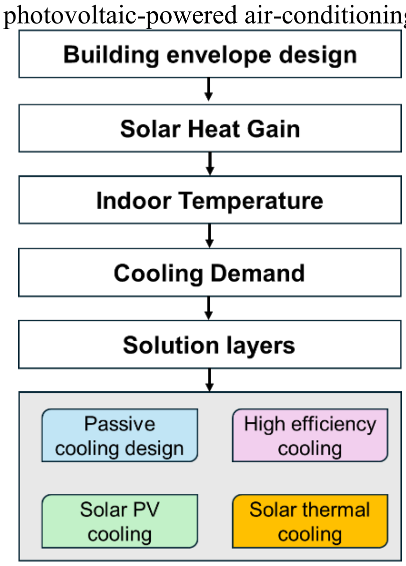

Fig. 2: Envelope–Cooling–Solar Solution Framework for High-Rise Residential Buildings