

Article

Effects of Building Height and Window-to-Wall Ratio on Cooling Demand, Passive Comfort, and Peak Demand in a Composite Climate: EnergyPlus Simulations and an Exploratory Surrogate Model

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Abstract

Rapid vertical growth in Tier-2 Indian cities is reshaping residential forms and may affect cooling demand, passive comfort, overheating severity, and peak electricity demand. This study examines the influence of building height and window-to-wall ratio (WWR) on residential thermal performance in Patna, India, a composite-climate context. Five archetypes—detached house, row-house, low-rise apartment, mid-rise apartment, and high-rise apartment—were simulated in DesignBuilder/EnergyPlus Version 23.1.0 under 20%, 30%, and 40% WWR scenarios. Passive and active operation modes were evaluated through 30 annual simulations, generating 262,800 hourly records. External shading was excluded, and occupancy and ventilation assumptions were standardized to create a controlled benchmark design. Performance was assessed using annual cooling energy demand (ACED), all-hour and occupied-hour passive comfort percentage, adaptive degree-hours (ADH), and peak demand indicators. At 20% WWR, ACED increased from 33.13 kWh/m²·yr in the low-rise archetype to 42.79 kWh/m²·yr in the high-rise archetype, while all-hour passive comfort decreased from 68.16% to 49.28%. The row-house archetype performed best due to reduced exposed envelope area. A second-order surrogate model provided exploratory scenario-level approximation across 15 archetype–WWR cases. The findings support further investigation of morphology-sensitive residential envelope guidance within bounded composite-climate benchmark conditions.

Keywords: residential building archetypes; building height; window-to-wall ratio; cooling energy demand; passive comfort; occupied-hour comfort; adaptive degree-hours; peak electrical demand; surrogate model; composite climate



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1. Introduction

The building sector is a major contributor to global energy use and greenhouse gas emissions, making building energy efficiency essential for climate mitigation and urban sustainability. In India, residential space cooling is growing rapidly due to the combined effects of urbanization, rising incomes, greater access to cooling appliances, and intensifying heat. Recent evidence indicates that India's residential space-cooling transition has accelerated sharply since 2000, reinforcing the importance of energy-efficient residential design as a pathway for limiting future cooling-related energy and carbon burdens [1].

Within this context, building geometry is a major driver of thermal performance. Classical and more recent studies show that urban texture, form, exposure and façade design influence how buildings gain, store and dissipate heat [2,3]. In residential buildings, variables such as building height, horizontal attachment, exposed surface area, surface-to-volume ratio and window-to-wall ratio (WWR) directly influence solar gains, conductive heat transfer, and cooling demand. Recent Indian studies confirm that geometry substantially alters cooling loads even when non-geometric factors are held constant [4].

In warm and composite climates, however, building performance extends beyond annual energy demand. A residential form that appears efficient on an annual basis may still expose occupants to prolonged overheating or contribute to high peak electrical demand during thermally stressful periods. For this reason, performance assessment should consider multiple indicators simultaneously, including annual cooling energy demand, passive comfort, overheating severity, and peak demand. This is especially relevant in India, where adaptive behavior is common in naturally ventilated and mixed-mode residences. The Indian adaptive comfort literature shows that occupants often accept a wider range of indoor conditions than assumed by fixed Western comfort standards, provided that conditions remain within locally adaptive comfort limits [5,6]. Related field studies in Indian composite climates also confirm broader comfort bands and stronger adaptive responses than conventional steady-state models [7]. These findings make adaptive metrics particularly relevant for evaluating passive habitability in Indian residential buildings.

Despite this established knowledge, an important research gap persists. Most studies on morphology and building energy examine general form–performance relationships, façade variables such as WWR, or dense metropolitan settings, while evidence for representative residential archetypes in rapidly transforming Indian cities remains limited [8]. This gap is critical because many such cities are experiencing rapid vertical transformation under the combined pressures of land scarcity, housing demand, and increasing floor-area intensification. Patna provides a relevant case in this regard. Recent remote-sensing evidence indicates measurable vertical urban growth across Patna urban agglomeration during 2015–2018, suggesting a clear shift toward taller residential forms in several parts of the city [9]. In this study, Patna represents a typical Tier-2 composite-climate city undergoing rapid verticalization.

This evidence gap is also regulatory and methodological in nature. In India, residential energy guidance under the Eco-Niwas Samhita and related code frameworks has advanced climate-responsive envelope regulation, yet the translation from code to actual operational thermal performance remains fragmented in practice [10]. More importantly, much of the current guidance remains effectively typology-agnostic even though buildings may differ substantially in height, exposure, and attachment condition. From a building physics perspective, the same WWR cannot be assumed to produce equivalent thermal consequences in a detached low-rise house, an attached row-house and a highly exposed mid- or high-rise building. Uniform envelope guidance is therefore unlikely to reflect morphology-dependent exposure conditions adequately.

At the same time, although high-fidelity simulation tools such as EnergyPlus are well suited to analyzing these interactions, they remain too expertise-intensive and time-consuming for routine use in rapid early-stage design assessment. This has encouraged growing interest in surrogate modeling as a bridge between detailed simulation and faster performance estimation. However, existing surrogate applications have focused more strongly on general energy prediction than on the coupled effects of residential morphology, adaptive comfort, overheating sensitivity, and peak electrical demand in Indian composite climates [11,12]. This gap is particularly important because the interaction between building height and WWR may not be linear: increases in glazing may impose disproportionately

greater thermal penalties in taller and more exposed forms than in lower-rise or attached configurations. Capturing this morphology-energy-comfort interaction is therefore essential if simplified tools are to support meaningful performance screening rather than merely reproduce generic energy trends.

Against this background, the primary aim of this study is to quantify how building height, attachment condition, and WWR jointly influence residential thermal performance under a controlled benchmark design in a composite climate. A secondary aim is to examine whether the principal annual performance indicators of this bounded archetype–WWR design space can be approximated using an exploratory reduced-order surrogate model. The study does not propose a new building code, universal design rule, or directly transferable WWR threshold. Instead, it provides controlled simulation evidence to support a more morphology-aware interpretation of residential cooling demand, passive comfort, overheating severity, and peak electrical demand.

The paper makes three principal contributions. First, it quantifies how building height and WWR jointly influence residential thermal performance across representative residential archetypes in a composite climate. Second, it compares the thermal implications of detached, attached/row-house, low-rise, mid-rise, and high-rise residential forms under standardized assumptions, including the effect of party-wall attachment. Third, it evaluates a bounded reduced-order pathway for faster morphology-informed screening of annual performance indicators while retaining full building simulation as the reference method.

2. Literature Review

The relationship between urban morphology and building energy use is well established, yet the literature does not provide a clear consensus on optimal forms. Existing findings are often diverse, fragmented, and sometimes contradictory because studies differ in scale, climate, typology, and performance metrics. Reviews of urban building energy modeling (UBEM) show that archetype-based and stock-level models are advancing quickly, but their translation into morphology-sensitive design or code-ready guidance remains incomplete [8,13,14]. This makes it necessary to distinguish between what is already known about urban form in general and what remains unresolved for residential archetypes, composite climates, and performance indicators beyond annual energy demand.

2.1. Urban Morphology, Form Factors, and Residential Energy

Classical work on building form established that geometry, exposure, and urban texture significantly affect environmental performance. Ratti et al. showed that urban texture and surface-to-volume characteristics can materially influence building energy use, while later studies emphasized that block form affects not only thermal behavior but also solar access and ventilation [3,15]. At the same time, these studies make it clear that the effect of morphology is not universal: the performance consequences of compactness, density, and exposure depend strongly on climate, surrounding context, and the way form indicators are defined and modeled.

This climate dependence is the first major unresolved issue in the literature. In heating-dominated contexts, compact forms often reduce exposed envelope area and are therefore associated with lower energy use. In cooling-dominated contexts, however, the same densification logic can produce the opposite effect if taller or more isolated forms increase façade exposure, solar load, or passive cooling challenges. Quan and Li's systematic review is particularly important in this regard because it highlights methodological heterogeneity and contradictory findings in urban form–energy relationships, especially with respect to densification and typology [8].

For residential design, this means morphology cannot be treated as a single-variable problem. A parameter such as compactness may appear beneficial in one context while concealing higher solar exposure or weaker nocturnal heat dissipation in another. This is precisely where the existing literature becomes limited for fast-growing Tier-2 Indian cities. Many studies examine urban form in general, but far fewer isolate the thermal consequences of building height, attachment condition, and glazing ratio across a controlled residential typology spectrum under composite-climate conditions.

2.2. Height, Attachment, and the Thermodynamic “Scale Penalty”

The second unresolved issue is vertical scaling. The literature increasingly suggests that building height is more than a geometric feature: it alters thermodynamic balance by changing roof-to-floor ratios, façade exposure, and the degree of interaction with surrounding form. Reviews of tropical and hot-climate envelope design emphasize that façade exposure and solar gains become especially important in cooling-dominated settings, while simulation studies confirm that morphology-related variables can substantially alter residential cooling loads in India even when other parameters are held constant [4,16].

At the same time, the literature does not resolve whether densification in warm climates should favor taller forms or attached lower-rise forms. Some studies associate density and compactness with improved energy performance, whereas others find that increased height and exposure can offset those benefits. In the Indian context, Ravichandran and Gopalakrishnan reported that building geometry alters cooling loads substantially, yet their results also demonstrate that morphology effects depend on the interaction among several variables rather than on height alone [4]. What remains notably scarce is a controlled archetype-level comparison that tests detached, attached, low-rise, mid-rise, and high-rise residential forms under comparable assumptions and asks whether height systematically amplifies cooling and comfort penalties across that spectrum.

Horizontal attachment through party walls introduces a related but different mechanism. Party walls reduce exposed envelope area and therefore alter heat-transfer pathways relative to detached forms. Existing party-wall studies confirm their thermal importance, but they focus mainly on heat-loss in retrofit contexts rather than on cooling performance across residential archetypes [17]. As a result, the energy and comfort implications of attached forms are still not consistently compared against tall apartment forms under identical envelope and operational assumptions.

2.3. Height, Window-to-Wall Ratio, Shading, and Morphology-Specific Glazing Behavior

Window-to-wall ratio (WWR) is one of the most widely studied envelope parameters because it directly influences solar heat gain, daylight and the balance between glazed and opaque surfaces. Recent review work also shows that façade and shading decisions are inherently multi-objective, involving trade-offs among energy demand, thermal comfort, daylight availability, and glare control [18]. Recent building-scale optimization studies likewise show that daylighting, energy consumption, and thermal comfort often need to be balanced simultaneously during early-stage design, rather than optimized through a single performance objective [19]. However, the present study remains intentionally bounded to thermal performance, passive comfort, overheating severity, and peak cooling demand rather than daylighting or visual-comfort analysis. Parametric studies in warm climates show that façade design and glazing proportions strongly influence indoor temperatures and cooling loads, while broader reviews confirm that envelope optimization cannot be reduced to a single universal glazing rule [16].

However, the literature remains too typology-agnostic to inform more targeted building guidance. Most WWR studies test a limited number of building forms, a single building

class, or façade variables in isolation. They therefore establish the importance of WWR but do not adequately quantify the thermal penalty of glazing and its relationship with height and attachment condition. This is the core unresolved question of the present study. The issue is not whether glazing matters, but whether a 30% or 40% WWR carries the same thermal consequence in a detached dwelling, a row-house, a low-rise block, and a highly exposed high-rise building. Existing research does not provide a robust answer to that question for Tier-2 Indian housing, and this absence becomes more consequential when the same envelope guidance is later applied across typologies in practice [2,4].

A further limitation is that glazing behavior is inseparable from shading and surrounding form. Sanaieian et al. argued that assessing a building without considering its urban context is methodologically incomplete because block form simultaneously affects the thermal behavior, solar access, and ventilation [15]. This is directly relevant in composite climates, where external shading, mutual shading, and façade exposure can interact strongly with WWR. However, even where the importance of surrounding form is recognized, the literature still provides limited morphology-specific glazing guidance that can be translated into simplified thresholds for residential design or code review.

2.4. Adaptive Comfort, Overheating, and Peak Demand in Indian Residences

A major weakness in the broader building-performance literature is the tendency to rely on annual energy demand alone. While annual energy demand is important, it is insufficient in warm climates because it overlooks passive habitability, overheating severity, and peak electrical demand. Reviews of overheating criteria increasingly argue that regulations and assessment frameworks understate heat-stress risk despite the direct impact of overheating on health, resilience, and passive survivability in residential homes [20]. At the city scale, urban overheating and higher ambient temperatures are also known to increase both total electricity use and peak power demand, reinforcing the need to treat peak demand as a building-performance issue rather than merely a grid-measurement issue [21].

For India, the adaptive comfort literature provides a more suitable performance basis than fixed Western setpoints. Manu et al. and Rawal et al. showed that Indian occupants accept a wider range of indoor temperatures in naturally ventilated and mixed-mode buildings than standard static comfort models assume [5,6]. This has two implications for the present study. First, residential performance in Indian composite climates should be assessed using adaptive metrics such as passive comfort percentage and adaptive degree-hours, rather than relying only on annual cooling energy. Second, morphology is not just an energy variable; it can determine whether a dwelling remains within adaptive comfort limits or is effectively pushed toward mechanical cooling. Despite the importance of this issue, studies that directly combine morphology, Indian adaptive comfort, overheating severity and peak demand for representative residential archetypes remain notably limited.

2.5. Codes, Archetype Modeling, and Surrogate Reduced-Order Models

The final unresolved issue lies at the intersection of standards, archetype modeling, and simulation speed. Recent reviews of Indian building codes show progress toward climate-responsive and net-zero oriented regulation, yet the transition from code compliance to operational performance remains incomplete. More importantly for this study, the logic of current guidance largely overlooks building typologies: buildings with very different exposures may still be assessed through broadly similar envelope rules. From a building-physics standpoint, this is difficult to defend because detached, row-house, and tall dwellings do not share the same thermal sensitivity to glazing or exposed surface area [10].

Archetype and UBE research help address this problem by organizing building stocks into manageable representations, but these approaches are usually broader in scope than the present study. Reviews by Reinhart and Cerezo Davila, Ali et al. and Shen and Wang et al. show that archetype-based and reduced-order urban models are increasingly useful for planning and stock analysis, yet they also emphasize the continuing need for application-specific frameworks, better data organization, and clearer integration between physics-based and data-driven methods [13,14,22]. In other words, the field has useful tools, but it does not yet offer a widely adopted pathway for rapid, morphology-sensitive screening of residential comfort and energy performance in emerging Indian cities.

Surrogate modeling offers a promising approach to bridge this gap, yet the literature again reveals a mismatch with the aim of the current study. Reviews confirm that surrogates can drastically reduce computational cost in simulation-based design, while recent studies demonstrate strong performance for energy and cost prediction for EnergyPlus-based building performance approximation [11,12]. However, most such work still focuses on general energy prediction, operational scenarios, or non-residential buildings. Very few studies target residential morphology, and even fewer still combine adaptive comfort, overheating, and peak electrical demand with simulation-driven surrogates. This creates a methodological gap for reduced-order models that are fast and sensitive to the specific morphology-comfort-energy interactions relevant to composite climate housing.

Taken together, the literature points to three unresolved problems that directly motivate the present study. First, the effects of urban form on building energy use are recognized, but the literature remains fragmented and sometimes contradictory regarding densification, especially in composite climates where compactness benefits may conflict with exposure penalties. Second, a systematic quantification of height-dependent glazing sensitivity across representative residential archetypes in Tier-2 composite climate cities remains limited. Third, while adaptive comfort and surrogate modeling are both active research domains, they have rarely been integrated into a single framework that compares detached, row-house, low-rise, mid-rise, and high-rise dwellings using annual cooling energy, passive comfort, adaptive degree-hours and peak electrical demand. These unresolved issues define the research focus addressed in the present study.

3. Materials and Methods

3.1. Research Design

This study was structured as a controlled archetype-level parametric building energy simulation (BES) benchmark to isolate the thermodynamic effects of building height, horizontal attachment, and window-to-wall ratio (WWR) on residential thermal performance in a composite climate. The methodological workflow comprised four stages:

- (1) Identification of representative residential archetypes for planned government housing in Patna
- (2) Development of normalized simulation archetypes under standardized boundary conditions
- (3) Annual simulation of each archetype under passive and active operation modes using DesignBuilder/EnergyPlus, and
- (4) Python-based post-processing of hourly outputs to derive energy, comfort, heat-stress, peak demand, and diagnostic physics indicators. This combination of archetype-based representation and physics-based simulation follows established building-stock and urban building energy modeling logic while retaining a controlled comparative framework suitable for hypothesis-driven analysis [13,14]. The overall methodological workflow adopted in the study is illustrated in Figure 1. The study was intentionally designed as a standardized benchmark experiment rather than a full urban-canopy or

neighborhood simulation. Non-morphological inputs such as construction, glazing type, infiltration, internal gains, and operation schedules were kept constant across all archetypes so that the reported differences could be attributed to the combined effects of height, attachment condition, exposed envelope geometry, and WWR under comparable boundary conditions. External shading from surrounding buildings was intentionally excluded to establish a standardized high-exposure reference condition. This assumption should be interpreted as a benchmark simplification used to isolate intrinsic morphology-sensitive thermal behavior rather than as a full representation of the real urban context.

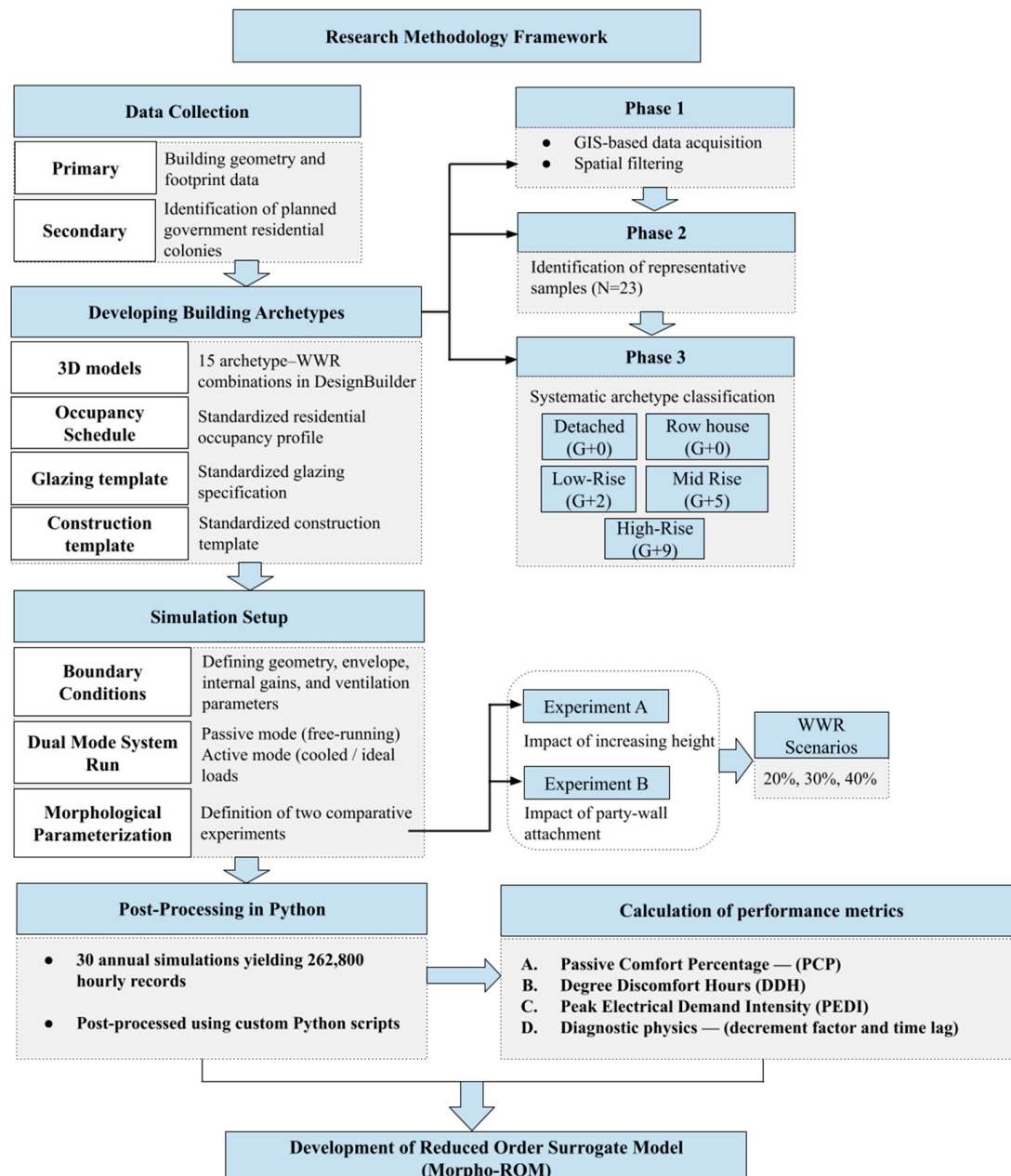


Figure 1. Research methodology framework.

3.2. Study Area and Climatic Context

Patna, Bihar, India (25.59° N, 85.13° E) was selected as the study area because it represents a rapidly transforming Tier-2 urban context in a composite climate that is experiencing rapid vertical growth in residential buildings alongside increasing cooling demand. Recent

remote-sensing analysis has documented measurable vertical urban growth across the Patna urban agglomeration, supporting its suitability as a representative case for archetype-based residential performance analysis under rising height intensification [9]. A Typical Meteorological Year (TMY) weather file for Patna in EPW format was used for all simulations. The use of a single annual weather file ensured that all archetypes were evaluated under the same climatic sequence, allowing comparative differences to be attributed to morphological variation rather than weather variability.

3.3. *Development of Representative Residential Archetypes*

3.3.1. Archetype Derivation Strategy

The representative archetypes were derived through a structured filtering and typological classification process within the Patna Municipal Corporation (PMC) area. The PMC boundary shapefile was used to define the study extent, after which a 200 m × 200 m grid was overlaid to structure the analysis. Residential pockets were then georeferenced from the Patna Master Plan 2031 land-use map and combined with building-footprint data to isolate built forms located within residential zones. From this set, only grids corresponding to planned government residential colonies identified from the master plan and verified through built-form inspection during field surveys were retained.

This approach is consistent with established archetype-based and building-stock modeling methodologies in which heterogeneous urban building stock is filtered, grouped, and abstracted into representative typologies for controlled simulation rather than modeled one building at a time [13,14,23–26]. In the present study, planned government housing was selected because it provides a comparatively standardized and morphologically consistent residential stock, allowing clearer isolation of archetype-level thermal effects. Private and incrementally developed areas were excluded because of their greater variation in plot subdivision, built form, and later-stage modification, which would reduce the comparability required for a controlled benchmark analysis [13,14].

To improve transparency of the archetype derivation process, the selection of planned government housing followed a staged filtering procedure. A total of 24 Master Plan-listed housing colonies were reviewed as the initial sampling frame, of which 14 planned government colony boundaries were digitized for detailed screening. From the residential land-use overlay, 1053 residential-dominant 200 m × 200 m grids with at least 70% residential land-use coverage were identified as the initial screening pool. After visual and typological screening, 80 candidate grids were manually reviewed using building footprints, georeferenced imagery, and field-based built-form interpretation. Within these reviewed grids, 31 building-footprint candidates were identified and grouped according to attachment condition, number of stories, footprint scale, and single-family versus multi-family configuration before abstraction into the final simulation archetypes. A summary of the sampling and screening process is presented in the Supplementary Materials.

Within the retained colonies, building footprints were consolidated into five dominant categories: detached housing, attached/row housing, low-rise apartments, mid-rise apartments, and high-rise apartments. The screened stock comprised 4 detached, 6 row-house, 9 low-rise apartment, 7 mid-rise apartment, and 5 high-rise apartment candidates. These were consolidated into five standardized simulation archetypes to isolate the effects of vertical scale, attachment condition, and glazing variation under controlled construction and operational assumptions. Although the current planned residential fabric of Patna is dominated mainly by low-rise and mid-rise forms, the high-rise typology was retained because ongoing residential verticalization in Patna makes taller apartment forms increasingly relevant for future housing scenarios and for testing height-dependent thermal sensitivity. Thus, the inclusion of the G+9 representative form was intended not to imply that such

buildings dominate the present stock, but to ensure that the benchmark framework captures the upper end of emerging planned residential verticalization.

3.3.2. Normalized Simulation Archetypes

The observed residential forms were translated into normalized simulation archetypes for controlled comparative analysis. The purpose of normalization was not to reproduce every dwelling exactly, but to isolate the effects of height, exposed envelope geometry, party-wall attachment, and WWR under consistent construction and operational assumptions. All final geometric quantities used for reporting and normalization were verified from the EnergyPlus summary outputs generated from the final simulation models. Therefore, where manually recorded plan dimensions and EnergyPlus-reported values differed slightly, the software-reported total building area, surface areas, and volumes were used for consistency.

Five final archetypes were modeled: ARCH-D as a detached single-story dwelling, ARCH-R as an attached/row-house single-story dwelling, ARCH-LR as a low-rise apartment block of three floors, ARCH-MR as a mid-rise apartment block of six floors, and ARCH-HR as a high-rise apartment block of ten floors. For the single-story archetypes, the total building area equals the modeled single-floor area. For the multi-story apartment archetypes, each floor was modeled as one conditioned thermal zone, and the building-level indoor operative temperature used in post-processing was calculated as the hourly arithmetic mean of the floor-level operative temperatures. This zoning approach was adopted to retain a comparable archetype-level benchmark structure rather than a room-by-room residential layout.

WWR was defined as the ratio of total glazed opening area to total above-ground external wall area of exposed façades. Glazing was applied uniformly on exposed façades for each archetype and WWR scenario. In the attached/row-house archetype, the party walls were treated as a non-exposed shared surface and did not receive external windows. This ensured that the difference between detached and attached forms reflected the thermal effect of reduced envelope area rather than differences in glazing definition. Table 1 presents the residential archetype classification and EnergyPlus-reported geometric characteristics.

Table 1. Residential archetype classification and geometric characteristics.

Archetype ID	Archetype Name	Representative Simulated Form	Floors	Total Building Area (m ²)	Volume (m ³)	Building Height (m)
ARCH-D	Detached house	G+0	1	176.08	616.28	3.0
ARCH-R	Attached/row-house	G+0	1	165.55	496.66	3.0
ARCH-LR	Low-rise apartment	G+2	3	1429.82	4861.39	9.0
ARCH-MR	Mid-rise apartment	G+5	6	2859.64	9651.29	18.0
ARCH-HR	High-rise apartment	G+9	10	4766.07	16,037.82	30.0

Note: Total building area and volume are EnergyPlus-reported values from the final simulation models. For single-story archetypes, the total building area corresponds to the modeled single-floor area. For multi-story archetypes, the total building area is the sum of modeled floor areas across all floors.

Table 2 shows that the archetypes do not differ only by height; they also differ in exposed envelope geometry, roof-to-floor relationship, and envelope-to-volume ratio. The detached archetype has the highest exposed envelope-to-volume ratio, while the attached/row-house archetype has a reduced exposed wall area because one façade is treated as a shared non-exposed party-wall. In the apartment archetypes, increasing height increases total exposed façade area but reduces the roof area per unit floor area. There-

fore, the simulated performance differences should be interpreted as the combined effect of vertical scaling, exposed heat-transfer area, roof dilution, party-wall shielding, and WWR, rather than height alone. This clarification is important because the same nominal WWR can produce different thermal consequences depending on the underlying exposed envelope geometry.

Table 2. Geometric exposure descriptors of the normalized archetypes at 20% WWR.

Archetype ID	Exposed Wall Area (m ²)	Roof Area (m ²)	Window Opening Area (m ²)	Actual WWR (%)	Exposed Envelope Area Excluding Ground (m ²)	Exposed Envelope-to-Volume Ratio (m ² /m ³)	Roof Area/Total Building Area
ARCH-D	194.60	192.00	37.28	19.16	386.60	0.627	1.090
ARCH-R	115.20	177.10	22.32	19.38	292.30	0.589	1.070
ARCH-LR	945.00	500.00	179.31	18.97	1445.00	0.297	0.350
ARCH-MR	1890.00	500.00	355.98	18.83	2390.00	0.248	0.175
ARCH-HR	3150.00	500.00	591.54	18.78	3650.00	0.228	0.105

Note: Exposed envelope area excluding ground was calculated as exposed above-ground wall area plus roof area. The exposed envelope-to-volume ratio was used as a geometric exposure descriptor to support the physical interpretation of heat-transfer potential across archetypes. Actual WWR differs slightly from nominal WWR because EnergyPlus reports WWR based on modeled gross exposed wall and opening areas.

3.4. Simulation Setup and Standardized Boundary Conditions

3.4.1. Simulation Platform and Common Input Assumptions

All archetypes were modeled in DesignBuilder v7 using the EnergyPlus 23.1.0 simulation engine. EnergyPlus is a heat-balance-based simulation platform widely used for whole-building energy and comfort analysis, and a controlled parametric simulation is an established approach for isolating the influence of selected design variables during early-stage performance studies [27,28]. In the present study, non-morphological variables were therefore standardized across all archetypes so that the reported differences could be attributed to building height, attachment condition, and window-to-wall ratio (WWR).

A customized construction template representative of typical urban Indian residential construction was applied to all models. External walls were modeled as 230 mm fired brick masonry with a U-value of 2.1 W/m²K, while roofs and floors were modeled as 150 mm reinforced concrete slab assemblies with roof weathering treatment, giving a U-value of 2.8 W/m²K. Glazing was defined as single clear 6 mm glass with a U-value of 5.7 W/m²K and SHGC = 0.81. These envelope assumptions are consistent with commonly reported brick and RCC residential construction in India and with the recognized importance of wall, roof and glazing performance in cooling-oriented building assessment [2,16,29].

For comparative consistency, glazing was distributed uniformly across the exposed façades of each archetype, while party walls were treated as non-exposed surfaces. Orientation was kept constant across the comparative cases so that the reported differences reflect morphology and WWR effects rather than orientation effects.

The principal simulation inputs were standardized as follows: 3.0 m floor-to-floor height, 0.05 people/m² occupancy density, 5.0 W/m² lighting power density, 3.5 W/m² equipment power density, 5 ACH natural ventilation, WWR scenarios of 20%, 30% and 40%, and an active-mode cooling setpoint of 26 °C. The WWR range was selected as a controlled comparative envelope variable to test morphology-dependent glazing sensitivity rather than to imply that higher WWR is preferable in cooling-dominated residential design. These values were not intended to reproduce the full variability of all households in Patna; rather, they were adopted as standardized control assumptions to support a consistent archetype-level benchmark comparison. The complete set of simulation inputs and boundary conditions is summarized in Table 3.

Table 3. Standardized simulation inputs and boundary conditions.

Category	Parameter	Input Value/Setting
Site and Climate	Weather file	Patna_TMY.epw
	Climate context	Composite climate
Geometry	Floor-to-floor height	3.0 m
	WWR scenarios	20%, 30%, 40%
	External shading	Excluded
Envelope	External walls	230 mm Brick Masonry ($U \approx 2.1 \text{ W/m}^2\text{K}$)
	Roof	150 mm RCC Slab + Weathering Course ($U \approx 2.8 \text{ W/m}^2\text{K}$)
	Glazing type	Single Clear 6 mm ($U \approx 5.7 \text{ W/m}^2\text{K}$, SHGC = 0.81)
	Infiltration	0.5 ACH
	Natural ventilation rate	5 ACH
Internal Gains	Occupancy density	0.05 people/m ²
	Lighting power density	5.0 W/m ²
	Equipment power density	3.5 W/m ²
Active-mode operation	Cooling system	Ideal Loads Air System
	Cooling setpoint	26 °C
	Coefficient of Performance (COP)	3.0
Simulation logic	Passive mode	Free-running with natural ventilation
	Active mode	Mechanically cooled
Benchmark assumption	Standardization intent	Non-morphological parameters held constant to isolate height, attachment condition, and WWR effects

External shading from surrounding buildings was intentionally excluded to establish a standardized exposure reference condition, thereby isolating the intrinsic thermodynamic sensitivity of each archetype under comparable solar exposure. This assumption should be interpreted as a benchmark simplification rather than a full representation of urban context, since mutual shading, balconies, and overhangs would reduce absolute cooling loads in many real residential settings. However, the controlled no-shading assumption was retained in order to ensure consistent comparison of morphology-dependent responses across archetypes [2,16].

3.4.2. Occupancy Schedule and Dual-Mode Simulation Protocol

A simplified residential schedule was adopted to represent a standardized commuter-household profile, as summarized in Table 4. Weekday occupancy was set at 100% during 0:00–08:00 and 18:00–24:00, and 0% during 08:00–18:00, while weekend occupancy was set at 100% throughout the day. This schedule was used to support controlled benchmark comparisons rather than to represent the full diversity of household occupancy in Patna. It influenced internal gains and simulation control, while adaptive metrics were later derived from both the full annual hourly record and the occupied-hour record during post-processing.

Each of the 15 archetype–WWR combinations was simulated annually in two modes: passive and active. In passive mode, all mechanical cooling systems were disabled, and natural ventilation was modeled at 5 ACH under free-running control logic. This represents a controlled upper-bound mixed-mode ventilation scenario rather than a direct measurement of residential air-change rates. In active-mode, an Ideal Loads Air System was used with a cooling setpoint of 26 °C and a fixed COP of 3.0. The dual-mode protocol distinguishes free-running thermal performance from mechanical cooling requirements, consistent with

mixed-mode assessments in which the selected operation mode can significantly influence both comfort and energy outcomes [30].

Table 4. Custom Residential Occupancy Schedule.

Time Period	Weekdays (Mon–Fri)	Weekends (Sat–Sun)	Assumed Occupancy State
00:00–08:00	100%	100%	Night-time/early morning occupancy
08:00–18:00	0%	100%	Daytime absence on weekdays
18:00–24:00	100%	100%	Evening/ Night occupancy

Because the passive-mode ventilation rate of 5 ACH represents an upper-bound benchmark assumption rather than a direct measurement of residential air-change rates, a limited passive sensitivity analysis was also performed at 2 ACH for all 15 archetype–WWR combinations. This additional sensitivity check was used to assess the robustness of passive comfort and overheating results under lower ventilation assumptions.

Taken together, the simulation matrix consisted of five archetypes $\times$ three WWR scenarios $\times$ two operation modes, yielding 30 annual simulations and 262,800 hourly timestep records. This dual-mode benchmark structure allowed detached, attached/row-house, and vertically scaled apartment forms to be compared on a common basis while controlling non-morphological variables.

3.5. Python-Based Post-Processing and Performance-Metric Extraction

Hourly simulation outputs from the passive and active DesignBuilder/EnergyPlus runs were exported as CSV files and post-processed using custom Python scripts to derive the annual performance indicators used in the study. In passive mode, the key variables were hourly indoor operative temperature and outdoor dry-bulb temperature, whereas in active mode, the principal output variable was DistrictCooling:Facility (W). For multi-story archetypes, the building-level indoor operative temperature series was computed as the hourly arithmetic mean across the modeled floor zones at each timestep. In addition to the annual all-hour passive comfort metric, an occupied-hour passive comfort metric was also derived by applying the occupancy schedule mask during post-processing. A limited 2 ACH passive sensitivity set was processed using the same workflow for comparison against the baseline 5 ACH passive runs. Such simulation-to-post-processing workflows are widely used in building-performance studies to transform annual dynamic outputs into interpretable energy, comfort, and overheating indicators for comparative analysis [31,32].

3.5.1. Passive Comfort Percentage (PCP)

Passive comfort was evaluated from the free-running simulations using the adaptive comfort equation implemented in the Python workflow, consistent with the Indian mixed-mode adaptive comfort framework reported in the literature [5,6]. The neutral comfort temperature was calculated as:

$$T_{neutral} = 0.28T_{rm} + 17.87 \quad (1)$$

where T_{rm} is the exponentially weighted running mean of daily outdoor dry-bulb temperature calculated using $\alpha = 0.8$. The 90% acceptability limits were defined as:

$$\begin{aligned} T_{lower} &= T_{neutral} - 3.48 \\ T_{upper} &= T_{neutral} + 3.48 \end{aligned}$$

At each hourly timestep, the building-level indoor operative temperature was compared against these adaptive limits. Passive comfort percentage (PCP) was then calculated as:

$$PCP = \frac{N_{comfort}}{N_{total}} \times 100 \quad (2)$$

where $N_{comfort}$ is the number of hourly records within the adaptive comfort band and N_{total} is the total number of annual hourly records. In the implemented workflow, PCP was calculated as an all-hour annual comfort metric rather than as an occupancy-filtered metric. This choice was retained to characterize the annual passive habitability of each archetype under the adopted adaptive benchmark, while the occupancy schedule influenced the simulations indirectly through internal gains and control logic.

In addition to all-hour PCP, an occupied-hour passive comfort percentage (PCP_occ) was calculated by applying the occupancy schedule mask to the passive-mode hourly record. The all-hour PCP metric was retained to characterize intrinsic annual passive habitability, whereas PCP_occ was used to assess comfort exposure during occupied periods.

$$PCP_{occ} = \frac{N_{comfort, occ}}{N_{occ}} \times 100 \quad (3)$$

where $N_{comfort, occ}$ is the number of occupied-hour records falling within the adaptive comfort band and N_{occ} is the total number of occupied-hour records.

3.5.2. Adaptive Degree-Hours (ADH)

To quantify overheating severity, the passive-mode results were further processed into adaptive degree-hours (ADH). Degree-hour type indices are widely used to capture the cumulative intensity of overheating over time because they combine both magnitude and duration of discomfort exceedance into a single measure [20,32]. In the present study, hourly overheating was defined relative to the adaptive upper comfort limit:

$$ADH_h = \max(0, T_{indoor,h} - T_{upper,h}) \quad (4)$$

and the annual cumulative value was calculated as:

$$ADH = \sum_{h=1}^{8760} ADH_h \quad (5)$$

where $T_{indoor,h}$ is the hourly building-level indoor operative temperature and $T_{upper,h}$ is the hourly adaptive upper comfort threshold. As implemented in the Python 3.12.7 workflow, ADH was computed over the full annual hourly record, thereby representing the cumulative annual intensity of overheating above the adaptive comfort limit.

3.5.3. Annual Cooling Energy Demand (ACED)

For the active-mode simulations, annual cooling demand was derived from the hourly DistrictCooling:Facility (W) output. The hourly thermal cooling load was summed over the full year and converted to a cooling-equivalent electrical energy demand using a fixed coefficient of performance (COP) of 3.0. The annual result was then normalized by the EnergyPlus-reported total building area:

$$ACED = \frac{\sum Q_{cool,h}}{1000 \times COP \times A} \quad (6)$$

where $Q_{cool,h}$ is the hourly cooling load in watts and A is the EnergyPlus-reported total building area in m^2 . ACED is reported in $kWh/m^2 \cdot yr$. Because the active simulations used an Ideal Loads Air System, this metric should be interpreted as a cooling-equivalent electrical energy intensity derived from ideal thermal load rather than as a directly simulated end-use electricity meter output.

3.5.4. Peak Electrical Demand Intensity (PEDI)

Peak electrical demand intensity (PEDI) was derived from the maximum annual hourly cooling load obtained from the active-mode simulations. The maximum hourly thermal load was converted to a cooling-equivalent electrical demand using $COP = 3.0$ and then normalized by EnergyPlus-reported total building area:

$$PEDI = \frac{\max(Q_{cool,h}) / COP}{A} \quad (7)$$

where $Q_{cool,h}$ is the hourly cooling load in watts and A is the EnergyPlus-reported total building area in m^2 . PEDI is reported in W/m^2 . The indicator was used as a comparative proxy for the relative peak-load implications of the archetypes consistent with the broader building-energy literature showing that higher ambient heat stress and indoor cooling requirements contribute not only to total electricity use but also to peak power demand [33].

In addition to PEDI, the whole-building peak cooling-equivalent electrical demand was also derived without area normalization:

$$P_{peak, abs} = \frac{\max(Q_{cool,h})}{COP \times 1000} \quad (8)$$

where $P_{peak, abs}$ is reported in kW. Reporting both normalized and absolute peak demand was used to distinguish peak-load intensity from whole-building peak-load magnitude.

3.5.5. Diagnostic Physics: Decrement Factor and Time Lag

In addition to annual comfort and energy indicators, the passive-mode temperature series was used to derive two diagnostic physics parameters: decrement factor and time lag. These indicators are commonly used to interpret the damping and delay behavior of building envelopes under periodic heat exposure [34]. In the implemented Python workflow, the single hottest day of the year was first identified as the day containing the annual maximum outdoor dry-bulb temperature. Indoor and outdoor temperature profiles for that day were then compared.

The decrement factor was calculated as:

$$f = \frac{A_i}{A_e} \quad (9)$$

where A_i is the indoor operative temperature amplitude and A_e is the outdoor temperature amplitude. The time lag was calculated as:

$$\phi = t_{in, max} - t_{out, max} \quad (10)$$

where $t_{in, max}$ and $t_{out, max}$ are the times of the indoor and outdoor maximum temperature, respectively. Together, these two metrics provide a compact diagnostic description of how strongly each archetype attenuates and delays outdoor heat signals under extreme summer exposure.

3.5.6. Output Synthesis

The post-processing workflow produced a final set of annual performance indicators for each archetype–WWR combination: all-hour passive comfort percentage (PCP), occupied-hour passive comfort percentage (PCP_occ), adaptive degree-hours (ADH), annual cooling energy demand (ACED), peak electrical demand intensity (PEDI), whole-building peak cooling-equivalent electrical demand, decrement factor, and time lag. These metrics formed the basis for the cross-archetype comparisons reported in Section 4. A summary of the performance metrics is provided in Table 5.

Table 5. Summary of performance metrics.

Domain	Performance Metric	Symbol/Unit	Calculation
Passive Habitability	All-hour Passive Comfort Percentage	PCP (%)	Fraction of annual hourly records for which indoor operative temperature lies within the adaptive comfort band
	Occupied-hour Passive Comfort Percentage	PCP_occ (%)	Fraction of occupied-hour records for which indoor operative temperature lies within the adaptive comfort band
Overheating severity	Adaptive degree-hours	ADH (°C·h)	Cumulative annual exceedance of indoor operative temperature above the adaptive comfort limit
Cooling Energy Performance	Annual cooling energy demand	ACED (kWh/m ² ·yr)	Annual DistrictCooling:Facility load converted to cooling-equivalent electrical demand using COP = 3.0 and normalized by EnergyPlus-reported total building area
Peak demand	Peak electrical demand intensity	PEDI (W/m ²)	Maximum hourly cooling load converted to cooling-equivalent electrical demand using COP = 3.0 and normalized by EnergyPlus-reported total building area
	Whole-building peak cooling-equivalent electrical demand	$P_{peak, abs}$ (kW)	Maximum hourly DistrictCooling:Facility load converted to cooling-equivalent electrical demand using COP = 3.0 without area normalization
Diagnostic physics	Decrement Factor	f	Ratio of indoor to outdoor temperature amplitudes (A_i/A_e), on the hottest day
	Thermal Time Lag	ϕ (hours)	Time difference between peak outdoor and peak indoor temperatures on the hottest day

Note: PCP, PCP_occ, and ADH were derived from passive-mode simulations using the adaptive comfort equation implemented in the Python workflow. ACED, PEDI, and whole-building peak cooling-equivalent electrical demand were derived from active-mode simulations. PEDI represents an area-normalized cooling-equivalent electrical demand proxy rather than a full system-level power output.

3.6. Comparative Analysis and Data Synthesis

The thermal behavior of the five archetypes across the three WWR scenarios was compared using the annual performance indicators derived through the post-processing workflow. In addition to the baseline annual comparisons, passive-mode results were also examined under a reduced natural ventilation assumption (2 ACH) to test the sensitivity of comfort and overheating outcomes to the ventilation-rate benchmark. Peak-demand analysis considered both area-normalized PEDI (W/m²) and whole-building peak cooling-

equivalent electrical demand (kW). The occupied-hour PCP and 2 ACH sensitivity results were used to test whether the principal comparative findings remained robust under more restrictive passive-ventilation assumptions.

Because the study employed a controlled full-factorial simulation matrix rather than empirical observations, the analysis relied on direct cross-comparison of deterministic simulation outputs instead of inferential statistical testing. This approach is consistent with parametric building-performance studies that systematically vary design variables to assess their effects on energy and comfort [28,35–37].

The comparative analysis addressed three principal questions: first, the thermal effects of horizontal attachment and party-wall condition through the comparison of ARCH-D and ARCH-R; second, the effect of vertical scaling through the comparison of ARCH-LR, ARCH-MR, and ARCH-HR under a common modeled roof/plan area and increasing floor count; and third, the sensitivity of each archetype to increasing WWR. To support integrated interpretation, the results were synthesized into tabular and graphical formats. Specifically, ACED and PCP were plotted simultaneously in a bivariate energy-comfort domain to reveal morphology-specific trade-offs between mechanical cooling intensity and passive habitability. The same comparative framework was subsequently used to interpret overheating severity and peak-demand implications in relation to occupant exposure and infrastructure stress.

3.7. *Exploratory Reduced-Order Surrogate Modeling*

3.7.1. Dataset Preparation and Feature Selection

An exploratory reduced-order surrogate model was developed to examine whether the annual performance indicators generated from the simulation stage could be approximated through a computationally lighter screening model. The objective of this stage was not to reproduce hourly thermal trajectories, but to estimate the aggregated annual outputs most relevant to early-stage design comparison. Accordingly, the surrogate targets were defined as annual cooling energy demand (ACED), all-hour passive comfort percentage (PCP), adaptive degree-hours (ADH), and peak electrical demand intensity (PEDI) for each archetype–WWR combination.

The input features were selected to represent the principal morphology variables explicitly investigated in the study: building height (vertical scaling across archetypes), window-to-wall ratio (façade openness and glazing exposure) and attachment condition (presence or absence of party-wall attachment). In the regression workflow, the attachment condition was coded as a binary variable, with the party-wall-connected archetype assigned a value of 1 and all non-party-wall-connected archetypes assigned a value of 0. These variables were selected because they directly correspond to the comparative simulation experiments and represent the dominant form-related drivers isolated in the study.

3.7.2. Model Structure

A second-order polynomial regression model was adopted as the surrogate structure. This formulation was selected because the design space was limited, structured, and physically interpretable, making a response-surface model more appropriate than a highly parameterized black-box model. In addition, the simulation results indicated that performance behavior was not purely linear, particularly with respect to the interaction between building height and WWR. Similar regression-based reduced-order formulations have been used in building energy research to approximate simulation outputs for early-stage design analysis [11,28,38].

For each target output, a separate regression model was defined as:

$$\hat{Y} = \beta_0 + \beta_1 h + \beta_2 WWR + \beta_3 A_c + \beta_4 h^2 + \beta_5 WWR^2 + \beta_6 (h \times WWR) + \beta_7 (h \times A_c) + \beta_8 (WWR \times A_c) + \varepsilon$$

where $\hat{Y}$ is the predicted annual performance metric, h is the building height, WWR is the window-to-wall ratio, A_c is the binary attachment-condition variable, β_0 is the intercept, $\beta_1 - \beta_8$ are regression coefficients, and ε is the residual error term. The interaction terms were retained to examine whether the performance penalty associated with increasing WWR changes with building height and attachment condition. Because A_c is binary, the A_c^2 term was omitted as mathematically redundant. The fitted coefficients for each surrogate model are reported in the Supplementary Materials.

3.7.3. Validation Strategy and Error Metrics

The surrogate model was validated at the scenario level rather than randomly splitting hourly simulation records. The independent cases in the dataset were the 15 annual archetype- WWR scenarios, whereas hourly outputs from the same annual simulation are temporally correlated and therefore not statistically independent. Model performance was therefore evaluated using leave-one-scenario-out cross-validation (LOOCV), in which each archetype- WWR case was excluded once from model fitting and predicted using the model trained on the remaining 14 cases.

Model performance was assessed using the coefficient of determination (R^2), root mean square error (RMSE), and mean absolute error (MAE). In addition, residual ranges were examined to identify whether errors were concentrated in specific performance indicators. Given the small number of independent scenarios, the surrogate model is interpreted as a bounded exploratory screening tool rather than a generalizable predictive model. The model coefficients and residual summary are provided in the Supplementary Materials to improve transparency and reproducibility.

4. Results

This section presents the simulated annual performance of the five residential archetypes across the three WWR scenarios under the standardized benchmark conditions defined in Section 3. The analysis focuses on annual cooling demand, passive comfort, overheating severity, peak-demand implications, and diagnostic thermal-response indicators derived from the passive and active simulations. The results are interpreted to examine three principal morphology effects: vertical scaling, party-wall attachment and glazing sensitivity.

4.1. Annual Cooling Demand and Passive Comfort Across Archetypes

Table 6 summarizes the annual cooling energy demand (ACED), all-hour passive comfort percentage (PCP), and occupied-hour passive comfort percentage (PCP_occ) for the five residential archetypes under the three WWR scenarios. ACED was derived from active-mode simulations and normalized using the EnergyPlus-reported total building area from the final simulation models. PCP was retained as a benchmark indicator of annual passive habitability, while PCP_occ was added to distinguish comfort conditions during the adopted occupied schedule. Together, these indicators show that increasing vertical scale is associated with higher cooling demand and lower passive comfort, while the attached/row-house archetype benefits from reduced exposed envelope area. The inclusion of PCP_occ confirms that the principal comfort trends remain consistent when the occupancy schedule is explicitly considered.

Table 6. Annual cooling energy demand and passive comfort across residential archetypes.

Archetype	WWR (%)	ACED (kWh/m ² ·yr)	PCP (%)	PCP_occ (%)
ARCH-D	20	25.42	67.12	68.67
ARCH-D	30	26.29	65.61	67.87
ARCH-D	40	26.73	64.32	66.98
ARCH-R	20	21.18	70.59	71.66
ARCH-R	30	21.97	69.37	70.89
ARCH-R	40	22.04	68.20	70.03
ARCH-LR	20	33.13	68.16	70.75
ARCH-LR	30	35.61	64.55	68.42
ARCH-LR	40	37.45	62.08	66.50
ARCH-MR	20	39.85	55.64	59.59
ARCH-MR	30	43.76	51.40	55.51
ARCH-MR	40	46.70	48.57	52.96
ARCH-HR	20	42.79	49.28	52.54
ARCH-HR	30	47.39	45.92	49.11
ARCH-HR	40	50.85	43.68	46.86

Note: ACED was recalculated using EnergyPlus-reported total building area from the final active simulation models. PCP represents all-hour annual passive comfort percentage, while PCP_occ represents occupied-hour passive comfort percentage calculated using the adopted residential occupancy schedule.

4.1.1. Vertical Scaling Effect

A strong height-dependent pattern is evident when the apartment archetypes are compared at a fixed glazing ratio. At 20% WWR, ACED increases from 33.13 kWh/m²·yr in the low-rise archetype (ARCH-LR) to 39.85 kWh/m²·yr in the mid-rise archetype (ARCH-MR) and 42.79 kWh/m²·yr in the high-rise archetype (ARCH-HR). Over the same range, PCP declines from 68.16% to 55.64% and then to 49.28%. Thus, relative to the low-rise baseline, the high-rise archetype shows a 29.2% increase in annual cooling load and an 18.88 percentage-point reduction in passive comfort at the same WWR. Similar monotonic deterioration is observed at 30% and 40% WWR, confirming that the thermal penalty associated with increased height is not restricted to a single glazing condition.

Within this benchmark design, increasing vertical scale is associated with both higher cooling intensity and lower annual passive comfort. This effect should not be interpreted as a consequence of height alone. As shown by the geometric exposure descriptors presented in Section 3.3.2, the apartment archetypes differ not only in floor count but also in exposed façade area, roof-area fraction per unit floor area, and the envelope-to-volume relationship. Accordingly, the observed differences reflect the combined influence of vertical scaling, increased exposed façade area, reduced roof-area fraction, and overall exposed-envelope geometry under standardized boundary conditions. Figure 2 reinforces this pattern by showing that the low-rise cases occupy the lower-energy, higher-comfort region of the bivariate map, whereas the mid-rise and especially the high-rise cases shift progressively toward higher ACED and lower PCP. Within this design space, increasing height imposes a morphology-dependent scale penalty that amplifies cooling burden and reduces passive habitability.

4.1.2. Party-Wall Attachment Effect

The comparison between the detached archetype (ARCH-D) and the attached/row-house archetype (ARCH-R) shows a clear performance advantage associated with party-wall attachment. At 20% WWR, ARCH-R records the lowest ACED among all archetypes at 21.18 kWh/m²·yr, compared with 25.42 kWh/m²·yr for ARCH-D, corresponding to a reduction of approximately 16.7% relative to the detached case. At the same time, PCP

increases from 67.12% in the detached archetype to 70.59% in the attached archetype, a gain of 3.47 percentage points. This pattern remains consistent across the higher glazing ratios: at 40% WWR, ARCH-R still performs better than ARCH-D with 22.04 kWh/m²·yr versus 26.73 kWh/m²·yr for ACED and 68.20% versus 64.32% for PCP.

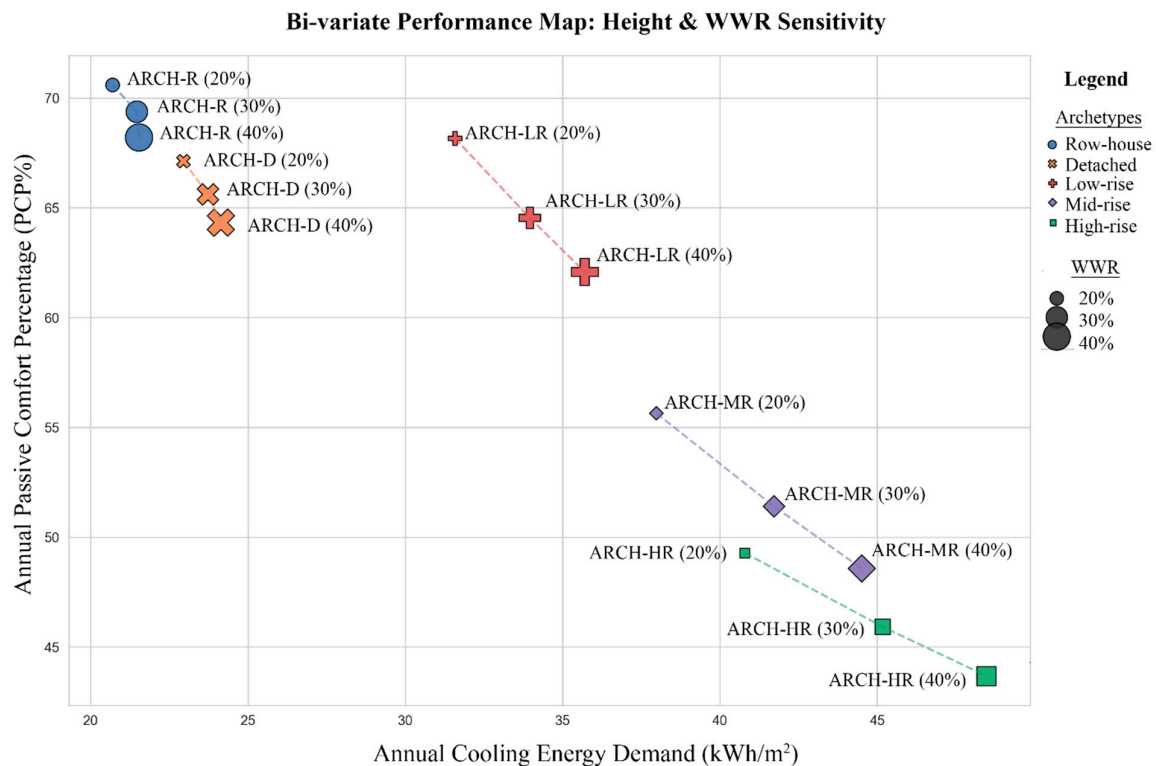


Figure 2. Bivariate energy-comfort performance map across archetypes (The dashed lines connect the 20%, 30%, and 40% WWR scenarios within the same archetype).

These results indicate that the attached/row-house archetype maintains both a lower cooling requirement and a higher passive comfort fraction than the detached archetype under identical benchmark conditions. Within the present modeling framework, this difference can be attributed to the reduced exposed envelope area associated with the party-wall condition, as reflected in the lower exposed wall area and lower exposed-envelope-to-volume ratio of ARCH-R. The attached/row-house archetype, therefore, emerges as the most thermally favorable case among the five studied archetypes in terms of annual cooling demand and passive comfort performance.

4.1.3. WWR Sensitivity Across Archetypes

The influence of WWR is not uniform across archetypes. In every case, increasing WWR leads to higher ACED and lower PCP, but the magnitude of change increases with building height. For the low-rise archetype, increasing WWR from 20% to 40% raises ACED from 33.13 to 37.45 kWh/m²·yr, an increase of 4.32 kWh/m²·yr, while PCP declines from 68.16% to 62.08%, a reduction of 6.08 percentage points. In contrast, for the high-rise archetype, the same WWR increase raises ACED from 42.79 to 50.85 kWh/m²·yr, an increase of 8.06 kWh/m²·yr, while PCP declines from 49.28% to 43.68%, a reduction of 5.60 percentage points. The cooling-energy penalty of increased glazing is therefore substantially stronger in the high-rise archetype than in the low-rise archetype.

A similar pattern occurs in the mid-rise archetype, where ACED increases by 6.85 kWh/m²·yr between 20% and 40% WWR, compared with 4.32 kWh/m²·yr for ARCH-LR. In contrast, the attached/row-house archetype shows the least sensitivity to glazing,

with ACED increasing by only 0.86 kWh/m²·yr and PCP decreasing by 2.39 percentage points over the same WWR range. These results show that WWR sensitivity is not an archetype-invariant property. Instead, the annual thermal consequence of glazing depends strongly on the underlying form, with taller and more exposed archetypes exhibiting greater sensitivity than attached or low-rise forms. This pattern is also visible in Figure 2, where the trajectories connecting the 20%, 30%, and 40% WWR cases become steeper and longer for the vertically scaled archetypes than for the attached and detached forms.

4.2. Overheating Severity: Adaptive Degree-Hours (ADH)

While passive comfort percentage (PCP) provides a useful annual measure of thermal acceptability, it does not capture the magnitude of overheating when indoor conditions exceed the adaptive upper comfort limit. To address this, overheating severity was evaluated using adaptive degree-hours (ADH), which represent the cumulative annual intensity of indoor thermal discomfort above the adopted adaptive threshold. Figures 3 and 4 summarize the resulting ADH patterns across archetypes and WWR scenarios.

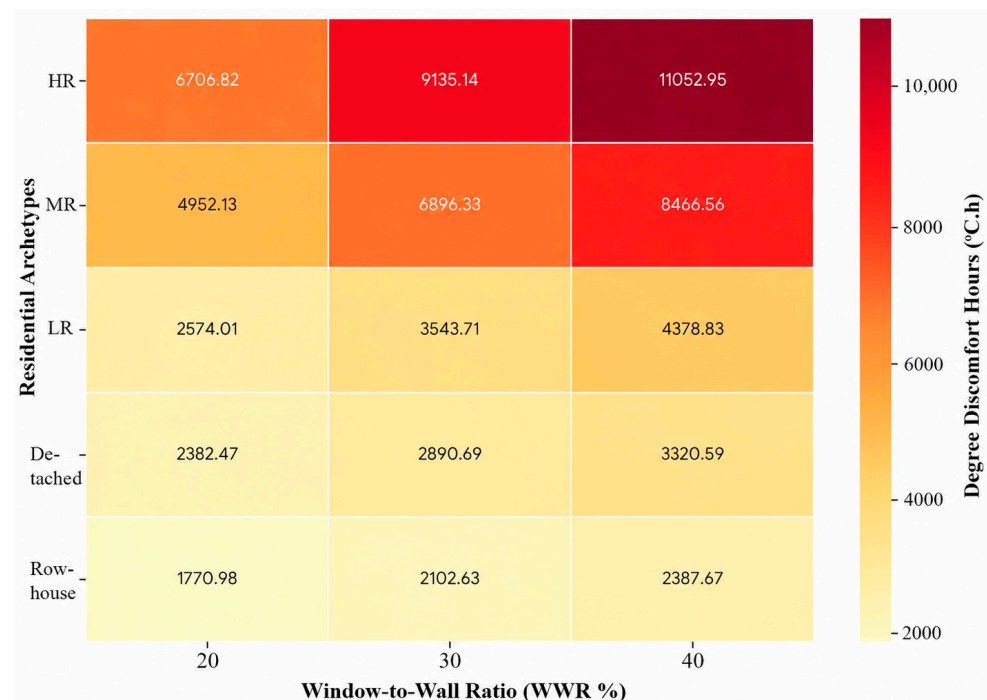


Figure 3. Adaptive degree-hours (ADH) across residential archetypes.

The results show a strong and non-uniform increase in overheating severity with both building height and glazing ratio. At 20% WWR, the attached/row-house archetype (ARCH-R) records the lowest overheating burden at 1771 °C·h, whereas the high-rise archetype (ARCH-HR) records 6706 °C·h, approximately 3.8 times higher. The low-rise archetype occupies an intermediate position, indicating that the increase in overheating severity with vertical scaling is substantial rather than incremental. This pattern is consistent with the deterioration in PCP observed earlier, but ADH reveals the intensity of exceedance more explicitly by showing how far and how persistently indoor temperatures rise above the adaptive comfort limit.

The effect of increasing WWR is also strongly archetype-dependent. For the high-rise archetype, increasing WWR from 20% to 40% increases ADH from 6706 °C·h to 11,053 °C·h, an increase of approximately 64.8%. In contrast, the corresponding increase is much smaller in the attached archetype, where ADH rises from 1771 °C·h to 2388 °C·h, and in the low-rise archetype, where it rises to 4379 °C·h at 40% WWR. These differences indicate

that the overheating penalty associated with additional glazing is amplified in taller and more exposed forms, whereas attached and lower-rise forms remain comparatively less vulnerable within the same benchmark design space.

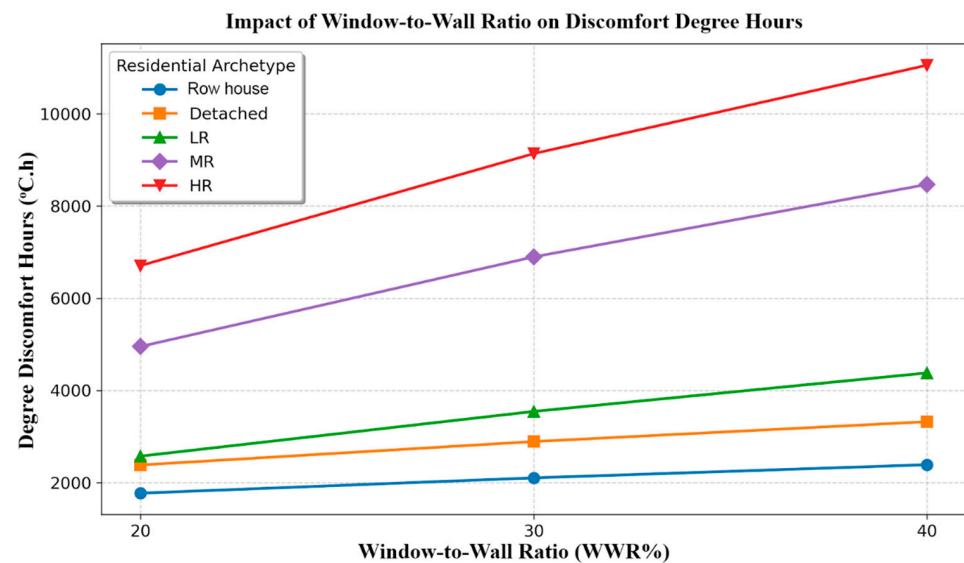


Figure 4. Effect of WWR on ADH across archetypes.

Figures 3 and 4 show that ADH distinguishes overheating severity across archetypes more clearly than PCP alone. High-rise cases with higher glazing ratios exhibit disproportionately greater cumulative overheating, reflecting the combined effects of greater exposed façade area, reduced roof-area fraction per unit floor area, and higher glazing sensitivity in the vertically scaled forms. By contrast, the attached/row-house archetype remains the least vulnerable to overheating across WWR levels, confirming the benefit of reduced exposed envelope area under the present controlled assumptions.

Ventilation Sensitivity Analysis

Because the benchmark passive simulations used a natural-ventilation input of 5 ACH, a sensitivity analysis was performed at 2 ACH to examine whether the passive comfort and overheating patterns were dependent on the upper-bound ventilation assumption. Table 7 compares all-hour PCP, occupied-hour PCP, and ADH under the 5 ACH benchmark and the 2 ACH sensitivity case.

The results show that reducing the natural-ventilation rate from 5 ACH to 2 ACH changes the absolute passive-performance values, particularly for the taller apartment archetypes. In ARCH-HR at 40% WWR, PCP decreases from 43.68% to 35.37%, while ADH increases from 11,053 °C·h to 15,504 °C·h. A similar but slightly smaller deterioration is observed in ARCH-MR. This confirms that passive comfort and overheating severity are sensitive to ventilation assumptions, especially in taller and more highly glazed forms.

For the single-story detached and attached archetypes, PCP increases slightly under the 2 ACH case, while ADH also increases. This is not contradictory because PCP counts hours within the complete adaptive comfort band, whereas ADH only measures overheating above the upper adaptive limit. Lower ventilation can reduce cool-period undercooling in some hours while still increasing cumulative overheating during warmer periods. Therefore, ADH provides a more direct overheating-severity signal in the ventilation sensitivity test.

Overall, the sensitivity analysis confirms that the main morphology-dependent pattern remains robust: high-rise and high-WWR cases continue to show the greatest overheating

burden, while the attached/row-house archetype remains the least vulnerable. However, the absolute passive comfort values should be interpreted as ventilation-dependent benchmark results rather than field-measured comfort predictions.

Table 7. Ventilation sensitivity of passive comfort and overheating under 5 ACH and 2 ACH natural ventilation.

Archetype	WWR (%)	PCP 5 ACH (%)	PCP 2 ACH (%)	PCP_occ 5 ACH (%)	PCP_occ 2 ACH (%)	ADH 5 ACH (°C·h)	ADH 2 ACH (°C·h)
ARCH-D	20	67.12	68.61	68.67	70.76	2382	2440
ARCH-D	30	65.61	66.86	67.87	69.61	2891	2953
ARCH-D	40	64.32	65.47	66.98	68.60	3321	3385
ARCH-R	20	70.59	72.26	71.66	73.98	1771	1818
ARCH-R	30	69.37	70.97	70.89	73.12	2103	2156
ARCH-R	40	68.20	69.89	70.03	72.37	2388	2444
ARCH-LR	20	68.16	66.95	70.75	69.80	2574	3197
ARCH-LR	30	64.55	62.61	68.42	66.55	3544	4335
ARCH-LR	40	62.08	59.74	66.50	64.13	4379	5303
ARCH-MR	20	55.64	49.27	59.59	52.49	4952	6955
ARCH-MR	30	51.40	44.46	55.51	47.56	6896	9461
ARCH-MR	40	48.57	41.38	52.96	44.29	8467	11,456
ARCH-HR	20	49.28	41.92	52.54	43.95	6707	9812
ARCH-HR	30	45.92	38.46	49.11	40.37	9135	12,999
ARCH-HR	40	43.68	35.37	46.86	37.90	11,053	15,504

Note: PCP represents all-hour passive comfort percentage, while PCP_occ represents occupied-hour passive comfort percentage calculated using the adopted residential occupancy schedule. The 2 ACH cases were generated by changing only the natural-ventilation input from 5 ACH to 2 ACH while keeping all other simulation inputs unchanged.

4.3. Peak Electrical Demand Intensity (PEDI)

While ACED captures the annual cooling burden, it does not indicate how sharply cooling demand peaks during the most thermally stressful hours. To address this, peak demand was evaluated using two complementary indicators: whole-building peak cooling-equivalent electrical demand (kW) and peak electrical demand intensity (PEDI, W/m²). Reporting both metrics is important because area-normalized PEDI captures intensity, whereas absolute peak demand indicates the total building-level load that may affect local electrical infrastructure. Table 8 summarizes both indicators across the archetypes–WWR scenarios.

The results show that the single-story archetypes have higher area-normalized PEDI than the apartment archetypes. However, the absolute peak demand follows the opposite pattern because total building area increases substantially with vertical scale. At 20% WWR, ARCH-D records a PEDI of 37.85 W/m² and an absolute peak electrical demand of 6.67 kW, whereas ARCH-HR records a lower PEDI of 24.76 W/m² but a much higher absolute peak electrical demand of 118.01 kW. This distinction shows that area-normalized and whole-building peak indicators should not be interpreted interchangeably. PEDI is useful for comparing intensity, while absolute peak kW is more relevant for understanding building-level infrastructure implications.

The influence of WWR on PEDI is positive across most archetypes, but the magnitude of increase differs by form. For the detached archetype, PEDI rises from 37.85 W/m² at 20% WWR to 40.57 W/m² at 40% WWR, while in the low-rise archetype, it increases from 25.55 W/m² to 30.13 W/m² over the same range. The high-rise archetype also shows a consistent increase from 24.76 W/m² to 27.98 W/m², indicating that additional glazing raises peak cooling demand intensity even in the high-rise forms. By contrast,

the attached/row-house archetype shows only a marginal change, remaining close to 32 W/m² across all three WWR scenarios. This again suggests that the party-wall condition moderates not only annual cooling demand and passive comfort but also sensitivity to higher glazing ratios.

Table 8. Peak cooling-equivalent electrical demand across residential archetypes and WWR scenarios.

Archetype	WWR (%)	Peak Thermal Load (kW)	Peak Electrical Demand (kW)	PEDI (W/m ²)
ARCH-D	20	20.00	6.67	37.85
ARCH-D	30	20.82	6.94	39.42
ARCH-D	40	21.43	7.14	40.57
ARCH-R	20	15.91	5.30	32.04
ARCH-R	30	16.31	5.44	32.84
ARCH-R	40	16.30	5.43	32.83
ARCH-LR	20	109.60	36.53	25.55
ARCH-LR	30	123.00	41.00	28.68
ARCH-LR	40	129.24	43.08	30.13
ARCH-MR	20	212.83	70.94	24.81
ARCH-MR	30	228.84	76.28	26.67
ARCH-MR	40	242.33	80.78	28.25
ARCH-HR	20	354.02	118.01	24.76
ARCH-HR	30	378.45	126.15	26.47
ARCH-HR	40	400.11	133.37	27.98

Note: Peak electrical demand was calculated from the maximum annual hourly DistrictCooling:Facility output using COP = 3.0. PEDI is the peak electrical demand normalized by EnergyPlus-reported total building area.

Taken together, these results show that ACED and PEDI vary across archetypes. In this benchmark design, detached and attached single-story forms have the highest PEDI per unit building area, while apartment archetypes, despite their higher annual cooling burden, exhibit lower values on an area-normalized basis. This distinction reveals that archetypes with high annual cooling energy use do not necessarily produce the highest peak demand intensity. Thus, PEDI complements ACED by highlighting morphology-dependent differences in peak-load behavior within this study's bounded design space.

4.4. Diagnostic Physics: Decrement Factor and Time Lag

To support the physical interpretation of annual energy and comfort results, two diagnostic physics indicators were derived from the passive-mode temperature series: decrement factor and time lag. These indicators were calculated for the hottest day of the annual weather file and were used to assess how each archetype attenuated and delayed the outdoor temperature signal under the standardized benchmark assumptions.

Table 9 shows the decrement factor values across archetypes and WWR scenarios. A lower decrement factor indicates stronger damping of outdoor thermal fluctuations, whereas a higher value indicates greater transmission of this variation into the indoor environment. The results show that the decrement factor increased consistently with WWR across all archetypes, indicating weaker thermal damping as the glazing proportion increased. In the apartment archetypes, the decrement factor increased from 0.373 to 0.444 in ARCH-LR, from 0.338 to 0.420 in ARCH-MR, and from 0.326 to 0.414 in ARCH-HR as WWR increased from 20% to 40%. A similar trend was observed in the single-story forms, with values increasing from 0.605 to 0.690 in ARCH-D and from 0.560 to 0.616 in ARCH-R over the same WWR range.

Time lag remained constant at 2.0 h across all archetype–WWR combinations. This limited variation is likely related to the use of the same envelope construction, thermal mass and material properties across all models, combined with the hourly resolution of the

simulation outputs. Therefore, time lag was not used as a differentiating indicator in the Results section. Within the present benchmark design, the decrement factor provided the more informative diagnostic measure because it captured the reduction in short-term thermal damping associated with increasing WWR. These findings support the broader ACED, PCP, and ADH results by showing that higher glazing weakens the archetypes' ability to attenuate outdoor heat fluctuations under fixed construction and operation assumptions.

Table 9. Decrement factor across archetypes and WWR scenarios.

Archetype	WWR (%)	Decrement Factor, f
ARCH-D	20	0.605
ARCH-D	30	0.651
ARCH-D	40	0.690
ARCH-R	20	0.560
ARCH-R	30	0.590
ARCH-R	40	0.616
ARCH-LR	20	0.373
ARCH-LR	30	0.412
ARCH-LR	40	0.444
ARCH-MR	20	0.338
ARCH-MR	30	0.384
ARCH-MR	40	0.420
ARCH-HR	20	0.326
ARCH-HR	30	0.375
ARCH-HR	40	0.414

Note: Time lag remained constant at 2.0 h across all archetypes–WWR combinations and is therefore omitted from the table.

4.5. Performance of the Exploratory Reduced-Order Surrogate Model

The exploratory surrogate model described in Section 3.7 was evaluated using leave-one-scenario-out cross-validation (LOOCV) across the 15 annual archetype–WWR scenarios. The model used building height, WWR, and binary attachment condition as inputs to approximate four annual performance indicators: ACED, all-hour PCP, ADH, and PEDI. Because the revised ACED and PEDI values were recalculated using EnergyPlus-reported total building area, the surrogate model performance was also recalculated using the updated dataset.

Table 10 shows that the surrogate model performed strongest for ACED and ADH. ACED was approximated with $R^2 = 0.993$, $RMSE = 0.86 \text{ kWh/m}^2\cdot\text{yr}$, and $MAE = 0.66 \text{ kWh/m}^2\cdot\text{yr}$, while ADH was approximated with $R^2 = 0.937$, $RMSE = 709 \text{ }^\circ\text{C}\cdot\text{h}$, and $MAE = 591 \text{ }^\circ\text{C}\cdot\text{h}$. Performance was moderate for all-hour PCP, with $R^2 = 0.846$, $RMSE = 3.60$ percentage points, and $MAE = 3.00$ percentage points. PEDI showed the weakest cross-validated performance, with $R^2 = 0.729$, $RMSE = 2.63 \text{ W/m}^2$, and $MAE = 2.20 \text{ W/m}^2$.

Table 10. LOOCV performance of the exploratory surrogate model.

Output Metric	R^2	RMSE	MAE	Residual Range
ACED ($\text{kWh/m}^2\cdot\text{yr}$)	0.993	0.86	0.66	−1.52 to 1.43
All-hour PCP (%)	0.846	3.60	3.00	−6.39 to 5.99
ADH ($^\circ\text{C}\cdot\text{h}$)	0.937	709.03	591.15	−1138.01 to 1099.43
PEDI (W/m^2)	0.729	2.63	2.20	−4.94 to 4.35

Note: Validation was performed using leave-one-scenario-out cross-validation across the 15 annual archetype–WWR scenarios. Residual range is reported as simulation-derived values minus predicted values.

The results indicate that the second-order response-surface model captures the broad annual performance trends for cooling demand and overheating severity within the tested design space. However, the weaker PEDI performance confirms that peak-load intensity is more sensitive to individual scenario behavior and is less smoothly represented by the reduced-order model. The parity plots in Figure 5 should therefore be interpreted as evidence of bounded scenario-level approximation rather than general predictive validity. Given the limited sample of 15 independent scenarios, the surrogate model is retained as an exploratory early-stage screening tool and not as a replacement for full building energy simulation.

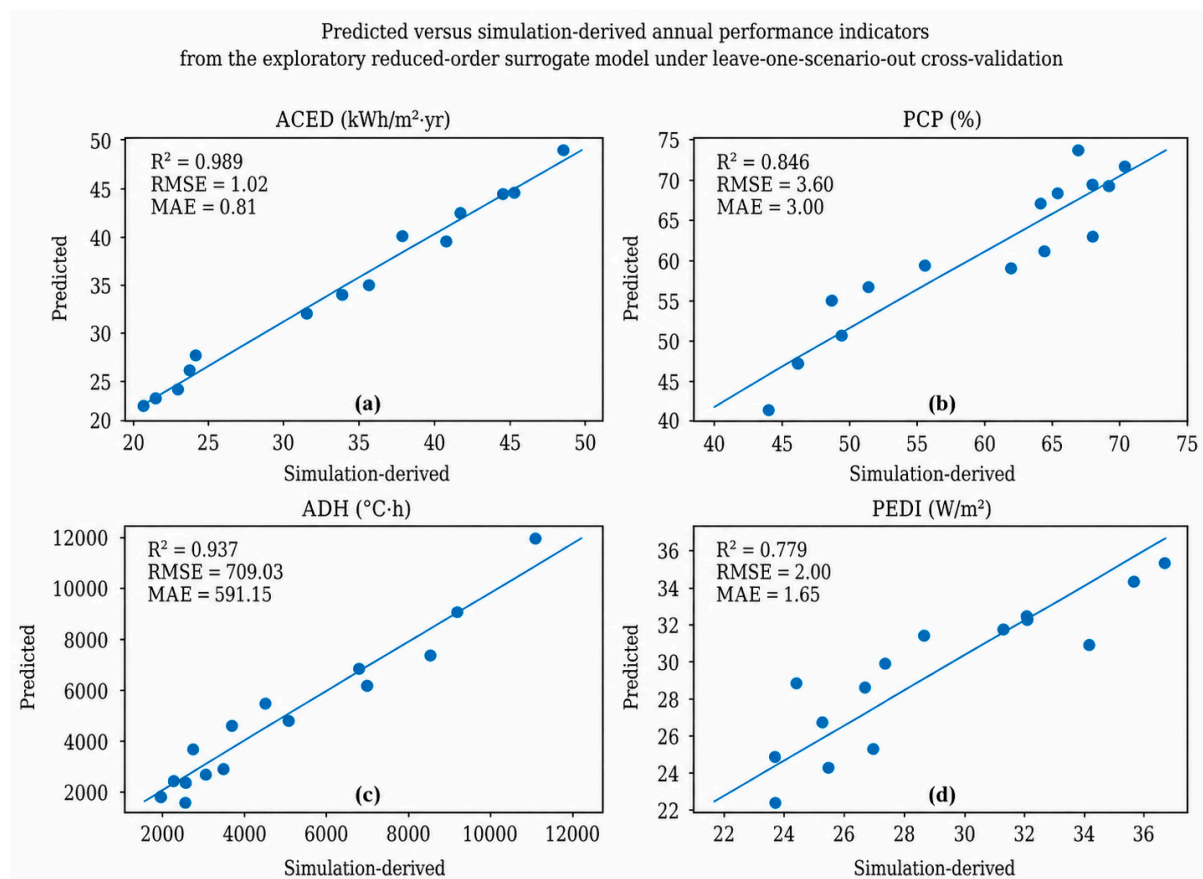


Figure 5. Surrogate-model parity plots under leave-one-scenario-out cross-validation: (a) annual cooling energy demand (ACED, kWh/m²·yr); (b) all-hour passive comfort percentage (PCP, %); (c) adaptive degree-hours (ADH, °C·h); and (d) peak electrical demand intensity (PEDI, W/m²).

5. Discussion

The results indicate that residential thermal performance in this benchmark design is strongly morphology-dependent, beyond glazing ratio alone. Across the five archetypes, increasing building height was associated with higher annual cooling demand, lower passive comfort, and substantially greater overheating severity, despite constant non-morphological inputs. At 20% WWR, ACED increased from 33.13 kWh/m²·yr in the low-rise archetype to 42.79 kWh/m²·yr in the high-rise archetype, while all-hour PCP declined from 68.16% to 49.28%. Similar trends were observed at higher WWR levels, indicating that vertical scaling introduced a consistent thermal penalty within the studied design space. Importantly, this effect should not be interpreted as a consequence of height alone. As shown by the geometric exposure descriptors, the taller apartment forms also differed in exposed façade area, roof-area fraction, and exposed envelope-to-volume relationship. The findings, therefore, support the interpretation of a morphology-dependent scale penalty arising

from the combined effects of vertical scaling and exposure geometry under otherwise standardized assumptions.

A second important finding is that horizontal attachment improves thermal performance, but not merely as a secondary geometric detail. The attached/row-house archetype consistently outperformed the detached archetype across all WWR scenarios, showing both lower ACED and higher all-hour PCP. At 20% WWR, the attached form recorded 21.18 kWh/m²·yr compared with 25.42 kWh/m²·yr for the detached form, while all-hour PCP increased from 67.12% to 70.59%. This indicates that party-wall attachment reduced exposed envelope area sufficiently to improve both annual cooling demand and annual passive habitability. The result is important because it shows that not all densification should be interpreted in the same way: vertical densification and horizontal attachment have very different thermodynamic consequences. Within this benchmark design, attached low-rise housing emerged as the most thermally favorable configuration among the five studied archetypes.

The study also demonstrated that WWR sensitivity is not archetype-invariant. Although higher WWR increased ACED and reduced all-hour PCP across all forms, the magnitude of that effect was substantially greater in the high-rise apartment archetype than in the attached and detached single-story forms. In the low-rise archetype, increasing WWR from 20% to 40% increased ACED by 4.32 kWh/m²·yr, whereas the corresponding increase in the high-rise archetype was 8.06 kWh/m²·yr. A similar escalation was visible in overheating severity: high-rise ADH rose from 6706 °C·h at 20% WWR to 11,053 °C·h at 40% WWR, while the increase remained much smaller in the attached archetype. This indicates that the thermal consequence of glazing is amplified by form, especially where a greater exposed façade area and reduced roof-area fraction intensify the thermal penalty of vertical scaling. From a design perspective, one of the most important implications of the study is therefore that uniform glazing guidance applied across all residential archetypes is unlikely to capture thermally relevant morphology-dependent differences within this bounded benchmark design space.

The inclusion of ADH adds an important layer of interpretation beyond all-hour PCP. All-hour PCP identifies the fraction of annual hours that remain within the adaptive comfort band, but ADH reveals how severe the departures become once comfort is exceeded. This distinction is especially visible in the taller and more highly glazed forms, where all-hour PCP declines while ADH increases sharply. In the present study, the attached/row-house archetype showed the lowest overheating severity, while the high-rise archetype showed the highest. This reinforces the broader point that morphology should not be assessed only through annual energy demand: the same built form that raises cooling demand may also increase the intensity and duration of overheating, which is more directly relevant to occupant exposure and thermal resilience.

The added ventilation sensitivity analysis further strengthens this interpretation. Reducing the passive-mode ventilation assumption from 5 ACH to 2 ACH changed the absolute comfort and overheating values, particularly for the apartment archetypes. In the high-rise archetype at 40% WWR, all-hour PCP decreased from 43.68% to 35.37%, while ADH increased from 11,053 °C·h to 15,504 °C·h. A similar, though slightly smaller, deterioration was observed in the mid-rise cases. At the same time, the relative pattern remained robust: the attached/row-house archetype remained the least vulnerable, whereas the taller and more highly glazed apartment forms remained the most overheating-prone. For the single-story detached and attached cases, all-hour PCP increased slightly under 2 ACH while ADH also increased, indicating that lower ventilation reduced some cool-period discomfort while worsening cumulative overheating during warmer periods. This confirms

that absolute passive comfort values are ventilation-sensitive, but the main morphology-dependent ranking is not simply an artifact of the 5 ACH benchmark assumption.

Considering PEDI alongside ACED reveals a more nuanced pattern. The apartment archetypes exhibit higher annual cooling demand but lower peak electrical demand intensity than the single-story forms when values are normalized by EnergyPlus-reported total building area. In contrast, the detached and attached archetypes exhibit lower annual energy use but higher area-normalized peak demand intensity. At 20% WWR, ARCH-D records a PEDI of 37.85 W/m^2 and an absolute peak electrical demand of 6.67 kW, whereas ARCH-HR records a lower PEDI of 24.76 W/m^2 but a much higher absolute peak electrical demand of 118.01 kW. This means that the forms with the highest annual cooling burden are not necessarily the same forms that impose the highest peak-load intensity, while the larger vertically scaled forms impose the largest absolute building-level peak loads. The PEDI results, therefore, add an important infrastructure perspective to the energy-comfort comparisons, underscoring the importance of form-sensitive planning for both building-scale performance and localized demand behavior.

The diagnostic physics indicators offer limited but useful support for this interpretation. Decrement factor increased consistently with WWR across all archetypes, indicating weaker damping of outdoor thermal variation as glazing increased, whereas time lag remained constant at 2.0 h across the tested cases. This suggests that, within the simplified envelope and controlled assumptions used here, the most important short-term effect of higher glazing is not a delay in peak transmission but a reduction in the envelope's ability to attenuate the daily outdoor heat signal. This is consistent with the observed increase in overheating severity in the more highly glazed cases. At the same time, these diagnostic indicators remain secondary to the annual performance findings, since time lag did not differentiate the archetypes meaningfully in the present design space.

The exploratory reduced-order surrogate model extends the practical relevance of the study, but requires careful interpretation. At the scenario level, the model reproduced ACED and ADH with strong cross-validated performance, while all-hour PCP and especially PEDI were approximated with lower but still acceptable accuracy for screening purposes. Since the model was trained and validated in only 15 annual archetype–WWR scenarios, it should be treated as a bounded proof-of-concept rather than as a generalizable predictive engine. Even so, the results demonstrate that the principal annual morphology-dependent performance trends of the present design space can be approximated through a compact second-order response-surface formulation without rerunning full dynamic simulations. That contribution is useful, particularly because it remains transparent and interpretable rather than relying on a black-box structure.

This study has several limitations that define the boundaries of interpretation. First, the models were intentionally designed as a controlled benchmark and therefore excluded contextual shading from neighboring buildings, balconies, vegetation, and surrounding urban form. This choice allowed consistent comparison of intrinsic archetype sensitivity, but means that the absolute cooling and comfort values should not be interpreted as a full neighborhood prediction. Second, occupancy and ventilation schedules were standardized rather than derived from monitored household behavior. The added 2 ACH sensitivity analysis shows that absolute passive comfort and overheating values are ventilation-sensitive, even though the broad morphology-dependent ranking remains evident. Third, the study is limited to five normalized residential archetypes, three WWR levels, one composite climate city, and one construction template. Finally, the surrogate model is based on only 15 independent annual scenarios and is, therefore, retained as a bounded screening demonstration rather than a general predictive model.

Overall, the discussion shows that the thermodynamic consequences of residential form in a composite climate are not adequately captured by typology-agnostic envelope guidance. In this study, height, attachment condition, glazing ratio, and exposure geometry interacted in ways that produced substantial differences in cooling demand, passive comfort, overheating severity, and peak-load behavior. The most important implication is therefore not that one archetype should universally replace another, but that benchmark-based residential performance interpretation should become more morphology-sensitive, especially where rapid vertical transformation is occurring under otherwise standardized assumptions.

6. Conclusions

This study examined the effects of building height and window-to-wall ratio (WWR) on residential thermal performance in a composite climate using five representative archetypes derived from planned government housing in Patna, India. Using a controlled archetype-level simulation framework in DesignBuilder/EnergyPlus, the study evaluated annual cooling energy demand (ACED), all-hour passive comfort percentage (PCP), occupied-hour passive comfort percentage (PCP_occ), adaptive degree-hours (ADH), peak electrical demand intensity (PEDI), whole-building peak cooling-equivalent electrical demand, and supporting diagnostic physics indicators under passive and active operation modes. The results show that the thermal consequences of residential form are strongly morphology-dependent, even when construction, internal gains, and operation assumptions are held constant.

The first major conclusion is that vertical scaling imposes a clear thermal penalty within the benchmark design space. Compared with the low-rise apartment archetype, the high-rise archetype exhibited higher annual cooling demand, lower passive comfort, and substantially greater overheating severity at the same WWR. At 20% WWR, ACED increased from 33.13 kWh/m²·yr in the low-rise archetype to 42.79 kWh/m²·yr in the high-rise archetype, while all-hour PCP declined from 68.16% to 49.28%. This indicates that increasing residential height under fixed envelope and operation assumptions tends to amplify cooling burden and reduce annual passive habitability. However, this effect should be interpreted as the combined consequence of vertical scaling and associated exposure geometry rather than height alone.

The second conclusion is that party-wall attachment improves performance. The attached/row-house archetype consistently recorded the lowest ACED and the highest all-hour PCP among the five archetypes, highlighting the thermal benefit of reduced exposed envelope area. At 20% WWR, the attached form recorded 21.18 kWh/m²·yr compared with 25.42 kWh/m²·yr for the detached form, while all-hour PCP increased from 67.12% to 70.59%. This indicates that horizontal attachment and vertical scaling should not be interpreted as equivalent forms of densification, since they yield distinct thermal outcomes.

The third conclusion is that the WWR sensitivity is not uniform across forms. Increasing glazing ratio raised cooling demand and overheating severity across all archetypes, but the penalty was substantially greater in the taller apartment forms than in the attached or detached single-story forms. For the low-rise archetype, increasing WWR from 20% to 40% increased ACED by 4.32 kWh/m²·yr, whereas the corresponding increase in the high-rise archetype was 8.06 kWh/m²·yr. Similarly, ADH rose much more sharply in high-rise cases as compared to lower-rise and attached forms. These results indicate that glazing sensitivity is conditioned by morphology and that uniform envelope guidance is unlikely to be thermally appropriate across different residential archetypes within the present benchmark design space.

A further conclusion is that the annual cooling burden and peak demand intensity vary across archetypes. The apartment forms showed higher annual cooling demand but lower PEDI than the single-story forms when values were normalized by EnergyPlus-reported total building area. At the same time, the vertically scaled forms imposed much greater absolute peak cooling-equivalent electrical demand in kW because of their larger overall building size. This suggests that the archetypes associated with higher energy use are not necessarily the same that impose the highest area-normalized peak demand intensity. Accordingly, annual energy planning and peak-demand planning should not be treated as interchangeable, especially under conditions of increasing residential vertical diversification.

The exploratory reduced-order surrogate model further showed that the principal annual performance indicators of the bounded design space can be approximated through a compact second-order polynomial formulation. Cross-validated predictive performance was strongest for ACED and ADH, moderate for all-hour PCP, and weaker for PEDI, indicating that such models may be useful for early-stage screening within a limited scenario space. However, the model should be interpreted as a bounded proof-of-concept rather than as a fully generalizable replacement for full building energy simulation.

Overall, the findings suggest that residential thermal performance in a composite climate is influenced not only by envelope properties but also by archetype-specific exposure geometry, attachment condition, roof-area fraction, and WWR sensitivity. The results do not establish universal envelope thresholds or code-ready prescriptions. Rather, they provide controlled benchmark evidence that typology-agnostic envelope guidance may overlook important morphology-dependent differences in cooling demand, passive habitability, overheating severity, and peak-load behavior.

Future research should extend the analysis to shaded urban contexts, additional climates, monitored occupancy and ventilation behavior, broader archetype datasets, and larger surrogate-model training sets before general design thresholds are proposed.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/buildings16112177/s1>; processed supplementary dataset and Python post-processing scripts used to derive passive comfort, adaptive degree-hours, annual cooling energy demand, peak electrical demand intensity, diagnostic physics indicators, and figure-generation outputs for the reported simulation study.

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References

1. Yan, R.; Zhou, N.; Ma, M.; Mao, C. India's residential space cooling transition: Decarbonization ambitions since the turn of millennium. *Appl. Energy* **2025**, *391*, 125929. [CrossRef]
2. Tong, S.; Wen, J.; Wong, N.H.; Tan, E. Impact of façade design on indoor air temperatures and cooling loads in residential buildings in the tropical climate. *Energy Build.* **2021**, *243*, 110972. [CrossRef]
3. Ratti, C.; Baker, N.; Steemers, K. Energy consumption and urban texture. *Energy Build.* **2005**, *37*, 762–776. [CrossRef]
4. Ravichandran, C.; Gopalakrishnan, P. Estimating cooling loads of Indian residences using building geometry data and multiple linear regression. *Energy Built Environ.* **2024**, *5*, 741–771. [CrossRef]

5. Manu, S.; Shukla, Y.; Rawal, R.; Thomas, L.E.; de Dear, R. Field studies of thermal comfort across multiple climate zones for the subcontinent: India Model for Adaptive Comfort (IMAC). *Build. Environ.* **2016**, *98*, 55–70. [\[CrossRef\]](#)
6. Rawal, R.; Shukla, Y.; Vardhan, V.; Asrani, S.; Schweiker, M.; de Dear, R.; Garg, V.; Mathur, J.; Prakash, S.; Diddi, S.; et al. Adaptive thermal comfort model based on field studies in five climate zones across India. *Build. Environ.* **2022**, *219*, 109187. [\[CrossRef\]](#)
7. Dhaka, S.; Mathur, J.; Brager, G.; Honnekeri, A. Assessment of thermal environmental conditions and quantification of thermal adaptation in naturally ventilated buildings in composite climate of India. *Build. Environ.* **2015**, *86*, 17–28. [\[CrossRef\]](#)
8. Quan, S.J.; Li, C. Urban form and building energy use: A systematic review of measures, mechanisms, and methodologies. *Renew. Sustain. Energy Rev.* **2021**, *139*, 110662. [\[CrossRef\]](#)
9. Prakash, A.; Diksha; Kumar, A. Measuring Vertical Urban Growth of Patna Urban Agglomeration Using Persistent Scatterer Interferometry SAR (PSInSAR) Remote Sensing. *Remote Sens.* **2023**, *15*, 3687. [\[CrossRef\]](#)
10. Latif, E.; Jain, V. State-of-the-Art of Net-Zero building standards and benchmarks in India: A Comprehensive review with notable case studies. *Energy Build.* **2026**, *350*, 116679. [\[CrossRef\]](#)
11. Westermann, P.; Evins, R. Surrogate modelling for sustainable building design—A review. *Energy Build.* **2019**, *198*, 170–186. [\[CrossRef\]](#)
12. Amasyali, K.; El-Gohary, N.M. A review of data-driven building energy consumption prediction studies. *Renew. Sustain. Energy Rev.* **2018**, *81*, 1192–1205. [\[CrossRef\]](#)
13. Reinhart, C.F.; Davila, C.C. Urban building energy modeling—A review of a nascent field. *Build. Environ.* **2016**, *97*, 196–202. [\[CrossRef\]](#)
14. Ali, U.; Shamsi, M.H.; Hoare, C.; Mangina, E.; O'Donnell, J. Review of urban building energy modeling (UBEM) approaches, methods and tools using qualitative and quantitative analysis. *Energy Build.* **2021**, *246*, 111073. [\[CrossRef\]](#)
15. Sanaieian, H.; Tenpierik, M.; Van Den Linden, K.; Seraj, F.M.; Shemrani, S.M.M. Review of the impact of urban block form on thermal performance, solar access and ventilation. *Renew. Sustain. Energy Rev.* **2014**, *38*, 551–560. [\[CrossRef\]](#)
16. Gupta, V.; Deb, C. Envelope design for low-energy buildings in the tropics: A review. *Renew. Sustain. Energy Rev.* **2023**, *186*, 113650. [\[CrossRef\]](#)
17. Caponetto, G.; Nocera, F.; Giuffrida, G.; Detommaso, M.; Palmer, J.; Terry, N. Looking Critically at Heat Loss through Party Walls. *Sustainability* **2022**, *14*, 3072. [\[CrossRef\]](#)
18. Alsukkar, M.; Ibrahim, A.; Eltaweel, A. Multi-objective optimization of daylighting systems for energy efficiency and thermal-visual comfort in buildings: A review. *Build. Environ.* **2026**, *288*, 113921. [\[CrossRef\]](#)
19. Wang, L.; Ibrahim, A.; Jiang, Y. Multi-Objective Optimization of Atrium Form Variables for Daylighting, Energy Consumption and Thermal Comfort of Teaching Buildings at the Early Design Stage in Cold Climates. *Buildings* **2025**, *15*, 4434. [\[CrossRef\]](#)
20. Sadeghi, M.; Chen, D.; Wright, A. A Critical Review of Overheating Risk Assessment Criteria in International and National Regulations—Gaps and Suggestions for Improvements. *Energies* **2024**, *17*, 6354. [\[CrossRef\]](#)
21. Santamouris, M.; Cartalis, C.; Synnefa, A.; Kolokotsa, D. On the impact of urban heat island and global warming on the power demand and electricity consumption of buildings—A review. *Energy Build.* **2015**, *98*, 119–124. [\[CrossRef\]](#)
22. Shen, P.; Wang, H. Archetype building energy modeling approaches and applications: A review. *Renew. Sustain. Energy Rev.* **2024**, *199*, 114478. [\[CrossRef\]](#)
23. Swan, L.G.; Ugursal, V.I. Modeling of end-use energy consumption in the residential sector: A review of modeling techniques. *Renew. Sustain. Energy Rev.* **2009**, *13*, 1819–1835. [\[CrossRef\]](#)
24. Mata, É.; Kalagasidis, A.S.; Johnsson, F. Building-stock aggregation through archetype buildings: France, Germany, Spain and the UK. *Build. Environ.* **2014**, *81*, 270–282. [\[CrossRef\]](#)
25. Pasichnyi, O.; Wallin, J.; Kordas, O. Data-driven building archetypes for urban building energy modelling. *Energy* **2019**, *181*, 360–377. [\[CrossRef\]](#)
26. Borges, P.; Travesset-Baro, O.; Pages-Ramon, A. Hybrid approach to representative building archetypes development for urban models—A case study in Andorra. *Build. Environ.* **2022**, *215*, 108958. [\[CrossRef\]](#)
27. Crawley, D.B.; Lawrie, L.K.; Winkelmann, F.C.; Buhl, W.; Huang, Y.; Pedersen, C.O.; Strand, R.K.; Liesen, R.J.; Fisher, D.E.; Witte, M.J.; et al. EnergyPlus: Creating a new-generation building energy simulation program. *Energy Build.* **2001**, *33*, 319–331. [\[CrossRef\]](#)
28. Hygh, J.S.; DeCarolis, J.F.; Hill, D.B.; Ranjithan, S.R. Multivariate regression as an energy assessment tool in early building design. *Build. Environ.* **2012**, *57*, 165–175. [\[CrossRef\]](#)
29. Ramesh, T.; Prakash, R.; Shukla, K.K. Life cycle energy analysis of a residential building with different envelopes and climates in Indian context. *Appl. Energy* **2012**, *89*, 193–202. [\[CrossRef\]](#)
30. Borgeson, S.; Brager, G. Comfort standards and variations in exceedance for mixed-mode buildings. *Build. Res. Inf.* **2011**, *39*, 118–133. [\[CrossRef\]](#)
31. Nutkiewicz, A.; Yang, Z.; Jain, R.K. Data-driven Urban Energy Simulation (DUE-S): Integrating machine learning into an urban building energy simulation workflow. *Energy Procedia* **2017**, *142*, 2114–2119. [\[CrossRef\]](#)

32. Rahif, R.; Amaripadath, D.; Attia, S. Review on Time-Integrated Overheating Evaluation Methods for Residential Buildings in Temperate Climates of Europe. *Energy Build.* **2021**, *252*, 111463. [[CrossRef](#)]
33. Waite, M.; Cohen, E.; Torbey, H.; Piccirilli, M.; Tian, Y.; Modi, V. Global trends in urban electricity demands for cooling and heating. *Energy* **2017**, *127*, 786–802. [[CrossRef](#)]
34. Asan, H. Investigation of wall's optimum insulation position from maximum time lag and minimum decrement factor point of view. *Energy Build.* **2000**, *32*, 197–203. [[CrossRef](#)]
35. Indraganti, M. Using the adaptive model of thermal comfort for obtaining indoor neutral temperature: Findings from a field study in Hyderabad, India. *Build. Environ.* **2010**, *45*, 519–536. [[CrossRef](#)]
36. Vartholomaïos, A. A parametric sensitivity analysis of the influence of urban form on domestic energy consumption for heating and cooling in a Mediterranean city. *Sustain. Cities Soc.* **2017**, *28*, 135–145. [[CrossRef](#)]
37. Wei, T. A review of sensitivity analysis methods in building energy analysis. *Renew. Sustain. Energy Rev.* **2013**, *20*, 411–419. [[CrossRef](#)]
38. Catalina, T.; Virgone, J.; Blanco, E. Development and validation of regression models to predict monthly heating demand for residential buildings. *Energy Build.* **2008**, *40*, 1825–1832. [[CrossRef](#)]

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