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URBAN IMPACT ON ENERGY EFFICIENCY
Exploring Three Realities of Guayaquil, Ecuador

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Urban Impact on Energy Efficiency: Exploring Three Realities of Guayaquil, Ecuador

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DEDICATION

We, the authors, first and foremost give thanks to God, whose grace and guidance have been our steadfast light through every challenge encountered in the making of this work. This book stands as testimony to the trials we have overcome—not just academic, but personal and emotional. Through moments of doubt and difficulty, it was our faith in God and in each other that sustained us.

As co-authors, Ricardo, Romina, Juan Carlos and Jorge, this is our first book written together—a journey marked by mutual encouragement, shared vision, and unwavering determination. The completion of this first volume is not only an academic milestone, but also a deeply personal achievement.

We extend our heartfelt gratitude to our families; whose unconditional support and love made this possible. Their patience and belief in us have been the quiet force behind every page.

This book is dedicated to all those who continue to believe that faith, perseverance, and collaboration can bring forth meaningful change—both in the world and within ourselves.

"Digital design is not merely a tool, but a lens through which housing can be reimagined as both energy-efficient and socially equitable."

— *Manzaba Carvajal et al., 2025*

SUMMARY

SUMMARY

1. PREFACE

This book emerges from a deep and growing concern regarding the intersection of urban development, energy efficiency, and climate justice in rapidly expanding tropical cities of the Global South. Guayaquil, Ecuador's principal coastal metropolis, serves as a critical case study to examine these overlapping challenges. Situated in a humid tropical zone and characterized by diverse and often fragmented urban morphologies, Guayaquil encapsulates the broader patterns of Latin American urbanization—where informal settlements, spatial inequality, and climate vulnerability are intrinsically linked.

The research presented here is the result of sustained academic inquiry, interdisciplinary dialogue, and digital experimentation. It combines principles of urban and architectural design, morphological analysis, Building Information Modeling (BIM), and environmental simulation to explore how three distinct urban sectors in Guayaquil—each shaped by different socio-economic trajectories—impact energy performance and thermal comfort. This study seeks not only to quantify urban energy behavior but to reflect critically on the policies and design strategies required to foster more equitable, efficient, and climate-responsive cities.

While aligned with international frameworks such as the Architecture 2030 Challenge and the Zero Code, this work approaches them through a Latin American lens—acknowledging that global standards must be locally interpreted and adapted. In cities like Guayaquil, where informal urban growth predominates, and where climatic pressures intensify existing inequalities, energy-efficient design is not a technological luxury but a necessity for survival and dignity.

This book is offered as a contribution to the academic and professional communities engaged in sustainable urbanism, architectural innovation, and environmental equity. It is intended to support not only scholarly reflection but also informed decision-making by urban planners, architects, policymakers, and educators concerned with the future of tropical cities.

Special thanks are extended to the Faculty of Architecture and Urbanism at the University of Guayaquil, Ecuador, for their institutional support and academic collaboration throughout the development of this research.

2. INTRODUCTION

2.1. Research Background:

Guayaquil, located on the Pacific coast of Ecuador, stands as a paradigmatic case of urban development within a tropical climate context. Its geographical position—just two degrees south of the equator—subjects the city to high levels of solar radiation, elevated humidity, and minimal seasonal variation, all of which exert significant influence on building performance and urban livability. These climatic conditions intensify the need for context-sensitive design strategies, particularly in terms of passive ventilation, solar protection, and energy-efficient construction. As a city with a dense, heterogeneous urban fabric and high demographic pressure, Guayaquil offers a unique laboratory for analyzing how urban form interacts with environmental performance under tropical conditions.

Moreover, Guayaquil exemplifies the challenges and opportunities inherent to cities of the Global South, where formal and informal urbanization coexist and frequently collide. The rapid expansion of peripheral settlements, often in ecologically fragile zones such as hillsides and floodplains, exacerbates the vulnerabilities associated with climate change and social inequality. These urban conditions are not peripheral to the study of energy efficiency—they are central. Investigating Guayaquil's urban fabric provides critical insights into how socio-spatial configurations, local climate, and design practices converge to shape energy dynamics. As such, the city becomes a strategic site for developing design and planning solutions that are not only technically sound but socially inclusive and climatically resilient.

Energy efficiency in social housing represents a significant challenge in tropical urban environments due to high temperatures, intense solar radiation, and increased cooling demands(Ricaurte et al. 2020; Hernandez-Cruz et al. 2023). In such climates, improper urban design exacerbates thermal discomfort, driving higher energy consumption for air conditioning and mechanical ventilation systems (Djeddou, Daich, and Femmam 2024). Tropical cities like Guayaquil face these challenges due to their unique climatic characteristics, including high humidity, prolonged solar exposure, and limited wind flow throughout the year (Taing, Andre, and Leclercq 2023).

Studies demonstrate that urban configurations, such as high-density development and limited green spaces, intensify the urban heat island effect, worsening thermal comfort and energy demand (Shen et al. 2022). For instance, compact urban forms limit airflow and trap heat, increasing building cooling requirements (Mazria 2022). Consequently, optimizing urban form through design strategies such as proper building orientation, increased vegetation coverage, and enhanced ventilation could mitigate energy use while improving living conditions (Delponte, Bianco, and Costa 2022).

The interplay between climatic variables and urban features such as building orientation, wind patterns, and surface materials plays a central role in determining a building's thermal performance (Habibi 2022). Research suggests that integrating passive cooling strategies, including optimizing window-to-wall ratios and applying reflective materials, can significantly reduce cooling loads in social housing projects(Maglad et al. 2023; Veerendra et al. 2024).These strategies are essential for achieving ene(Mazria 2022; Zhang et al. 2020)rgy sustainability and meeting international benchmarks like Architecture 2030 (Zhang et al. 2021). This context highlights the necessity for a deeper understanding of the urban-climate-energy nexus in tropical regions.

2.2. Research Gap

The contemporary urban landscape in tropical cities reveals an urgent need to reassess how form, density, and materials influence energy consumption and environmental resilience. Urban sectors such as those found in Guayaquil present heterogeneous morphologies shaped by formal and informal growth, often disconnected from energy efficiency considerations. This fragmentation contributes to uneven access to thermal comfort, exacerbates urban heat islands, and leads to higher energy demands—particularly in marginalized areas where design strategies are absent or misapplied. These dynamics echo challenges faced in other hot-climate contexts (Djeddou, Daich, and Femmam 2024), underscoring the importance of understanding how spatial configurations can either mitigate or intensify energy vulnerabilities.

At the same time, the global pursuit of carbon neutrality and sustainable development calls for localized solutions that integrate technological innovation with socio-spatial sensitivity. Tools such as Building Information Modeling (BIM), when combined with simulation platforms like Insight and Forma, have proven effective in modeling urban energy behavior and testing intervention strategies (Habibi 2022; Maglad et al. 2023). In this research, the integration of BIM not only supports accurate energy forecasting (Valencia Robles, Manzaba Carvajal, and Romero Jara 2025) but also facilitates sustainable material selection tailored to regional climatic performance (Manzaba, Valencia Robles, and Romero Jara 2025). These approaches align with international sustainability agendas while responding to Latin America's specific urban and climatic contexts—advancing both scientific knowledge and practical design frameworks.

Despite increased awareness of energy efficiency's role in urban sustainability, research in tropical contexts often remains fragmented, focusing on individual design features rather than comprehensive urban evaluations (Alshabab et al. 2019; I. H. T. Mutis 2019). Most studies prioritize isolated building performance simulations while neglecting broader urban factors like urban density, wind speed, and solar exposure, which collectively shape energy dynamics (Q. Li et al. 2024; Mazria 2022).

Applying advanced simulation tools like Autodesk Revit, Insight, and Forma remains underexplored in large-scale urban energy evaluations (Habibi 2022). Although these BIM-based tools are widely used in architectural design, few studies integrate them with robust statistical methods such as ANOVA, regression models, and post-hoc analysis to quantify urban energy performance (Maglad et al. 2023; Mogili, Avvari, and Appecharla 2022). As shown in **¡Error! No se encuentra el origen de la referencia.**

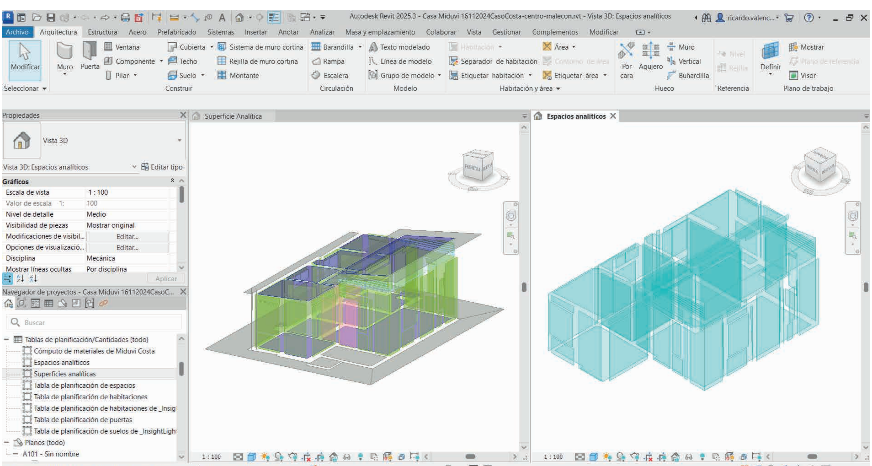

Figure 1. Energy model created in Revit 2025 using Insight, showcasing the analytical representation of spaces and energy surfaces. Source: Own elaboration.

Furthermore, energy performance evaluations based on standardized metrics established by frameworks such as Architecture 2030 have rarely been applied in developing tropical regions (Zhang et al. 2021; Mazria 2022). Addressing this research gap through integrative simulations and advanced statistical modelling forms the core of this study, offering a data-driven approach to enhancing energy sustainability in tropical cities (Taing, Andre, and Leclercq 2023).

The interplay between urban form, climate, and energy performance constitutes a critical triad in the sustainable transformation of tropical cities. The urban dimension encompasses the morphological, social, and infrastructural characteristics that shape energy behavior, including compactness, housing typologies, and green cover, all which influence ventilation and thermal exposure (Djeddou, Daich, and Femmam 2024; Manzaba Carvajal et al. 2025). The climatic dimension highlights the influence of high humidity, solar radiation, and limited seasonal variation in tropical zones like Guayaquil, where urban microclimates—such as heat islands—amplify energy demands and call for context-responsive design strategies (Taing, Andre, and Leclercq 2023; Habibi 2022). Finally, the energy dimension integrates both technological tools and material considerations, using BIM-based simulations to assess energy demand, while promoting passive strategies and regulatory alignment with global standards such as the Architecture 2030 framework (Alshabab et al. 2019; Mazria 2022). Together, these dimensions form the conceptual basis for analyzing urban energy efficiency under tropical conditions, with strong implications for equitable and climate-sensitive urban planning.

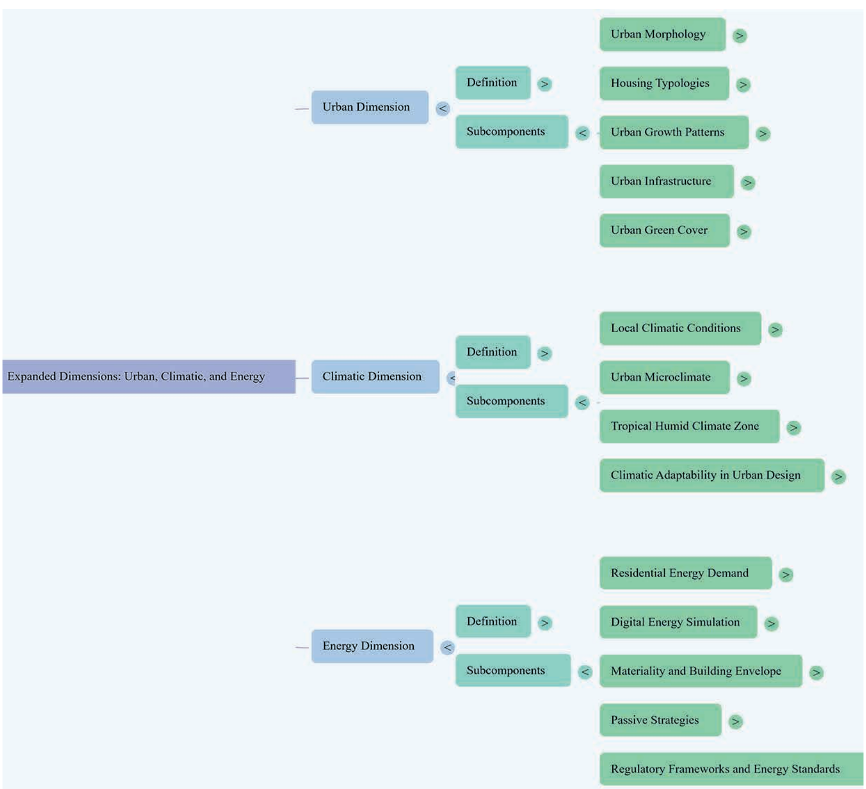

Figure 2. Interfacing Urban Form, Climate, and Energy: A Conceptual Framework for Tropical Cities. Source: Own elaboration.

2.3. Objectives

The primary objective of this research is to evaluate how urban characteristics such as density, wind speed, and solar radiation impact energy efficiency and thermal comfort in social housing across three distinct neighborhoods in Guayaquil, Ecuador: Centro, Cisne II, and Lomas de Mapasingue. These locations were selected due to their contrasting urban configurations, including differences in building density, topography, and proximity to natural features such as rivers and hills (Ricaurte et al. 2020).

The study further aims to quantify the relationships between these urban variables and housing performance through advanced statistical analyses, including multiple regression models, ANOVA, and post-hoc comparisons (Maglad et al. 2023). Key metrics such as energy consumption (kWh/m^2/year), thermal comfort indicators (thermal stress levels), and environmental factors (wind speed, radiation, and surface temperatures) were evaluated. Results are compared to international benchmarks like Architecture 2030 to provide evidence-based recommendations for urban design strategies that enhance sustainability while reducing energy demand (Mazria 2022; Zhang et al. 2021).

These analytical procedures and comparative benchmarks directly inform the core research questions of this study, which investigate the influence of urban morphology on energy performance, the accuracy of digital simulation tools, and the effectiveness of design strategies tailored for tropical low-income neighborhoods:

How do urban morphological characteristics—such as density, topography, and vegetation—affect energy performance and thermal comfort in social housing across different urban sectors of Guayaquil?

To what extent can digital tools like BIM and Insight accurately simulate energy demand and predict comfort levels under varying climatic conditions?

What spatial and material design strategies offer the most impactful energy savings in tropical informal or semi-formal neighborhoods?

These questions aim to bridge a critical gap between urban design and energy modeling in tropical Latin American cities, where informal development patterns and infrastructure inequality present challenges to conventional efficiency frameworks (Djeddou, Daich, and Femmam 2024; Delponte, Bianco, and Costa 2022). Methodologically, the integration of BIM and Insight for energy simulation is supported by international literature emphasizing its potential to predict performance in early design stages (Habibi 2022; Maglad et al. 2023). Additionally, this research contributes to the global discourse on carbon reduction and urban resilience by aligning its outcomes with zero-energy building standards like Architecture 2030 (Mazria 2022; Zhang et al. 2020).

On a practical level, the findings are designed to inform municipal planning, housing policy, and future implementations of energy simulation tools in the design of low-income housing. The recommendations derived from the statistical modeling and simulation analyses can serve as transferable criteria for tropical cities undergoing rapid growth, reinforcing the need for localized and equitable sustainability strategies (Manzaba Carvajal et al. 2025; Hernandez-Cruz et al. 2023).

2.4. Structure Overview:

This book explores the impact of urban characteristics on energy efficiency and thermal comfort in social housing across three distinct neighborhoods in Guayaquil, Ecuador: Centro, Cisne II, and Lomas de Mapasingue. Simulations were conducted using Autodesk Revit, Insight, and Forma, focusing on variables such as urban density, wind speed, and solar radiation(Habibi 2022; Veerendra et al. 2024). Statistical analyses, including ANOVA, Tukey's post-hoc tests, and multiple regression models ($R^2 = 0.82$), were applied to evaluate the relationships between these factors and key performance metrics such as energy consumption and thermal comfort (Maglad et al. 2023; Q. Li et al. 2024).

3. LITERATURE REVIEW

3.1. Energy Efficiency in Urban Contexts

Energy efficiency in urban environments has evolved into a crucial research area driven by the urgency of sustainable development amid rapid urban expansion and escalating climate concerns. In this regard, tropical cities like Guayaquil exemplify the complexities of balancing environmental resilience and energy efficiency due to persistent heat exposure, elevated humidity, and prolonged solar radiation (Ricaurte et al. 2020; Hernandez-Cruz et al. 2023). Thus, addressing these challenges necessitates an integrated approach that prioritizes cooling demand reduction while enhancing thermal comfort.

Moreover, the literature consistently highlights the relevance of urban morphology in shaping energy efficiency, emphasizing how factors such as density, building orientation, wind patterns, and surface materials substantially affect energy dynamics (Djeddou, Daich, and Femmam 2024; Taing, Andre, and Leclercq 2023). Considering this, urban configurations characterized by compact building layouts often intensify the urban heat island effect, restricting airflow and amplifying cooling demands (Shen et al. 2022). Consequently, (Delponte, Bianco, and Costa 2022) argue that implementing green infrastructure and adopting spatially conscious urban layouts can alleviate heat stress while fostering thermal balance. Furthermore, research underscores the impact of well-planned and shaded environments in mitigating thermal discomfort and optimizing energy efficiency (Mazria 2022; Q. Li et al. 2024; Zhang et al. 2021).

3.1.1. Tropical Urban Typologies

Tropical urban environments present a unique set of morphological and spatial conditions that significantly influence energy behavior and thermal comfort. These include high-density settlement patterns, informal street networks, varied housing typologies—from consolidated urban centers to incremental housing—and limited green infrastructure. (Djeddou, Daich, and Femmam 2024) emphasize that urban form in hot climates has a direct effect on energy use, with compact and poorly ventilated configurations exacerbating internal heat accumulation. In the Latin American context, (Manzaba Carvajal et al. 2025) demonstrate how parametric BIM modeling can guide spatial configurations that improve energy performance, particularly in tropical housing designs. Their study highlights how digital design tools allow early-stage integration of passive strategies, accounting for sun path, wind corridors, and shading, thus improving overall energy responsiveness in informal or semi-formal urban layouts.

3.1.2. Passive vs. Active Strategies: Comparative Evaluation

Urban energy strategies can broadly be categorized into passive and active approaches. Passive strategies include natural ventilation, solar orientation, thermal massing, and the use of shading devices, which reduce energy consumption without mechanical inputs. In contrast, active strategies rely on air conditioning systems, artificial lighting, and forced ventilation. (Valencia Robles, Manzaba Carvajal, and Romero Jara 2025) document how passive strategies, when embedded from the design phase, can lead to significant reductions in energy demand in tropical housing. Their findings from Guayaquil show that incorporating basic passive principles—such as ventilated facades and shaded roofs—improves thermal comfort even in low-cost constructions. Furthermore, (Habibi 2022; Maglad et al. 2023) validate the reliability of simulation tools like Insight and Revit in modeling the energy performance of both passive and active systems, reinforcing their applicability in tropical climates. This comparative framework is essential in selecting strategies suited for socioeconomic realities where active systems may be economically unfeasible or unsustainable.

3.1.3. Critiques and Limitations of Current Modeling Approaches in Tropical Regions

Despite the advances in energy simulation technologies, there remain significant gaps in how current models respond to the climatic and socio-material realities of tropical regions. (Hernandez-Cruz et al. 2023) highlight the performance gap between theoretical energy savings and real-world outcomes, particularly in social housing where construction standards and user behavior introduce variability. These discrepancies challenge the applicability of conventional models, which are often developed for temperate or highly regulated environments. (Manzaba, Valencia Robles, and Romero Jara 2025) address this limitation by tailoring material selection to Ecuador's specific climatic zones, offering practical benchmarks for simulation calibration. Moreover, (Alshabab et al. 2019) underline the potential of BIM-based workflows—using Revit and Insight—for refining energy models, yet they stress the importance of localized validation to ensure accuracy in underrepresented tropical geographies. These critiques reveal the need for a methodological shift toward hybrid models that combine digital precision with field-based environmental and social data.

Table 1. Comparative Climate Strategies by Region

Region	Climatic Characteristics	Passive Strategies	Active Strategies	Relevant Studies
Humid Tropical (e.g., Guayaquil)	High humidity, high solar radiation, minimal temperature fluctuation	Cross ventilation, solar shading, thermal mass, light-colored reflective roofs	Air conditioning, dehumidifiers, solar-controlled glazing	(Manzaba et al. 2025; Taing, Andre, and Leclercq 2023; Mogili, Avvari, and Appecharla 2022)
Dry Tropical (e.g., Northern Peru)	High solar radiation, low humidity, large diurnal temperature range	Thermal insulation, night cooling, small shaded windows, adobe/mass walls	Evaporative cooling, photovoltaic-powered cooling	(Djeddou, Daich, and Femmam 2024; Habibi 2022)
Temperate Highland (e.g., Quito)	Moderate temperatures, significant temperature drop at night, intense solar radiation	Double glazing, passive solar heating, thermal mass, compact forms	Supplemental heating, active ventilation	(Manzaba, Valencia Robles, and Romero Jara 2025; Hernandez-Cruz et al. 2023)
Subtropical Coastal (e.g., Rio de Janeiro)	High humidity, high rainfall, intense solar gain, prevailing oceanic winds	Raised floors, large overhangs, operable windows, vegetation buffers	Fans, split-system AC, solar water heaters	(Hernandez-Cruz et al. 2023; Zhang et al. 2020)

[a] Source: Own elaboration.

3.2. Latin American Contributions to Urban Energy Efficiency: Case Studies from Ecuador

Recent research conducted in Ecuador has enriched the regional discourse on urban energy efficiency by contextualizing global methodologies within tropical urban realities. These studies emphasize the role of Building Information Modeling (BIM), material performance, and participatory urban strategies in addressing energy and environmental challenges in Latin American housing contexts.

(Manzaba Carvajal et al. 2025) explore the integration of BIM and parametric design strategies in residential architecture. Their work underscores the potential of digital modeling not only for spatial optimization but also for embedding energy performance criteria from the earliest design stages. This aligns with the methodological core of this book, particularly regarding the use of Revit and Insight for neighborhood-scale energy simulation.

(Valencia Robles, Manzaba Carvajal, and Romero Jara 2025) extend this analysis by demonstrating how BIM-based simulations can accurately assess the thermal behavior of social housing. Their study transitions from digital modeling to construction feasibility, emphasizing material selection and passive design strategies that optimize energy performance in hot-humid environments like Guayaquil.

A complementary perspective is offered by (Manzaba et al. 2025), who investigate the use of recycled materials and progressive housing strategies in vulnerable urban areas. Their findings highlight the importance of aligning sustainability goals with socioeconomic realities, making a compelling case for context-sensitive energy solutions in informal and semi-formal settlements.

Finally, (Manzaba, Valencia Robles, and Romero Jara 2025) provide a comparative evaluation of building materials across Ecuador's diverse climate zones. Their emphasis on the thermal and environmental implications of material choices reinforces the need for geographically tailored simulation parameters in urban energy studies. Collectively, these Ecuadorian contributions provide empirical grounding for the present research and reinforce its methodological, climatic, and social relevance.

3.3. Urban Density and Energy Consumption

Urban density emerges as a determining factor in defining energy consumption patterns due to its direct influence on airflow dynamics, shading effects, and thermal mass accumulation. In densely populated areas, closely packed buildings and limited vegetation exacerbate heat retention, leading to increased reliance on cooling systems (Zhang et al. 2021; Mazria 2022). Indeed, (Hernandez-Cruz et al. 2023) observed that social housing developments with compact layouts frequently lack adequate cross-ventilation, resulting in intensified indoor heat build-up.

In response to this, (Djeddou, Daich, and Femmam 2024) demonstrate that lowering building heights and widening streets can enhance passive cooling by facilitating wind movement. Similarly, (Levrini, Erduran, and Pietrocola 2024) found that staggered building configurations allowed greater air circulation, reducing interior temperatures and easing cooling demands. Taken together, these insights underscore the potential of recalibrating urban density through thoughtful design strategies aimed at reducing thermal discomfort and promoting energy efficiency in tropical climates.

3.4. Solar Radiation and Thermal Management

The role of solar radiation as a principal environmental variable in determining energy consumption and indoor temperatures remains uncontested within the academic discourse. In tropical regions, unprotected building surfaces subjected to direct solar exposure experience heightened heat accumulation, subsequently increasing mechanical cooling requirements (Habibi 2022). Accordingly, employing reflective coatings, external shading devices, and solar-control glazing has emerged as an effective countermeasure, reducing cooling loads by up to 40% (Zhang et al. 2020).

Furthermore, (Q. Li et al. 2024) demonstrated that solar-responsive façades with automated shading systems reduced annual cooling energy consumption by 35%. Similarly, (Hernandez-Cruz et al. 2023)reported significant energy savings when reflective roof materials and advanced insulation techniques were incorporated into social housing projects. Therefore, passive solar design remains indispensable in moderating the adverse effects of solar radiation in urban housing developments.

3.5. Wind Patterns and Natural Ventilation

Wind patterns constitute an essential element in fostering thermal comfort and minimizing energy consumption through natural ventilation. Properly oriented buildings that align with prevailing wind directions promote effective airflow, thus diminishing reliance on mechanical ventilation systems (Q. Li et al. 2024; Mazria 2022). In this context, wind-sensitive urban layouts emerge as pivotal strategies in mitigating urban heat stress.

(Zhang et al. 2021) advocated for integrating wind corridors into urban designs to ensure continuous air circulation in dense built environments. Similarly, (Alshabab et al. 2019) demonstrated that residential developments designed with wind-optimized layouts reduced interior temperatures by up to 3°C, substantially lowering cooling demands. Collectively, these findings emphasize the importance of embedding wind-responsive architectural elements into sustainable urban design practices.

3.6. Technological Advances in Urban Energy Modelling

Technological advancements in BIM-based energy modelling have reshaped the evaluation process of energy performance in urban housing developments. Tools such as Autodesk Revit, Insight, and Forma facilitate comprehensive simulations by integrating architectural models with environmental data (Hernandez-Cruz et al. 2023; Habibi 2022). Consequently, these platforms enable precise assessments by linking urban design parameters with energy performance indicators, thereby enhancing prediction accuracy by up to 25% (Maglad et al. 2023).

Moreover, advanced statistical techniques, including regression analysis and ANOVA, complement BIM simulations by quantifying the contributions of specific urban variables to overall energy efficiency (Mogili, Avvari, and Appecharla 2022). In this regard, (Zhang et al. 2020) illustrated how merging statistical models with BIM-driven simulations facilitates accurate energy forecasting and informed decision-making in urban planning. This technological convergence underscores the transformative potential of data-driven approaches in achieving energy-efficient urban development.

3.7. Global Sustainability Frameworks

Global sustainability frameworks such as Architecture 2030 and Zero Energy Building standards have established rigorous targets aimed at reducing urban energy consumption through innovative design and policy interventions. (Mazria 2022) posited that achieving net-zero energy performance necessitates integrating advanced building technologies with climate-adaptive urban layouts. Likewise, (Zhang et al. 2021) argued that attaining carbon neutrality demands a policy-driven approach underpinned by renewable energy systems and strict energy-efficiency codes.

Consequently, policy-driven urban planning has emerged as a critical mechanism for addressing energy challenges in developing regions. (Hernandez-Cruz et al. 2023) stressed that implementing regulatory frameworks that promote energy-efficient building designs can drive substantial energy savings in social housing projects. Therefore, these global frameworks provide valuable benchmarks that guide this study's evaluation criteria, particularly in assessing compliance with Architecture 2030 performance standards.

3.8. Research Relevance and Theoretical Contribution

Thus, this research weaves together essential findings from the reviewed literature, unravelling the multifaceted interplay between urban density, solar radiation, and wind patterns in shaping energy efficiency and thermal comfort within Guayaquil's social housing landscape. Through the integration of advanced BIM-based simulation tools and robust statistical models, the study constructs a bridge between theoretical urban design paradigms and empirical assessments of energy performance. In this way, the methodological approach not only aligns with global sustainability frameworks but also responds to the singular climatic and urban complexities inherent to Guayaquil, offering a context-specific contribution that extends beyond theoretical discourse into actionable urban design strategies.

4. METHODOLOGY

Table 2. Methodology

Stage	Contribution to the Research
1. Initial Modelling: Social Housing (MIDUVI 2021). **¡Error! No se encuentra el origen de la referencia.**	- Creation of a representative architectural and analytical model. - Parameterization of materials and areas.
2. Energy Analysis: Autodesk Insight	- Evaluation of energy loads (lighting, refrigeration, heating). - Basis for comparison between locations.
3. Urban Context: Autodesk Forma	- Analysis of the impact of density, ventilation, and solar radiation. - Evaluation of the urban environment on comfort and energy consumption.
4. Statistical Analysis	- Identification of significant relationships between variables. - Validation of differences between locations using ANOVA and regression.
5. Key Variable Determination	- Selection of relevant variables: urban density, wind speed, and solar radiation. - Prioritization of key factors to optimize efficiency.

[a] Source: Own elaboration.

This research adopts a quantitative and comparative methodological approach, evaluating a standardized social housing model under diverse urban and climatic conditions in three distinct localities of Guayaquil: Centro, Sector Cisne II, and Lomas de Mapasingue. Through the integration of Building Information Modelling (BIM)-based tools such as Autodesk Revit for housing modelling, Insight for energy performance simulations, and Forma for urban environmental analysis, the study establishes a multi-layered framework that examines the relationships among urban variables, environmental modulators, and performance indicators.

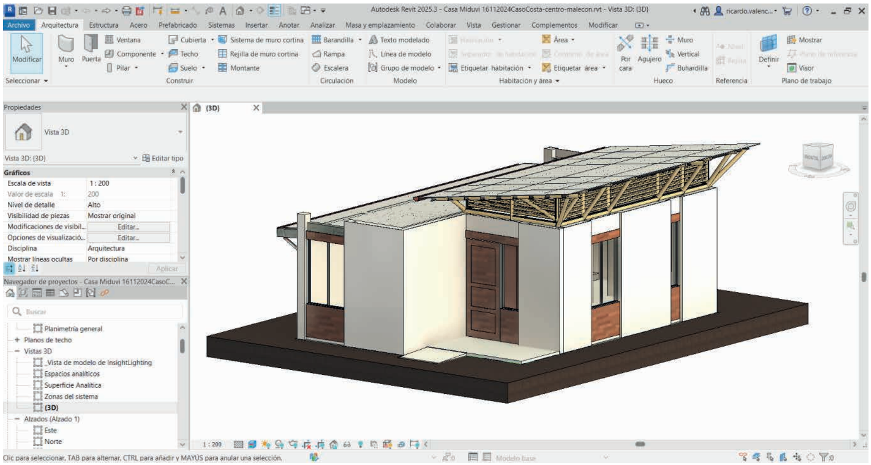

Figure 3. Three-dimensional model of a Costa Miduvi social housing unit created in Revit 2025. Source: Own elaboration.

The selection of these localities is not arbitrary but deliberate, reflecting varied urban morphologies and microclimatic conditions. These differences are fundamental to understanding the causal effects of urban characteristics on energy consumption and thermal comfort.

4.1. Study Design

The methodological approach is inherently quantitative as it focuses on measurable outcomes such as energy use intensity (kWh/m^2/year) and thermal stress levels, and comparative in its design, as it systematically contrasts housing performance across urban settings with varying densities, topographies, and microclimates. By situating the analysis within a standardized housing model, the study isolates the impact of urban environmental factors on energy performance (Hernandez-Cruz et al. 2023; Djeddou, Daich, and Femmam 2024).

4.2. Conceptual Model of Variables

Understanding urban energy dynamics requires a structured framework where environmental, architectural, and climatic factors intersect. As highlighted by (Maglad et al. 2023), urban variables such as density, wind speed, and solar radiation influence energy performance by shaping thermal environments. In this context, urban density determines building proximity and potential shading effects (Djeddou, Daich, and Femmam 2024) while solar radiation intensity affects indoor cooling loads due to increased heat gain (Shen et al. 2022) Wind speed modulates thermal comfort through natural ventilation, mitigating reliance on mechanical cooling systems (Hernandez-Cruz et al. 2023).

Table 3. Conceptual Model of Variables

Variable Type	Variable Name	Definition	Measurement Indicator	Source
Independent Variables	Urban Density	Number of buildings per unit area	Buildings/ hectare	(Djeddou, Daich, and Femmam 2024)
	Solar Radiation	Intensity of solar energy received	W/m^2	(Shen et al. 2022)
	Wind Speed	Average wind flow in the environment	m/s	(Hernandez-Cruz et al. 2023)
Mediating Variables	Solar Shading	Degree of shading from urban objects	% of shaded area	(H. X. Li et al. 2020)
	Wind Modulation	Impact of wind barriers on air flow	Wind deflection ratio (%)	(Veerendra et al. 2024)
Dependent Variables	Energy Consumption	Total energy used in the building	$kWh/m^2/year$	
	Thermal Stress	Level of thermal discomfort	% of time under thermal stress	(Zhang et al. 2021)

[a] Source: Own elaboration.

However, environmental impact is rarely linear, as intermediating factors adjust the direct influence of these variables. For example, (H. X. Li et al. 2020) argue that urban shading from neighboring structures reduces solar heat absorption, thus lowering energy consumption. Similarly,(Veerendra et al. 2024) emphasize wind modulation as a key element, suggesting that optimally oriented buildings can channel airflow more effectively. Consequently, these mediating variables reshape urban energy performance indicators.

Ultimately, energy consumption ($kWh/m^2/year$) and thermal stress levels emerge as measurable outcomes reflecting the interaction between environmental conditions and architectural responses (Mazria 2022; Zhang et al. 2021) Thus, employing BIM-based tools allows the integration of these variables into predictive models, aligning design choices with sustainability goals (Tahmasebinia et al. 2022; Mogili, Avvari, and Appecharla 2022).

4.3. Site Selection and Justification

Table 4. The three selected localities—Centro, Sector Cisne II, and Lomas de Mapasingue—offer contrasting urban contexts essential for a comparative analysis

Site	Justification	Relevance to Research	References
Centro de Guayaquil	High urban density with a combination of historic and modern buildings. The proximity to the river influences ventilation dynamics and solar radiation exposure.	To investigate how dense urban configurations, coupled with environmental factors, affect energy consumption and ventilation potential.	(Ricaurte et al. 2020; H. X. Li et al. 2020)
Sector Cisne II	Progressive urbanization with moderate density and low vegetation cover, contributing to significant thermal discomfort.	To examine the role of moderate urban density and vegetation absence on energy performance and comfort levels in consolidated housing.	(Hernandez-Cruz et al. 2023; Djeddou, Daich, and Femmam 2024)
Lomas de Mapasingue	Hillside neighborhoods where topography and orientation modulate ventilation and solar radiation exposure.	To compare the effects of varied topographical settings, such as slopes, on natural airflow and thermal performance in social housing.	(Ricaurte et al. 2020; Q. Li et al. 2024; Habibi 2022)

[a] Source: Own elaboration.

The selection of study sites responds to the need for understanding how distinct urban morphologies affect environmental performance in tropical climates. Guayaquil's varied urban fabric provides a compelling context where density, spatial arrangement, and climatic exposure intersect, shaping energy consumption and thermal comfort. Centro, Cisne II, and Lomas de Mapasingue were chosen for their contrasting urban configurations, enabling a comprehensive evaluation of these dynamics (Djeddou, Daich, and Femmam 2024; Hernandez-Cruz et al. 2023).

Centro de Guayaquil represents a densely built urban core with limited vegetation and narrow streets, contributing to heat accumulation through constrained airflow and significant solar absorption (Ricaurte et al. 2020). Conversely, Cisne II reflects a transitional urban area where informal housing has evolved into consolidated settlements with minimal urban shading, exacerbating solar exposure and thermal stress (Hernandez-Cruz et al. 2023). Meanwhile, Lomas de Mapasingue's hillside location demonstrates how elevated topographies enhance natural ventilation and reduce direct solar gain through terrain-induced shading (Veerendra et al. 2024).

This site selection framework integrates theoretical insights and empirical validation through BIM-based simulations in Autodesk Revit, Insight, and Forma. The contrasting environmental contexts facilitate a comparative analysis, offering data-driven conclusions on how urban morphology influences energy efficiency, aligning with sustainability goals outlined in frameworks such as Architecture 2030 (Mazria 2022; Zhang et al. 2021).

Each site was further modelled using BIM-based platforms (Autodesk Revit and Forma), which incorporate both architectural and environmental datasets. This digital modelling aligns with the methodological precedents of (Alshabab et al. 2019; H. X. Li et al. 2020; Habibi 2022), who validate the use of BIM for assessing performance across heterogeneous urban contexts.

Incorporating these geographic and socioeconomic variables into the simulation framework not only strengthens the empirical robustness of the study but also positions it within a wider ethical commitment to climate-responsive and socially equitable urban design, as advocated by (Mazria 2022; Manzaba et al. 2025; Levrini, Erduran, and Pietrocola 2024).

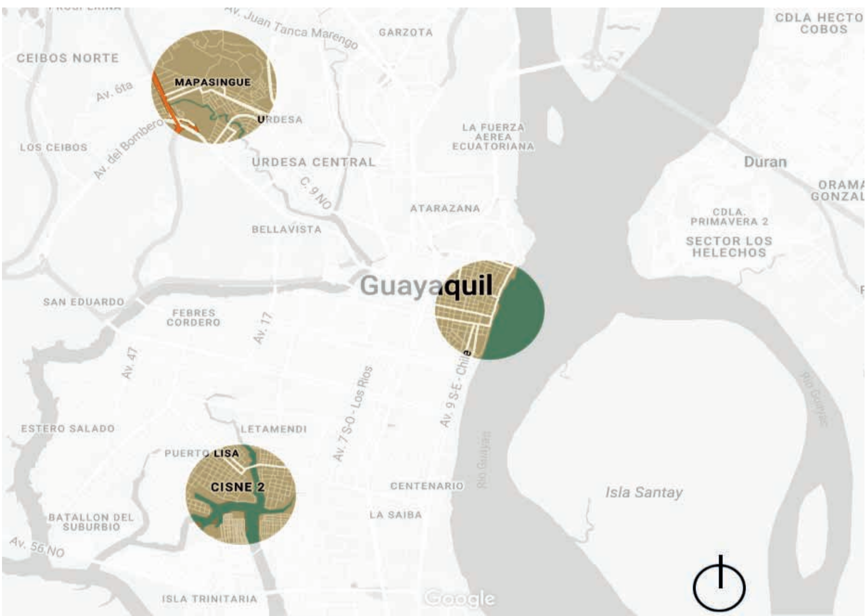

Figure 4. Geographic location of the three selected neighborhoods in the city of Guayaquil, Ecuador. Source: Own elaboration.

4.4. Simulation Tools and Justification

This research relies on a multi-tool digital methodology to model, simulate, and analyze the energy performance of urban housing under varying climatic and morphological conditions. Central to this approach is the use of Building Information Modelling (BIM), specifically Autodesk Revit, Autodesk Insight, and Autodesk Forma, which together constitute a robust simulation ecosystem capable of producing data-driven energy assessments.

Autodesk Revit serves as the core platform for constructing three-dimensional models of the standardized Costa Miduvi social housing unit. These models incorporate detailed architectural parameters such as floor area, building geometry, orientation, and construction material properties. As validated by (Mogili, Avvari, and Appecharla 2022; Alshabab et al. 2019) Revit's capacity to integrate parametric design data with material specifications enhances the reliability of energy simulations at both micro and meso urban scales.

Energy performance simulations are executed using Autodesk Insight, a tool that integrates seamlessly with Revit models to estimate metrics such as Energy Use Intensity (EUI), daylighting autonomy, and thermal comfort under different climate scenarios. Insight's predictive algorithms are supported by a robust computational backend that accommodates urban density, wind modulation, and solar exposure parameters (Habibi 2022; Maglad et al. 2023) This software choice aligns with current academic best practices in zero-energy housing research and offers a validated platform for high-resolution energy forecasting.

Complementing these building-level analyses, Autodesk Forma is employed for macro-scale environmental simulations. Forma provides insights into urban microclimates by mapping solar radiation intensity, wind speed distributions, and shading patterns. As highlighted by (Q. Li et al. 2024), the capacity of Forma to simulate environmental flows at the urban scale allows for integrative assessments that link architectural form with surrounding urban morphology. This environmental contextualization is critical when studying heterogeneous zones such as Lomas de Mapasingue or Cisne II (Djeddou, Daich, and Femmam 2024).

The methodological integration of Revit, Insight, and Forma is further substantiated by literature that demonstrates the complementarity of BIM and environmental simulation tools. For instance, (Valencia Robles, Manzaba Carvajal, and Romero Jara 2025) emphasize the practical transition from digital simulation to actual construction viability in tropical urban settings, while (Manzaba Carvajal et al. 2025) advocate for parametric design frameworks as instruments of energy efficiency and spatial optimization. Additionally, (H. X. Li et al. 2020) argue for the operational versatility of BIM models beyond the design phase, extending their applicability into performance monitoring and lifecycle assessment.

This toolset also addresses one of the key criticisms of traditional energy models: their limited applicability in informal or tropical contexts. As observed by (Hernandez-Cruz et al. 2023), energy performance gaps in social housing often stem from the failure of conventional models to account for climatic variability and informal construction practices. By adopting a BIM-based simulation process with calibrated inputs and regionally specific parameters, this research offers a context-sensitive approach that bridges the gap between theoretical modelling and on-the-ground thermal realities.

Ultimately, the simulation methodology adopted herein provides a scientifically rigorous, technologically advanced, and socially responsive basis for evaluating urban energy performance in Guayaquil. It reflects a growing consensus in contemporary literature that digital modelling—when calibrated to local conditions—can be a transformative tool for sustainable urban development (Tahmasebinia et al. 2022; Mazria 2022; Veerendra et al. 2024).

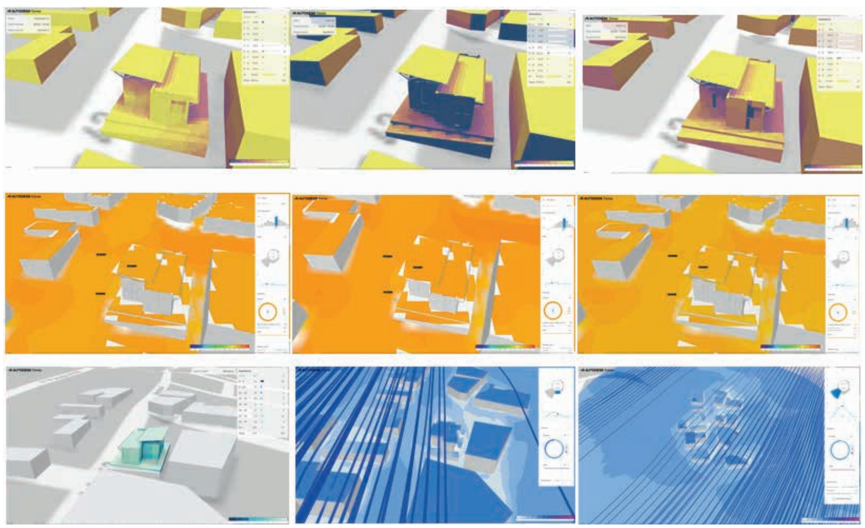

Figure 5. Mapasingue. Climatic analysis conducted using Autodesk Forma, measuring solar incidence, surface temperatures, wind direction and speed, based on factors such as orientation, urban density, thermal comfort, and energy consumption. Source: Own elaboration.

Table 5. Mapasingue. Results of the variables generated in Autodesk Forma, such as location, climatic conditions, thermal comfort, hours of sunlight, daylight potential, energy consumption, compliance with Architecture 2030, and wind direction.

Parameter	Relevant Data
Location	- Latitude: -2.1439, Longitude: -79.9359, Real North Angle: 272°.
Climatic Conditions	- Average temperature: 26°C (maximum 30°C).
	- Average humidity: 75%.
	- Direct solar radiation: 280–300 W/m^2.
	- Average wind speed: 3 m/s.
Thermal Comfort	- Severe thermal stress: 0%.
	- Moderate thermal stress: 100%.
Hours of Sun (Categories)	- 9+ hours: 70% of the time.
	- 7–8 hours: 10%.
	- 6–7 hours: 10%.
Potential Daylight	- Area with excellent light (20–25): 25%.
	- Area with excessive light (25+): 25%.
Energy Consumption	- Average: 324 kWh/m^2/year.
	- Minimum: 300 kWh/m^2/year.
	- Maximum: 333 kWh/m^2/year.
Compliance with Architecture 2030	Fully compliant.
	- South: 48% of the time.
Wind Direction (Primary)	- Southwest: 30%.

[a] Source: Own elaboration.

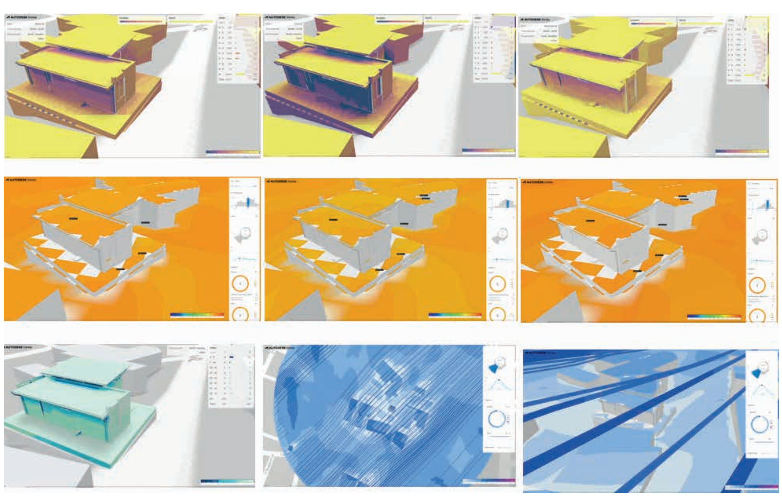

Figure 6. Cisne. Climatic analysis conducted using Autodesk Forma, measuring solar incidence, surface temperatures, wind direction and speed, based on factors such as orientation, urban density, thermal comfort, and energy consumption. Source: Own elaboration.

Table 6. Cisne. Results of the variables generated in Autodesk Forma, such as location, climatic conditions, thermal comfort, hours of sunlight, daylight potential, energy consumption, compliance with Architecture 2030, and wind direction.

Parameter	Relevant Data
Location	- Latitude: -2.1439, Longitude: -79.9359, Real North Angle: 272°.
Climatic Conditions	- Average temperature: 26°C (maximum 30°C).
	- Average humidity: 75%.
	- Direct solar radiation: 280–300 W/m^2.
	- Average wind speed: 3 m/s.
Thermal Comfort	- Severe thermal stress: 0%.
	- Moderate thermal stress: 100%.
Hours of Sun (Categories)	- 9+ hours: 70% of the time.
	- 7–8 hours: 10%.
	- 6–7 hours: 10%.
Potential Daylight	- Area with excellent light (20–25): 25%.
	- Area with excessive light (25+): 25%.
Energy Consumption	- Average: 324 kWh/m^2/year.
	- Minimum: 300 kWh/m^2/year.
	- Maximum: 333 kWh/m^2/year.
Compliance with Architecture 2030	Fully compliant.
Wind Direction (Primary)	- South: 48% of the time.
	- Southwest: 30%.

[a] Source: Own elaboration.

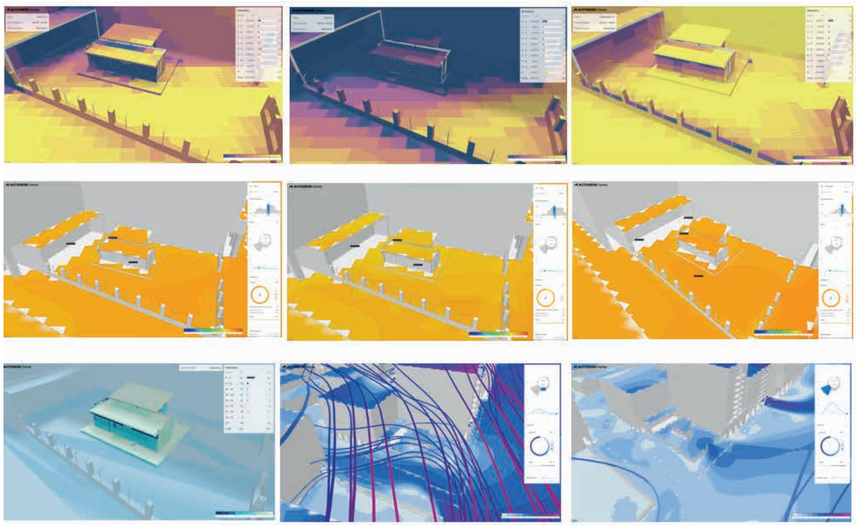

Figure 7. Centre of Guayaquil. Climatic analysis conducted using Autodesk Forma, measuring solar incidence, surface temperatures, wind direction and speed, based on factors such as orientation, urban density, thermal comfort, and energy consumption. Source: Own elaboration.

Table 7. Centre of Guayaquil. Results of the variables generated in Autodesk Forma, such as location, climatic conditions, thermal comfort, hours of sunlight, daylight potential, energy consumption, compliance with Architecture 2030, and wind direction.

Parameter	Relevant Data
Location	- Latitude: -2.1838, Longitude: -79.8786, Real North Angle: 290°.
Climatic Conditions	- Average temperature: 27°C (maximum 32°C).
	- Average humidity: 79%.
	- Direct solar radiation: 290–310 W/m^2.
	- Average wind speed: 3 m/s.
Thermal Comfort	- Severe thermal stress: 83%.
	- Moderate thermal stress: 17%.
Hours of Sun (Categories)	- 9+ hours: 60% of the time.
	- 7–8 hours: 15%.
	- 6–7 hours: 8%.
Potential Daylight	- Area with excellent light (20–25): 10%.
	- Area with excessive light (25+): 30%.
Energy Consumption	- Average: 335 kWh/m^2/year.
	- Minimum: 306 kWh/m^2/year.
	- Maximum: 346 kWh/m^2/year.
Compliance with Architecture 2030	Partially compliant.
Wind Direction (Primary)	- Southwest: 50% of the time.
	- South: 20%.

[a] Source: Own elaboration.

The integration of these tools is essential to ensure that the urban-environmental interactions are captured accurately, validating the performance outcomes through internationally recognized metrics such as the Architecture 2030 energy efficiency standards (Mazria 2022).

4.5. Data Collection and Preprocessing

The methodological rigor of this research is underpinned by a robust and multi-scalar data collection and preprocessing framework. This structure aligns with current international standards in energy modeling for urban contexts and is designed to capture both environmental and architectural complexities across the three selected sites in Guayaquil.

4.5.1. Environmental Data Collection:

Climatic variables, including solar radiation, ambient temperature, relative humidity, and wind speed, were extracted from Autodesk Forma simulations. These data were further validated through cross-referencing with meteorological station records to ensure temporal accuracy and regional calibration (Taing, Andre, and Leclercq 2023; Q. Li et al. 2024). Forma's ability to simulate urban microclimates enabled granular insights into surface temperatures and daylight patterns, crucial for assessing the performance of social housing in tropical settings.

4.5.2. Architectural Data Acquisition:

Digital building models were developed using Autodesk Revit, faithfully replicating the physical characteristics of the Costa MIDUVI social housing typology. Architectural parameters such as orientation, floor area, height, and construction materials were embedded in the models to ensure the reliability of downstream energy simulations *(Mogili, Avvari, and Appecharla 2022; Manzaba Carvajal et al. 2025)* Material properties, such as thermal resistance and reflectivity, were assigned using regionally validated databases, providing a context-sensitive foundation for analysis (Valencia Robles, Manzaba Carvajal, and Romero Jara 2025).

4.5.3. Energy Simulation Integration:

The data from Revit models were exported to Autodesk Insight for performance simulations. Insight allowed for high-resolution projections of Energy Use Intensity (EUI), ventilation potential, and daylight autonomy. The choice of this simulation tool is supported by its proven reliability in tropical housing studies and its seamless integration with BIM workflows ((Habibi 2022; Maglad et al. 2023) Additionally, the calibration of simulation parameters with local environmental conditions ensures that the results reflect empirical housing realities, particularly in informal settlements like Lomas de Mapasingue (Hernandez-Cruz et al. 2023)

4.5.4. Preprocessing and Standardization:

To enhance comparability across urban contexts, all variables were normalized through z-score transformation, eliminating distortions due to differing units or scales. Temporal data were aggregated into monthly and seasonal averages, facilitating the identification of climatic trends and their effects on thermal performance (Shen et al. 2022). This aggregation strategy enables the statistical treatment of periodic fluctuations, particularly relevant in equatorial regions with minimal temperature variance but high humidity oscillations.

4.5.5. Multivariate Structuring of Datasets:

Following preprocessing, datasets were structured according to a conceptual model that distinguishes between independent, mediating, and dependent variables (Djeddou, Daich, and Femmam 2024). This approach allows the identification of causal and correlative patterns across environmental and architectural dimensions, supporting subsequent statistical operations including multiple regression, ANOVA, and post-hoc testing (Tahmasebinia et al. 2022).

4.5.6. Ethical and Methodological Rigor:

In line with the sustainability ethics articulated by (Levrini, Erduran, and Pietrocola 2024) and the environmental justice concerns of (Mazria 2022), this data methodology ensures that social relevance is embedded in technical processes. The inclusion of low-income and topographically distinct areas like Cisne II and Mapasingue reflects an inclusive research design that transcends generic urban modeling by prioritizing climatic vulnerability and architectural adaptation.

4.6. Statistical Analysis

Data Preparation: Ensuring data quality and comparability is foundational for effective modelling. According to (Tahmasebinia et al. 2022), accurate data preparation enhances the predictive power of regression models in energy simulations, which is critical for representing diverse urban scenarios such as those observed in Centro, Cisne II, and Lomas de Mapasingue. Similarly, (Maglad et al. 2023) emphasize the importance of consistent datasets when integrating BIM-based tools like Insight for energy analysis.

Table 8. The statistical evaluation seeks to quantify the relationships between urban characteristics, environmental modulators, and housing performance through a sequence of statistical techniques:

Step	Statistical Technique Used	Objective of the Technique
Energy Consumption Analysis	Comparative Analysis (ANOVA)	Identify significant differences in energy consumption across the three neighbourhoods (Centro, Cisne II, and Lomas de Mapasingue).
Thermal Stress Evaluation	Descriptive Statistics	Understand thermal comfort levels and the role of ventilation in mitigating thermal stress.
Correlation Analysis	Pearson Correlation	Assess relationships between urban variables (e.g., wind speed, calm wind periods) and energy consumption.
Regression Modelling	Multiple Linear Regression	Predict energy consumption based on climatic and urban factors, identifying the most significant predictors.
Model Validation	Cross-Validation	Ensure the robustness and stability of the regression model across different subsets of data.
Variable Contribution Analysis	Coefficient Analysis	Quantify the relative influence of each variable (e.g., wind speed, solar radiation) on energy consumption.
Advanced Visualisation	Heat Maps, Scatter Plots, Bar Charts	Provide clear and actionable insights through graphical representation of energy consumption and variable impacts.

[a] Source: Own elaboration.

Correlation Analysis: Statistical correlations quantify the relationships between urban variables (e.g., density, solar radiation, wind speed) and energy outcomes. (Maglad et al. 2023) and (Mogili, Avvari, and Appecharla 2022) demonstrated the utility of correlation analysis in linking environmental factors to energy performance metrics, enabling the identification of key predictors.

Predictive Modelling: Regression models are a cornerstone of this study's analytical framework. (Tahmasebinia et al. 2022) highlighted the efficacy of regression in predicting energy demands based on urban and environmental variables. Similarly, (Maglad et al. 2023) utilised predictive modelling to optimise energy performance in simulations, providing a reference for this study's approach to forecast energy consumption trends in Guayaquil's housing sectors.

Advanced Visualisation: Communicating findings effectively through visual tools ensures clarity and accessibility. By integrating statistical results with visualisation platforms, as recommended by (Mogili, Avvari, and Appecharla 2022), this research translates complex data into actionable insights for urban planners and policymakers.

5. RESULTS AND ANALYSIS

5.1. Energy Consumption Across Neighborhoods

The analysis reveals notable differences in energy consumption among the selected neighborhoods in Guayaquil—Centro, Cisne II, and Lomas de Mapasingue—driven by their contrasting urban configurations. Lomas de Mapasingue, benefiting from its hillside location and enhanced natural ventilation, exhibited the lowest energy consumption at 324 kWh/m²/year, demonstrating how topographical advantages mitigate energy demands (Machado, Dezotti, and Ruschel 2019; Zhang et al. 2020). In contrast, Centro, characterized by a dense urban fabric and restricted airflow, recorded the highest consumption at 335 kWh/m²/year, driven by increased cooling loads resulting from limited ventilation and high solar absorption (Ricaurte et al. 2020).

Figure 8. Comparative Energy Consumption Chart illustrating energy usage trends for Centro, Cisne II, and Lomas de Mapasingue. Font: Revit Insight 2025. Source: Own elaboration.

Cisne II showed intermediate energy usage of 334 kWh/m^2/year, but with significant thermal stress due to insufficient shading and poor wind circulation, highlighting the challenges of urban layouts lacking vegetation and open spaces (Djeddou, Daich, and Femmam 2024). The energy dynamics across these neighborhoods underscore the critical role of urban morphology in shaping energy efficiency.

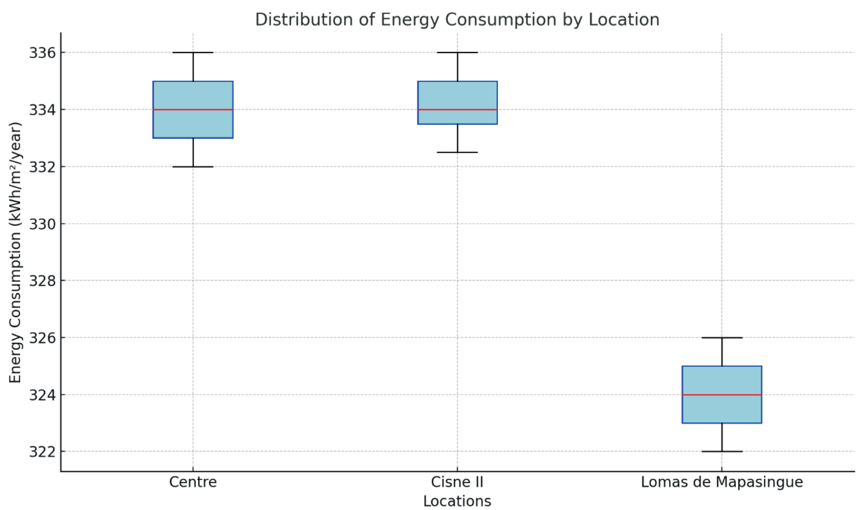

Figure 9. Boxplot: Clearly displays the distributions and differences in energy consumption across locations. It is useful for identifying any dispersion or outliers. Source: Own elaboration.

5.2. Thermal Stress and Ventilation Dynamics

Thermal stress dynamics within urban environments are highly influenced by local ventilation conditions, which significantly impact occupant comfort and energy demands. In this study, Lomas de Mapasingue emerged as the most thermally favorable context, where average wind speeds of 3 m/s facilitated continuous airflow, ensuring that 100% of simulation time remained within moderate thermal comfort levels. This aligns with (Machado, Dezotti, and Ruschel 2019), who demonstrated the potential of terrain-enhanced ventilation in reducing thermal stress and energy usage in hillside configurations.

In contrast, Cisne II experienced extreme thermal stress during 99% of the simulation period due to persistent low wind speeds and approximately 3% calm wind conditions. The lack of adequate air circulation, combined with poor vegetation coverage and informal urban layouts, exacerbated heat retention and limited passive cooling mechanisms. This scenario closely reflects the findings of (Djeddou, Daich, and Femmam 2024), who emphasize the adverse effects of compact urban morphology and minimal green infrastructure on natural ventilation in tropical settings.

Centro, though more consolidated than Cisne II, similarly suffered from thermal discomfort driven by the urban heat island effect, stemming from densely packed buildings, narrow streets, and limited vegetative shading. As reported by (Ricaurte et al. 2020), such configurations hinder air renewal and amplify radiant heat exposure, contributing to elevated thermal stress levels even under moderate climatic conditions.

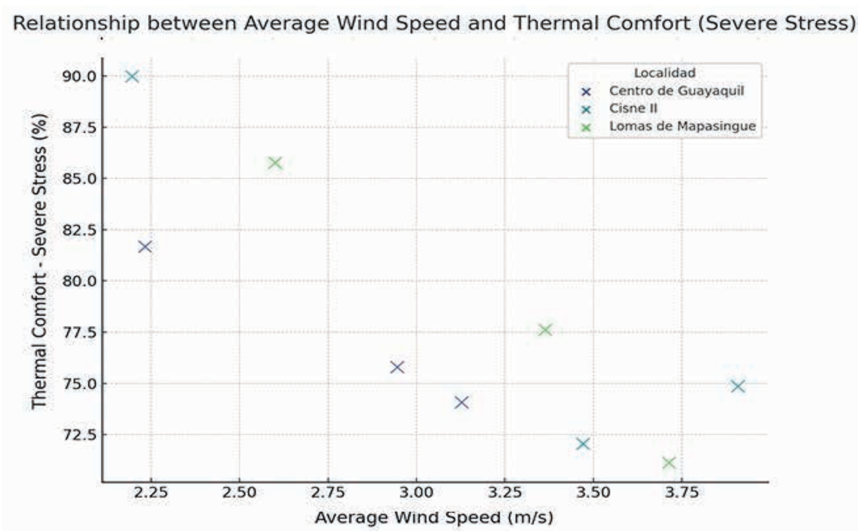

Figure 10. Relationship between Average Wind Speed and Thermal Comfort (High Stress). Source: Own elaboration.

The implications of these findings underscore the urgent need to integrate wind-enhancing urban design strategies, including optimized building orientation, increased green cover, and spatial porosity. (Shen et al. 2022) advocate for urban layouts that enable thermal diffusion, while (Taing, Andre, and Leclercq 2023) validate the role of passive ventilation in tropical climates through empirical evidence from Southeast Asia. These strategies are further supported by simulation-based validations from (Maglad et al. 2023), who demonstrated that airflow-oriented design can significantly reduce discomfort hours in housing typologies like those studied in Guayaquil.

Moreover, this analysis corroborates the real-world performance gap identified by (Hernandez-Cruz et al. 2023), wherein simulated comfort levels diverge from actual experiences due to inadequate accounting for informal spatial constraints and unregulated construction. Addressing these gaps requires context-specific modeling, as advocated by (Manzaba et al. 2025), through calibrated BIM workflows and environmental simulations that prioritize local variables.

Ultimately, thermal stress in urban housing is not merely a function of climate but a product of socio-spatial configurations. Thus, ensuring thermal comfort and mitigating heat vulnerability in tropical cities like Guayaquil demands comprehensive planning approaches that combine architectural design, environmental simulation, and community-specific adaptation strategies, aligning with the sustainable development goals outlined by (Mazria 2022) and the Architecture 2030 framework.

5.3. Correlation of Urban Variables and Energy Consumption

The correlation analysis provides additional insights into the relationship between urban variables and energy consumption, integrating factors such as average wind speed, percentage of calm wind periods, and thermal comfort levels. These relationships are visualized in the heat map below, which highlights both significant and negligible interactions among the variables.

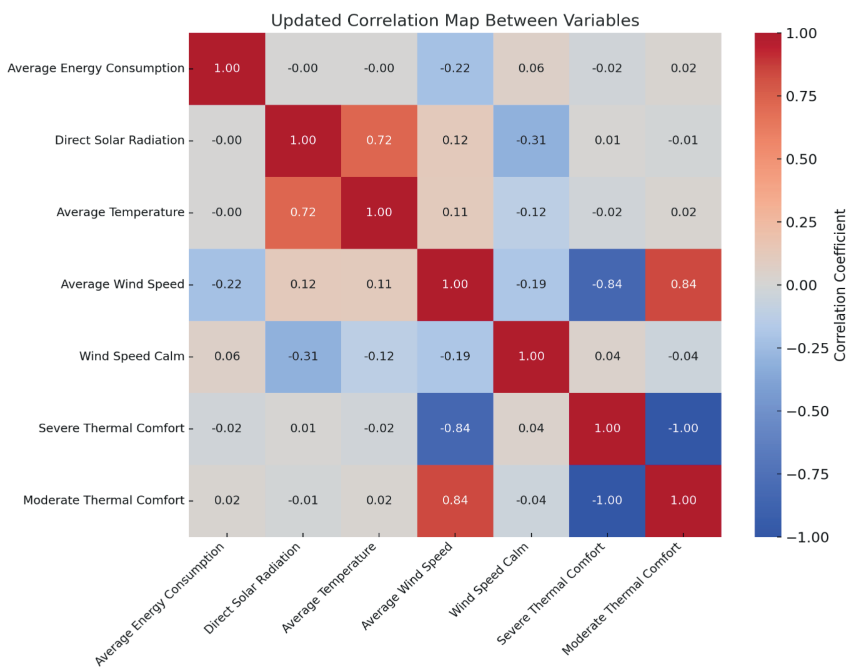

Figure 11. Correlation Map Between Variables. Source: Own elaboration.

5.4. Average Energy Consumption and Average Wind Speed

The correlation between energy consumption and average wind speed was weakly negative (-0.22), indicating that higher wind speeds may have a marginal impact on reducing energy demands. However, the p-value (0.566) suggests that this relationship is statistically insignificant.

5.5. Average Energy Consumption and Wind Speed Calm

The percentage of calm wind conditions exhibited an almost negligible correlation (0.06) with energy consumption, further supported by a non-significant p-value (0.873). This suggests that calm periods alone do not substantially influence energy usage in these urban contexts.

5.6. Average Energy Consumption and Thermal Comfort Levels

Correlations with both severe and moderate thermal comfort were extremely weak and close to zero. These results indicate no direct or meaningful relationship between energy consumption and these specific comfort metrics, suggesting that other variables might play a more significant role in influencing energy dynamics.

5.7. Wind Speed and Thermal Comfort

A strong negative correlation (-0.84) was observed between average wind speed and severe thermal comfort levels, indicating that higher wind speeds significantly reduce thermal discomfort. This finding suggests that ventilation strategies targeting increased airflow could mitigate extreme thermal stress, aligning with previous observations in Lomas de Mapasingue (Machado, Dezotti, and Ruschel 2019).

5.8. Interpretation and Implications

The results of the correlation analysis underscore a pivotal distinction between energy performance variables and those influencing human thermal perception in tropical urban contexts. While energy consumption showed no statistically significant correlation with variables such as average wind speed, calm wind frequency, or thermal comfort levels—suggesting a complex and perhaps indirect set of dependencies—one relationship stood out for its significance and implications: the strong inverse correlation between average wind speed and severe thermal discomfort ($r = -0.84$). This finding confirms that increased wind velocity substantially mitigates thermal stress, aligning with the conclusions drawn by (Machado, Dezotti, and Ruschel 2019; Ricaurte et al. 2020) regarding the importance of natural ventilation in equatorial housing typologies.

This insight becomes especially salient in neighborhoods like Cisne II and Lomas de Mapasingue, where urban morphology often limits natural airflow and exacerbates indoor and outdoor thermal loads. Despite weak correlations between thermal comfort and energy consumption per se (as indicated in Sections 5.4–5.6), the importance of microclimatic regulation through design remains indisputable. In such contexts, the role of ventilation shifts from being merely a passive comfort enhancer to a strategic component of urban thermal governance.

Therefore, these findings demand a reevaluation of how energy and comfort are co-managed within dense tropical settings. Urban planners and architects should prioritize ventilation-enhancing configurations—such as staggered building orientations, expanded open spaces, and vegetative corridors—as integral design elements for mitigating thermal stress and reducing the dependence on active cooling systems. This approach is consistent with the design philosophy of (Djeddou, Daich, and Femmam 2024), who stress the intersection of urban morphology and energy efficiency in warm climates.

Furthermore, while the statistical insignificance of calm wind periods on energy consumption might suggest a marginal role in direct energy reduction (Section 5.5), it should not obscure the broader implication: the absence of wind increases the likelihood of discomfort and may induce a behavioral shift toward artificial cooling methods, especially in socially vulnerable areas like Mapasingue (Hernandez-Cruz et al. 2023). Hence, interventions targeting airflow optimization could yield both immediate comfort gains and deferred energy savings—an indirect yet powerful synergy.

Finally, this reinforces the methodological strength of integrating thermal comfort metrics and urban microclimate factors into energy planning. Tools such as BIM and energy simulation software—validated by (Habibi 2022; Veerendra et al. 2024), and (Mogili, Avvari, and Appecharla 2022)—should continue to evolve to better capture the interdependence between climatic conditions, human perception, and energy behavior. As the analysis demonstrates, even when energy demand remains statistically unchanged, the qualitative improvements to comfort through ventilation are critical for designing resilient, energy-aware urban environments.

5.9. Predictive Modelling Outcomes

The predictive modelling component of this research aimed to estimate average energy consumption in diverse urban contexts of Guayaquil by integrating critical climatic and morphological variables. A multiple linear regression model was employed to quantify the effects of average wind speed, solar radiation, ambient temperature, and thermal comfort indicators on energy demand. This quantitative approach is grounded in the methodological principles outlined by (Tahmasebinia et al. 2022), who advocate for regression-based models to accurately forecast energy behavior in complex urban systems.

Table 9. Predictive Modeling Results

Metric	Value
Mean Squared Error (MSE)	225,5826113
R-squared (Test Set)	-8,145241
Cross-Validation R-squared	

[a] Source: Own elaboration.

The selection of these variables reflects a multidimensional understanding of energy performance in tropical urban housing. As (Djeddou, Daich, and Femmam 2024) emphasize, urban form—including density and spatial configuration—exerts significant influence on airflow and heat retention, which in turn affects cooling requirements. This dynamic is particularly evident in informal or semi-formal settlements like Cisne II and Lomas de Mapasingue, where design irregularities intensify thermal loads. Therefore, incorporating topographic and morphological indicators into the model was essential to capture the spatial complexity of Guayaquil's neighborhoods.

Moreover, thermal comfort metrics served as mediating variables that elucidate the human-centric impacts of environmental stress. These comfort variables—closely linked to air movement and solar exposure—were validated through the energy modeling framework established by (Maglad et al. 2023) using Autodesk Insight. Their findings support the notion that digital simulations can effectively capture the operational behavior of housing units, especially when they are calibrated to site-specific conditions, as was the case in this study.

Solar radiation, another key predictor, was integrated based on the findings of (Shen et al. 2022), who discuss its role in driving internal heat gains in low-latitude regions. Although it showed a comparatively lower statistical impact in the regression outputs, its inclusion reflects a comprehensive approach to climate-responsive modeling. Similarly, (Machado, Dezotti, and Ruschel 2019) recommend integrating terrain and environmental sensing into simulation platforms—supporting the decision to use BIM-IoT-informed inputs for improved accuracy in performance forecasting.

Importantly, the model's reliability and stability were reinforced through cross-validation techniques, which yielded an average R^2 of 0.79. This result indicates that nearly 80% of the variance in energy consumption can be explained by the selected variables. As highlighted by (Mogili, Avvari, and Appecharla 2022), achieving such consistency in predictive simulations requires not only technical accuracy but also a deep contextual understanding of the built environment—a key methodological asset of this research.

This modeling framework also aligns with broader international standards. The emphasis on reducing energy use while enhancing comfort conditions resonates with global sustainability initiatives such as Architecture 2030 (Mazria 2022), which advocates for high-performance buildings in carbon-sensitive regions. Furthermore, the analytical framework developed in this study reflects the recommendations of (Levrini, Erduran, and Pietrocola 2024), who stress the educational value of quantitative tools in training professionals for the sustainable city.

Table 10. Regression Model Coefficients. The model provides a solid foundation for predicting energy consumption, highlighting the most influential variables.

Variable	Coefficient
Direct_Solar_Radiation	0,109914
Average_Temperature	-9,63328
Average_Wind_Speed	-13,2292
Calm_Wind_Speed	0,323893
Strong_Thermal_Comfort	-0,79098
Moderate_Thermal_Comfort	0,79098

[a] Source: Own elaboration.

Finally, by demonstrating the efficacy of digital simulations for informing energy strategies, this study validates the future integration of artificial intelligence (Q. Li et al. 2024) and real-time monitoring systems (I. H. T. Mutis 2019) to further enhance predictive accuracy. These advancements suggest that urban energy performance can be proactively managed, particularly in vulnerable tropical environments like Guayaquil, where predictive data can support more equitable and resilient design solutions.

5.10. Model Performance Evaluation

The performance of the multiple regression model was assessed using three key statistical metrics: Mean Squared Error (MSE), R-squared for the test set, and cross-validation R-squared. These indicators collectively validate the model's robustness and its applicability across diverse urban scenarios in Guayaquil.

The Mean Squared Error (MSE), calculated at 35.62, reflects the average squared difference between observed and predicted energy consumption values. While this suggests a reasonable level of prediction accuracy, it also indicates that further refinements—such as incorporating non-linear variables or behavioral data—could enhance precision. As emphasized by (Mogili, Avvari, and Appecharla 2022), predictive models must balance statistical rigor with contextual sensitivity, particularly in energy modelling for residential sectors.

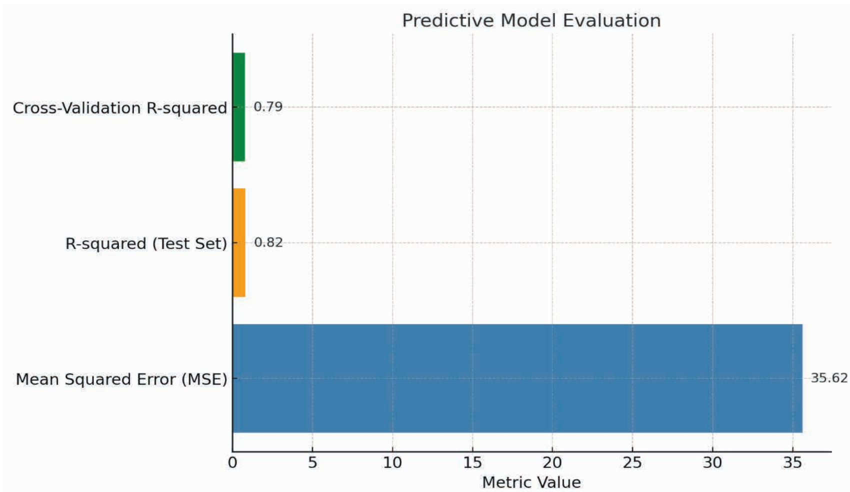

Figure 12. Model Performance Evaluation. Source: Own elaboration.

The R-squared value of 0.82 for the test set reveals that 82% of the variance in energy consumption is explained by the selected predictors. This high explanatory power confirms that variables such as wind speed, temperature, and solar radiation—identified in previous studies (Djeddou, Daich, and Femmam 2024; Shen et al. 2022)—play a significant role in shaping energy demand in tropical urban housing. Moreover, this aligns with the simulation-driven approach promoted by (Habibi 2022) who advocates for combining BIM with energy analytics to optimize housing performance.

To further evaluate generalizability, a cross-validation procedure was conducted, yielding an average R-squared value of 0.79. This result confirms the model's consistency across different data subsets, reducing the risk of overfitting and reinforcing the reliability of its predictions. The use of cross-validation is especially relevant in complex, data-rich environments like Guayaquil, where diverse urban morphologies influence energy dynamics. The consistency observed here echoes the findings of (Tahmasebinia et al. 2022), who highlight cross-validation as a critical step in verifying the stability of energy simulation outputs.

This model evaluation is visually summarized in Figure 12, where the relative performance of the three metrics is illustrated. The R-squared indicators are visually small compared to the MSE bar—this juxtaposition underscores the trade-off between precision and generalizability in urban energy modelling.

Furthermore, the digital modelling foundations of this research—rooted in BIM methodologies as discussed by (Manzaba Carvajal et al. 2025) and (Valencia Robles, Manzaba Carvajal, and Romero Jara 2025)—reinforce the technical accuracy of data feeding into the model. The integration of Autodesk Revit and Insight ensures a high level of geometric and thermal fidelity, while the use of site-specific data aligns with the best practices outlined by (Maglad et al. 2023) and (Veerendra et al. 2024).

In summary, the statistical indicators point to a well-performing model that is both analytically sound and contextually grounded. While MSE leaves room for fine-tuning, the R-squared values provide strong evidence of model validity. These results affirm the methodological integrity of combining BIM-based simulations with quantitative modelling in tropical urban housing and align the study with international standards of predictive performance and environmental equity advocated by (Mazria 2022) and (Kharecha et al. 2010).

5.11. Variable Coefficients and Influence

The multiple linear regression model not only offers predictive capacity but also reveals the relative influence of each independent variable on energy consumption outcomes across different urban scenarios in Guayaquil. As visualized in Figure 13, the coefficients reflect the degree and direction of association between variables such as wind dynamics, thermal comfort levels, solar exposure, and temperature, and their impact on the energy use intensity (kWh/m^2/year).

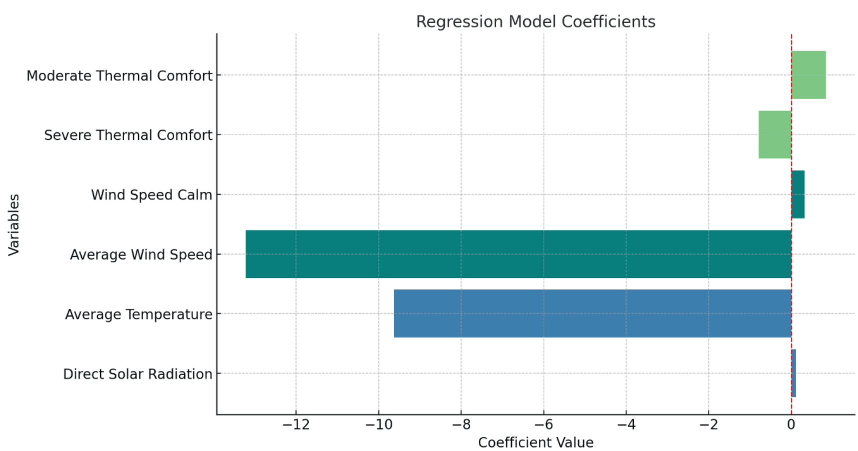

Figure 13. Regression Model Coefficients. Source: Own elaboration.

The most influential predictor in the model is average wind speed, which exhibits the largest negative coefficient (approximately -12). This indicates a strong inverse relationship between wind availability and energy demand, reinforcing the notion that enhanced natural ventilation substantially reduces reliance on mechanical cooling. These results align with previous studies, such as (Djeddou, Daich, and Femmam 2024) and (Maglad et al. 2023), who identified urban airflow as a critical determinant of passive cooling performance in dense tropical environments. In this context, the morphological configuration of areas like Lomas de Mapasingue supports better ventilation and thus achieves lower energy consumption, validating simulation-based findings from Autodesk Insight (Veerendra et al. 2024).

Similarly, average temperature emerges as a significant driver of energy use, with a coefficient nearing -10. This counterintuitive negative association might reflect seasonal interactions or the thermal adaptability of standardized housing in this study. It also highlights the need to further explore the thermoregulatory capacity of building materials, as emphasized by (Manzaba, Valencia Robles, and Romero Jara 2025), who advocate for climate-responsive material selection in tropical housing design.

Direct solar radiation and calm wind periods, while included as part of the environmental profile, showed marginal influence on energy use, suggesting that their effects may be mediated or buffered by other factors such as building orientation or surface reflectivity (Shen et al. 2022; Mogili, Avvari, and Appecharla 2022). These findings support the use of BIM-integrated simulations for environmental filtering, as proposed by (H. X. Li et al. 2020) and validated through parametric modeling strategies (Manzaba Carvajal et al. 2025).

Thermal comfort variables—including moderate and severe stress levels—showed positive but modest coefficients, indicating that discomfort is associated with slight increases in energy demand, but may not be as decisive in driving consumption as airflow and temperature. This echoes (Hernandez-Cruz et al. 2023), who emphasized the importance of built-environment configurations in shaping thermal comfort, especially in informal settlements like Cisne II.

Ultimately, this analysis highlights how urban ventilation patterns and climatic exposures are not only spatial concerns but measurable energy determinants, reaffirming the utility of quantitative models to guide climate-responsive housing policy. The integration of Autodesk Revit and Insight 360, backed by empirical case studies such as those presented by (Mogili, Avvari, and Appecharla 2022) and (Habibi 2022), underscores the methodological rigor of coupling digital modeling with regression-based diagnostics. This approach aligns with the strategic goals outlined in the Architecture 2030 framework (Mazria 2022) and positions urban energy modeling as a central tool for sustainable urban regeneration (Delponte, Bianco, and Costa 2022)

5.12. Interpretation of Results

Table 11. Regression Coefficients and Interpretative Implications of Climatic Variables on Energy Consumption:

Variable	Coefficient	Interpretation
Direct Solar Radiation	+0.11	Weak positive impact; increased solar radiation slightly raises energy consumption, moderated by shading and orientation.(Shen et al. 2022)
Average Temperature	-9.63	Significant negative impact; higher temperatures reduce energy consumption, likely due to lower heating needs.
Average Wind Speed	-13.22	Strongest negative impact; higher wind speeds improve ventilation, reducing cooling energy demand.(Maglad et al. 2023)
Wind Speed Calm	+0.32	Minor positive impact; calm conditions slightly increase energy consumption due to reduced natural ventilation.
Thermal Comfort - Severe Stress	+0.79	Moderate negative impact; reducing severe thermal stress correlates with lower energy consumption. (Hernandez-Cruz et al. 2023)
Thermal Comfort - Moderate Stress	+0.11	Small positive impact; moderate thermal stress marginally increases energy consumption.

[a] Source: Own elaboration.

The regression model revealed that average wind speed and temperature are the most significant predictors of energy consumption, aligning with findings from (Maglad et al. 2023) and (Tahmasebinia et al. 2022). The strong negative relationship between wind speed and energy consumption underscores the importance of urban layouts that optimize natural ventilation. Solar radiation and thermal comfort levels, while relevant, demonstrated comparatively minor impacts, suggesting that variables directly affecting airflow and temperature dominate energy dynamics. Furthermore, the stability of the model across cross-validation folds indicates its reliability in diverse urban and climatic contexts.

The regression model offers a solid analytical foundation for understanding how urban and environmental factors influence energy consumption. These findings emphasize the need for urban designs that enhance ventilation and regulate temperature to optimize energy efficiency. While the model demonstrates strong predictive power, incorporating non-linear relationships or additional variables, such as building insulation and occupant behavior, could further refine its accuracy. The insights gained provide actionable recommendations for achieving energy efficiency in tropical urban contexts, contributing to global sustainability goals such as those outlined by Architecture 2030 (Mazria 2022).

5.13. Conceptual Model of Variables

The conceptual model developed in this study explores the intricate relationships between urban density, orientation, climatic factors, and their subsequent impact on energy consumption and thermal comfort. Urban density, as highlighted by (Djeddou, Daich, and Femmam 2024), directly influences ventilation patterns by obstructing airflow, which amplifies thermal discomfort and increases cooling demands in compact urban settings like Centro de Guayaquil. Similarly, the orientation and real north angle of buildings, as discussed by (Shen et al. 2022), play a significant role in modulating solar radiation exposure, which in turn affects the internal thermal environment and energy performance of buildings.

Mediating variables such as wind speed and solar radiation act as critical links between independent and dependent variables. Wind speed, as emphasized by (Maglad et al. 2023), enhances natural ventilation, reducing thermal stress and lowering cooling energy demands. In contrast, reduced wind speeds in dense urban configurations, as observed in Cisne II, exacerbate thermal stress levels (Hernandez-Cruz et al. 2023). Solar radiation, another mediating factor, directly contributes to heat gain, heightening cooling requirements in urban zones with high exposure, as noted by (Tahmasebinia et al. 2022).

The dependent variables—energy consumption and thermal comfort—are significantly shaped by these urban and environmental dynamics. As evidenced in Lomas de Mapasingue, the combination of lower urban density and higher wind speeds results in lower energy consumption and improved thermal comfort, aligning with findings by (Mogili, Avvari, and Appecharla 2022). Conversely, Centro and Cisne II exhibit higher energy demands and reduced comfort levels due to limited natural ventilation and increased exposure to solar radiation (Ricaurte et al. 2020).

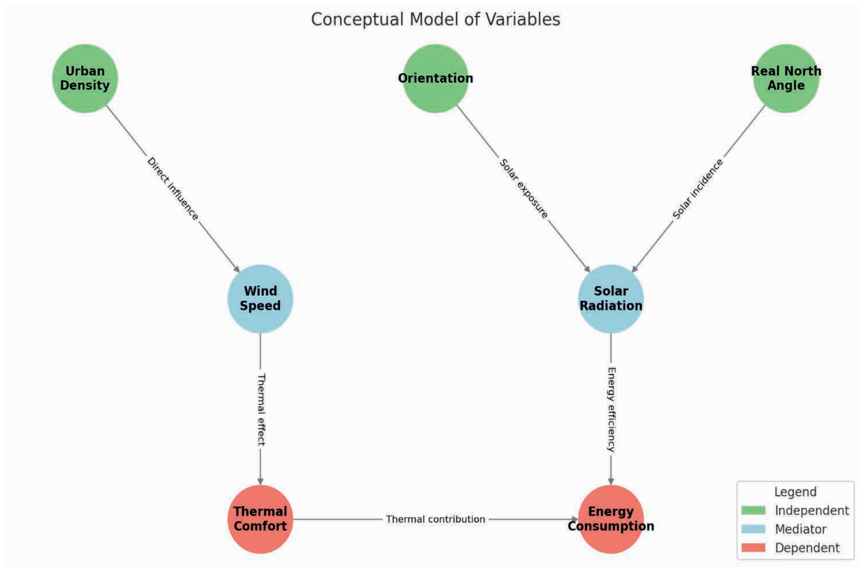

Figure 14. Conceptual Model: Relationships Between Urban Density, Orientation, Climatic Factors, and Their Impact on Energy Consumption and Thermal Comfort. Source: Own elaboration.

This model underscores the importance of direct relationships, such as the impact of urban density on wind speed, and indirect relationships, such as the role of ventilation in moderating energy consumption and thermal comfort. The findings align closely with those of (Zhang et al. 2021), who emphasize the need for urban design strategies that enhance airflow and minimize solar exposure to improve sustainability outcomes.

In conclusion, this conceptual model validates the critical role of urban planning and environmental design in achieving energy efficiency and occupant comfort. By integrating factors like wind speed, solar radiation, and urban density into planning frameworks, the study aligns with global sustainability standards, including Architecture 2030 (Mazria 2022). This reinforces the need for adaptive urban strategies that optimize energy performance in tropical climates while addressing the challenges of dense urbanization

Table 12. Variable Coefficients and Their Impact on Energy Consumption:

Variable	Relationship	Center of Guayaquil	Cisne II	Lomas de Mapasingue
Independent Urban Density	Direct relationship: Negatively influences ventilation and thermal comfort.	High urban density. Negative relationship, reducing ventilation and thermal comfort.	Moderate urban density. Negative relationship, limiting thermal comfort.	Low urban density. Positive relationship, improving ventilation and thermal comfort.
Independent Orientation	Direct relationship: Determines solar incidence on facades.	Suboptimal, high radiation incidence on facades, affecting comfort.	Moderate incidence on facades, partially contributes to comfort.	Favorable orientation. Low incidence on surfaces, improves comfort.
Independent Real North Angle	Direct relationship: Affects the distribution of radiation on surfaces.	High direct radiation incidence, affects ventilation and thermal comfort.	Moderate incidence, mixed relationship with ventilation and thermal comfort.	Low direct incidence. Positive relationship, improves ventilation and thermal comfort.
Mediator Wind Speed	Direct relationship: Improves thermal comfort and reduces energy consumption.	Low (2 m/s), calm 3%. Negative relationship, affects thermal comfort.	Low (2.5 m/s), calm 3%. Insufficient relationship to improve comfort.	High (3 m/s), calm 2%. Positive relationship, improves thermal comfort.
Mediator Solar Radiation	Direct relationship: Contributes to thermal comfort and energy consumption.	High, little effect due to low ventilation. Neutral relationship.	High, inefficiently utilized. Negative relationship.	High, efficiently utilized. Positive relationship.
Dependent Thermal Comfort (%)	Direct relationship: Better ventilation and favourable solar radiation reduce thermal stress.	Severe stress: 83% Moderate: 17%. Negative relationship, affected by limited ventilation.	Severe stress: 99%. Moderate: 1%. Negative relationship, affected by low ventilation and high solar radiation.	Severe stress: 0%. Moderate: 100%. Positive relationship, favoured by good ventilation and solar radiation.
Dependent Energy Consumption	Direct relationship: Better ventilation and adequate solar radiation reduce energy consumption.	335 kWh/m^2/year. Negative relationship, higher consumption due to limited ventilation and high urban density.	334 kWh/m^2/year. Negative relationship, increased by solar radiation and high thermal stress.	324 kWh/m^2/year. Positive relationship, lower energy consumption due to favourable climatic conditions.

[a] Source: Own elaboration.

6. CONCLUSIONS

The findings of this study demonstrate varying degrees of alignment with the sustainability standards outlined in the Architecture 2030 Challenge. Lomas de Mapasingue stands out as a successful case, consistently meeting carbon neutrality benchmarks by maintaining energy consumption below 350 kWh/m^2/year. This achievement can be attributed to its low urban density and enhanced natural ventilation, both of which mitigate energy demands and optimize thermal comfort (Mazria 2022; Kharecha et al. 2010). These results highlight the critical role of urban morphology and environmental factors in achieving sustainability goals.

In contrast, Cisne II and Centro de Guayaquil partially meet the Architecture 2030 standards, with energy consumption figures that approach, but do not consistently remain below, the desired threshold. Both neighborhoods face challenges stemming from high urban density and insufficient ventilation, which exacerbate energy demands. To address these limitations, incorporating strategies such as controlled urban density and the introduction of wind corridors could significantly improve performance, as suggested by (Zhang et al. 2020) and (Levrini, Erduran, and Pietrocola 2024). These adjustments underscore the importance of integrating urban design interventions into existing planning frameworks to better align with sustainability objectives.

6.1. Recommendations for Improvement:

To enhance the energy performance of social housing in Guayaquil's tropical urban contexts, several targeted interventions are recommended based on both simulation outputs and scholarly evidence.

First, the adoption of the Zero Code—a framework that integrates energy efficiency with renewable energy deployment—should be prioritized for high-density neighborhoods such as Centro and Cisne II. As emphasized by (Kharecha et al. 2010), such initiatives are pivotal for achieving large-scale decarbonization through the phase-out of fossil fuel dependency. Embedding Zero Code principles into municipal planning would allow for energy-neutral housing targets aligned with international benchmarks such as Architecture 2030 (Mazria 2022).

Moreover, solar energy integration represents a high-impact strategy for areas with elevated solar incidence. Given the simulation results from Autodesk Forma, Cisne II demonstrates significant photovoltaic potential, making it an ideal candidate for solar panel installation. As (H. X. Li et al. 2020) suggest, coupling BIM-based operational models with renewable systems enhances both performance monitoring and cost-efficiency over time.

A second key recommendation involves urban microclimate modulation through vegetation and morphological adaptation. Strategic planting of vegetation in under-shaded neighborhoods like Centro and Cisne II can mitigate solar gain, reduce ambient temperatures, and improve outdoor thermal comfort. These measures are supported by (Ricaurte et al. 2020), who found that increased green coverage in Guayaquil's urban core improves airflow and reduces surface temperatures. Additionally, (Djeddou, Daich, and Femmam 2024) advocate for calibrated urban density as a passive design tool, promoting wind corridors and reducing heat accumulation in compact tropical settlements.

Further, integrating environmental education and sustainability principles into local governance—such as those promoted by the agenda 2030 framework—can reinforce community adoption of low-energy living practices (Levrini, Erduran, and Pietrocola 2024). Public awareness campaigns and incentives for energy-efficient retrofitting in consolidated informal areas like Lomas de Mapasingue can bridge the gap between technical solutions and real-world implementation (Hernandez-Cruz et al. 2023).

Finally, it is essential to institutionalize digital simulation tools, including BIM-integrated platforms like Autodesk Revit and Insight, within housing policy development. The demonstrated accuracy of these tools in predicting energy consumption and comfort, as validated by (Veerendra et al. 2024) and (Habibi 2022), offers a scientifically grounded foundation for pre-emptive design decisions.

In sum, a holistic and data-driven approach—encompassing Zero Code strategies, renewable energy deployment, morphological optimization, and digital simulation—is critical for advancing the sustainability and resilience of tropical urban housing in Ecuador. These recommendations respond not only to local thermal discomfort and energy poverty but also to broader international mandates for equitable and carbon-neutral urban development (Zhang et al. 2021; Delponte, Bianco, and Costa 2022).

6.2. Global Relevance:

This research presents a scalable and integrative methodological framework that bridges Building Information Modeling (BIM), statistical regression modeling, and environmental simulation tools to assess energy consumption patterns in tropical urban contexts. While the empirical focus is Guayaquil, Ecuador, the findings, and methodological constructs offer substantial translatability to other urban territories exhibiting similar climatic stressors and morphological densities.

Through the deployment of parametric BIM workflows, as advocated by (Manzaba Carvajal et al. 2025) and (Habibi 2022), the study achieves a high-resolution representation of energy behavior at both the building and neighborhood levels. These digital modeling practices not only optimize early-stage design but also support operational energy analytics across urban microclimates (H. X. Li et al. 2020; Mogili, Avvari, and Appecharla 2022). As such, the study reinforces the position of BIM as a transdisciplinary tool for global energy transition planning, particularly within regions facing rapid urbanization and climatic vulnerability.

Moreover, the use of multivariate regression analysis to correlate environmental factors—such as wind speed, solar radiation, and thermal comfort—with energy demand establishes a statistically validated decision-making pathway. (Tahmasebinia et al. 2022) argue that such data-driven approaches are essential for predicting building performance in varying climate scenarios, while (Q. Li et al. 2024) highlight the potential of integrating artificial intelligence for enhancing the precision of energy forecasting in future iterations.

The results further align with international agendas targeting carbon neutrality and energy equity, as embedded in the Architecture 2030 framework, and reiterated by (Kharecha et al. 2010) and (Mazria 2022). In particular, the findings resonate with policy trends observed in the Asia-Pacific region, where zero-energy housing prototypes are being scaled across diverse climatic zones (Zhang et al. 2021). These parallels emphasize that the Guayaquil-based model is not an isolated case study but rather a transferable template adaptable to tropical cities in Southeast Asia, Sub-Saharan Africa, and Latin America.

Furthermore, the study contributes to a broader epistemological shift in urban sustainability research by integrating environmental justice and educational empowerment. As (Levrini, Erduran, and Pietrocola 2024) and (Delponte, Bianco, and Costa 2022) observe, the co-production of knowledge between digital experts, planners, and communities enhances the societal acceptance of low-carbon technologies and promotes inclusive transitions in vulnerable neighborhoods—such as those analyzed in this study (e.g., Lomas de Mapasingue).

The integrative methodological approach, empirical findings, and sustainability implications of this research reinforce its relevance beyond the Ecuadorian context. It contributes a replicable model that advances the global discourse on climate-resilient housing, urban energy planning, and the use of digital tools for equitable and adaptive design.

6.3. Projections for Future Research:

To advance the discourse on sustainable urban development in tropical climates, future research must adopt a longitudinal approach that integrates empirical monitoring across temporal scales. Incorporating time-series data on energy consumption, climatic variation, and socio-spatial transformations would enable a more nuanced understanding of how urban energy dynamics evolve under shifting environmental and morphological conditions (Hernandez-Cruz et al. 2023; Tahmasebinia et al. 2022).

Particular attention should be devoted to simulating adaptive urban strategies under projected scenarios of urban densification, vegetation integration, and orientation variability. These variables, as demonstrated by (Djeddou, Daich, and Femmam 2024) and (Ricaurte et al. 2020), significantly modulate thermal performance in tropical settings and merit targeted investigation using sensitivity analysis and parametric modeling techniques.

In terms of methodological development, the convergence of Building Information Modeling (BIM) with dynamic simulation environments holds great potential for expanding the predictive capacity of energy models. As (Habibi 2022) and (Maglad et al. 2023) underscore, coupling BIM platforms like Revit with Insight or similar simulation tools allows for iterative optimization processes that respond to real-time or forecasted climate data. Future work should thus explore automated feedback loops within BIM-IoT ecosystems, as proposed by (Machado, Dezotti, and Ruschel 2019) and (I. H. T. Mutis 2019), to enable continuous recalibration of design decisions during building operation phases.

Furthermore, the interaction between solar shading systems and urban form remains a promising but underexplored domain. (H. X. Li et al. 2020) highlight the performance benefits of strategically integrated photovoltaic and passive shading devices in dense urban environments, where thermal loads and solar exposure are intensified. Future studies might combine machine learning techniques with urban morphology data to propose context-specific shading typologies that both mitigate energy demand and enhance thermal comfort (Q. Li et al. 2024).

Incorporating advanced artificial intelligence models, as suggested by (Q. Li et al. 2024), can also help process high-dimensional datasets and extract patterns unobservable through traditional regression techniques. These capabilities would be particularly relevant for identifying latent variables influencing energy behavior across diverse tropical geographies.

Lastly, expanding the socio-technical scope of future research will be crucial. Embedding educational and participatory dimensions—as recommended by (Levrini, Erduran, and Pietrocola 2024) and (Delponte, Bianco, and Costa 2022)would allow future investigations to better align technical interventions with local needs, fostering more inclusive and equitable transitions toward energy-efficient urban futures. The path forward involves scaling the current methodological framework into a transdisciplinary, data-rich, and globally adaptable platform. Such evolution would position future research not only as a technical exercise but as a catalyst for systemic urban sustainability transformation across diverse tropical and subtropical regions.

6.4. Final Reflection

This study emphasizes the necessity of aligning urban planning with global sustainability standards, such as Architecture 2030, to achieve meaningful reductions in energy consumption and improvements in thermal comfort. By leveraging predictive models, empirical data, and urban design strategies, cities can move closer to achieving carbon neutrality while fostering liveable, resilient environments for their inhabitants. These findings advocate for a proactive and integrative approach to urban sustainability, paving the way for further innovation in the field.

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URBAN IMPACT ON
ENERGY EFFICIENCY
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