

Optimization of energy consumption in lighting through window-to-wall ratio (WWR) in prefabricated social housing under warm climate conditions

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Abstract

The influence of window-to-wall ratio (WWR) on energy consumption for lighting and visual comfort in a social housing building in Bucaramanga, Colombia, was investigated. Using parametric simulations in Design Builder, WWR between 0% and 100% were modeled in 10% increments, while structural and climatic conditions were kept constant. The results show that WWR values below 30% do not meet the minimum illuminance levels requires by Colombian regulations, while values above 70% lead to over-illumination and glare. The optimal range is between 40% and 60%, ensuring that regulations are met in most rooms. Monthly lighting energy consumption is reduced by up to 65% (approximately 650 kWh per year), and lighting uniformity is optimized. These results confirm that WWR regulation is an effective, reproducible, and cost-effective passive design strategy for increasing energy efficiency and living quality in social housing in warm climates.

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1. Introduction

Globally, the construction sector accounts for a significant share of energy consumption, as it is responsible for more than 30% of total demand and considerable proportion of greenhouse gas emissions [1], [2]. In this context, exploring passive strategies that simultaneously improve energy efficiency and user comfort has become a central focus of current research [3], [4]. One of these strategies is that natural lighting serves a dual purpose: on the one hand, it promotes health, productivity, and well-being of residents. In regions with warm climates such as Bucaramanga (Colombia), this issue is particularly relevant due to high solar radiation and the need to control energy consumption in social housing [5], [6]. Consequently, the window-to-wall (WWR) is becoming established as a decisive factor in planning, the consideration of which is fundamental for the formulation of strategies and guidelines for improving living conditions and reducing energy consumption in social housing construction projects [7], [8].

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The conceptual background shows that the relationship between window-to-wall ratio (WWR) and glazing systems has been extensively studied due to their impact on the energy performance of buildings [9]. A study conducted in China used dynamic simulations to analyze the behavior of WWR in different climate zones. The results have shown that there is no single optimal ratio, but that this varies depending on the orientation of the façade and the specific climate of the respective location. However, it was found that WWR values between 30% and 60% represent a good compromise between daylight incidence and energy saving [10]. Using a combined approach of experiments and simulations, a study conducted in Saudi Arabia investigated the effects of increasing the WWR from 12% to 40%. It was found that each 10% increase in the window-to-wall ratio raises the indoor temperature by around 1°C, leading to an increase in cooling capacity, Therefore it is recommended that the WWR should not exceed 20% in hot climates to ensure thermal comfort and limit energy consumption [11]. In Algeria, however, a study was conducted in a school building using simulation with Design Builder and TRNSYS to investigate the effects of different glazing and window-to-wall ratios (WWR) where the results have shown that a WWR of 30% in combination with sunshades with 60°angle reduces annual energy consumption by 11%. These findings underscore the need to consider sunshades in environments with high solar radiation [12].

In parallel with the investigation of window area, the type of glazing has emerged as a decisive factor in the energy performance of buildings. The available findings, including comparisons between single-pane, double-pane, low-E, electrochromic, and bronze-colored glass, show that this variable has an important influence on visual comfort and thermal loads [13]. In the Colombian context, particularly in regions with cold climates, studies have been conducted using Design Builder models calibrated with monitoring data, which showed that the use of bronze glass increases indoor comfort hour by 14,2%. This finding confirms that glazing can be used as a passive heating strategy in extreme climates [14]. At the international level, research into advanced building technologies has also investigated systems such as building-integrated photovoltaics (BIPV), which generate electricity while regulating solar gain [15], [16]. Combinations of semi-transparent photovoltaic glass and natural ventilation have also been studied, improving both the quality of natural light and the thermal performance of buildings [17].

In the field of prefabrication, current research findings underscore the suitability of this construction method for the development of nearly zero-energy buildings, which, in combination with passive strategies, achieve high energy efficiency without additional costs [18]. In Brazil, the “Selo Casa Azul” certification has shown that WWR and window type have a direct impact on the sustainability rating of social housing, confirming the need for considering these variables early in the design phase [19]. In parallel, innovative approaches such as generative design with artificial intelligence have shown that they can optimize modular buildings while taking into account orientation, WWR, and materials [20]. Studies in South Africa support this view by pointing out that passive strategies, including WWR optimization, are key to the transition to a low-carbon economy [21].

Although research has made progress in many areas, there are still some parts that are not fully explored. This applies, for example, to social prefabricated housing in regions with warm climates in Latin America, which is a topic that contrasts with the preferential attention given to office or institutional buildings in temperate climates. This geographical and typological bias is particularly serious when one considers that lower-income families, who occupy precisely these dwellings, are most affected by the financial burden of high energy consumption. This concern gives rise to two most important research questions:

RQ1: What influence does changing the window-to-wall ratio (WWR) have on electricity consumption for lighting and visual comfort in a prefabricated social housing building in a warm climate?

RQ2: How does the variation of the window-to-wall ratio (WWR) influence lighting energy consumption and visual comfort in a prefabricated social housing unit in a warm climate?

To answer the questions, this study took a quantitative experimental approach based on the energy simulation of buildings. The general objective is to evaluate and optimize energy consumption for lighting in a

prefabricated social housing building by controlling modification of the window-to-wall ratio (WWR). The specific objectives of the study are: (i) to define the relevant technical and normative principles for the use of WWR as a passive strategy; (ii) to investigate the natural lighting and energy consumption of the residential building under different WWR configurations; and (iii) to determine WWR interval that best balances energy efficiency and visual comfort. To this end, a model was developed in Design Builder using climate data from Bucaramanga, simulating WWR between 0% and 100% in 10% intervals. The methodology comprised three phases: characterization of the residential building and applicable regulations; modeling and simulation of scenarios; and comparative analysis of the results based on comfort and consumption criteria.

In summary, the review of the state of the art confirms that the window-to-wall ratio (WWR) is a crucial parameter for both energy efficiency and visual comfort in various types of buildings. However, there is little scientific evidence on prefabricated social housing in tropical climates, which justifies the relevance and innovative nature of this study. On this basis, a simulation-base methodology was developed to systematically evaluate different WWR scenarios and determine the optimal range for the housing case under investigation. The following section describes the methodology used in this study in detail.

2. Research method

The study was conducted using a quantitative experimental methodology based on the building energy performance (BEP) approach using simulation. This approach enabled a controlled analysis of the effects of changing the window-to-wall ratio (WWR) in a prefabricated social housing building in Bucaramanga, Colombia. The methodological process involved creating a digital model in Design Builder, using official climatic data, and generating parametric WWR scenarios. The results were evaluated using measurements of an hourly illuminance, daylight uniformity, and energy consumption for lighting, which allowed direct correlations to be established between window design and the energy efficiency of the residential building. The methodology was developed in several interconnected phases. First, the climate parameters of the study area were determined using nearby weather stations monitored and controlled by the Institute of hydrology, meteorology and environmental studies (IDEAM). These official records served as the initial input data for creating the digital model of the residential building in Design Builder, a software that integrates the EnergyPlus engine for energy simulations and radiance for natural light analysis.

The energy model of the prefabricated house was then created using its actual dimensions, building materials, layout, and orientation. The house was modeled without occupants, as the aim was to isolate the influence of WWR on illuminance and energy consumption without considering usage times, lighting profiles, or internal loads. Based on this model, parametric scenarios with WWR ranging from 0% to 100% increments were simulated, with the remaining conditions kept constant. Finally, a comparative analysis was performed, evaluating the illuminance and energy consumption for lighting for each scenario. This procedure made it possible to identify trends and determine the most appropriate WWR ranges for prefabricated houses in warm climates.

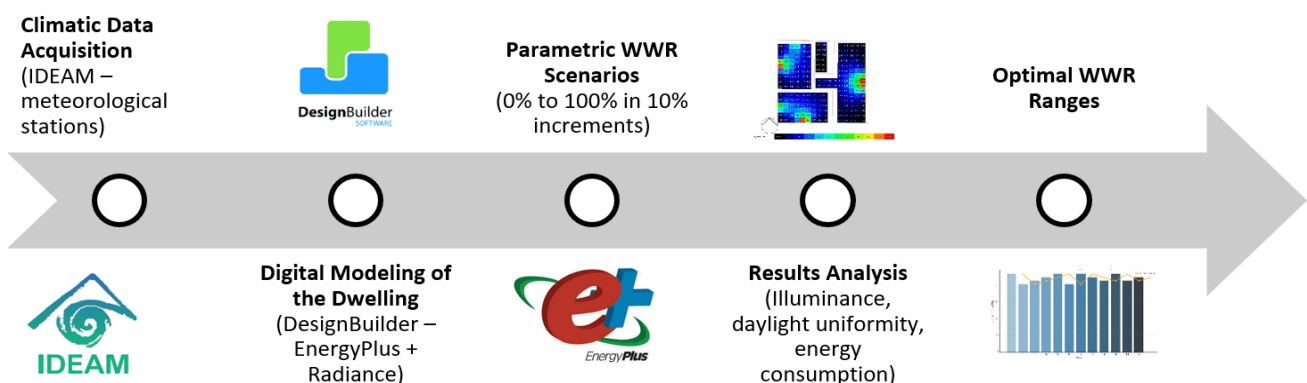


Figure 1. Methodological framework

Figure 1 provides a graphical summary of the methodological workflow developed in this study. It shows the complete sequence of the most important stages: the collection of climate data from IDEAM, the creation of the digital model of the residential building in Design Builder, the simulation of the various parametric scenarios from WWR, and finally the comparative analysis of illuminance and energy consumption. This visual diagram contributes to a better understanding of the process and illustrates the logical connection between the different phases of the methodology applied.

3. Results and discussion

The results are based on a parametric simulation of the window-to-wall ratio (WWR) and are structured according to three aspects: characterization of the apartment, interior illuminance, and energy consumption for artificial lighting.

3.1. Characterization of the house

The residential building examined consists of prefabricated concrete elements and was designed according to the principles of clean construction, rapid execution, and dimensional accuracy. Figure 2 shows the floor plan, which covers a built-up area of 24.60 m² divided into four main room: living room (3.00 m × 2.00 m), kitchen (2.00 m × 2.00 m), bedroom 1 (3.00 m × 2.00 m), and bedroom 2 (3.00 m × 2.00 m), supplemented by a bathroom and the necessary circulation areas. This layout follows a logic of optimizing the interior space, which is typical for simple housing solutions.

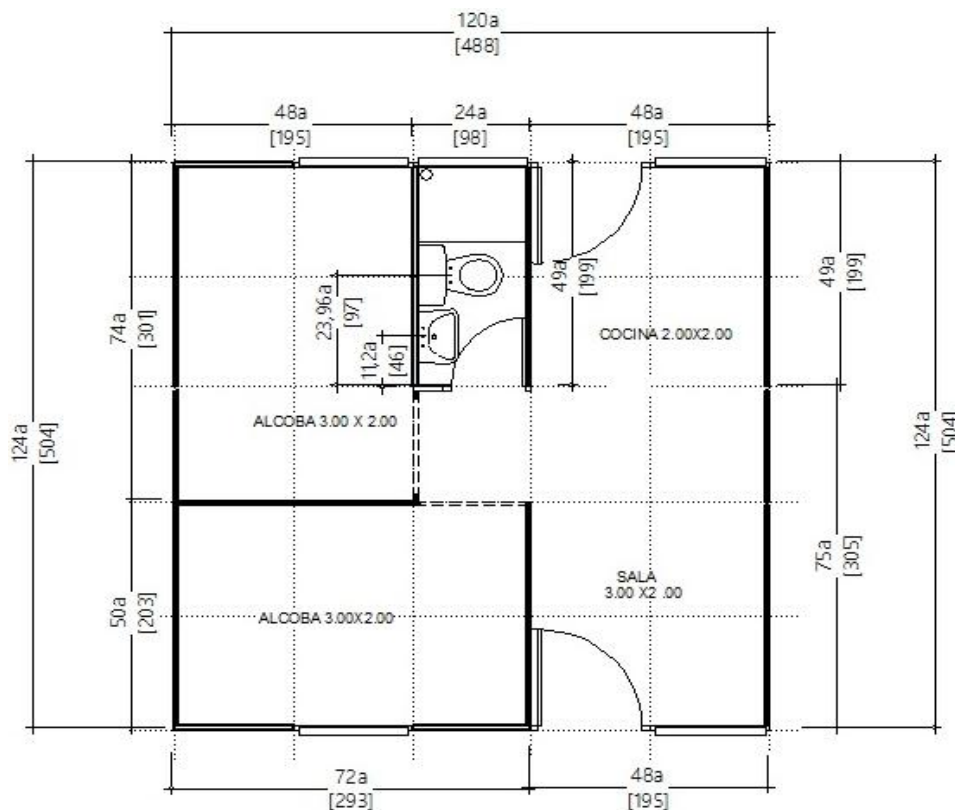


Figure 2. Floor plan showing spatial arrangement of the prefabricated house

Structurally, the house consists of 22 standardized prefabricated components, including L-type, C-type, H-type, as well as flat elements, with rectangular or trapezoidal geometries. These elements form the facade, interior walls, front wall, entrances, and roof. The connection mechanism is based on lateral tongue- and-groove guides that ensure continuous sealing and structural strength without the need for additional adhesives or mortar.

Figure 3, taken from the technical data sheet, shows the dimensions of the components together with the arrangement of the openings and the configuration of the roof.

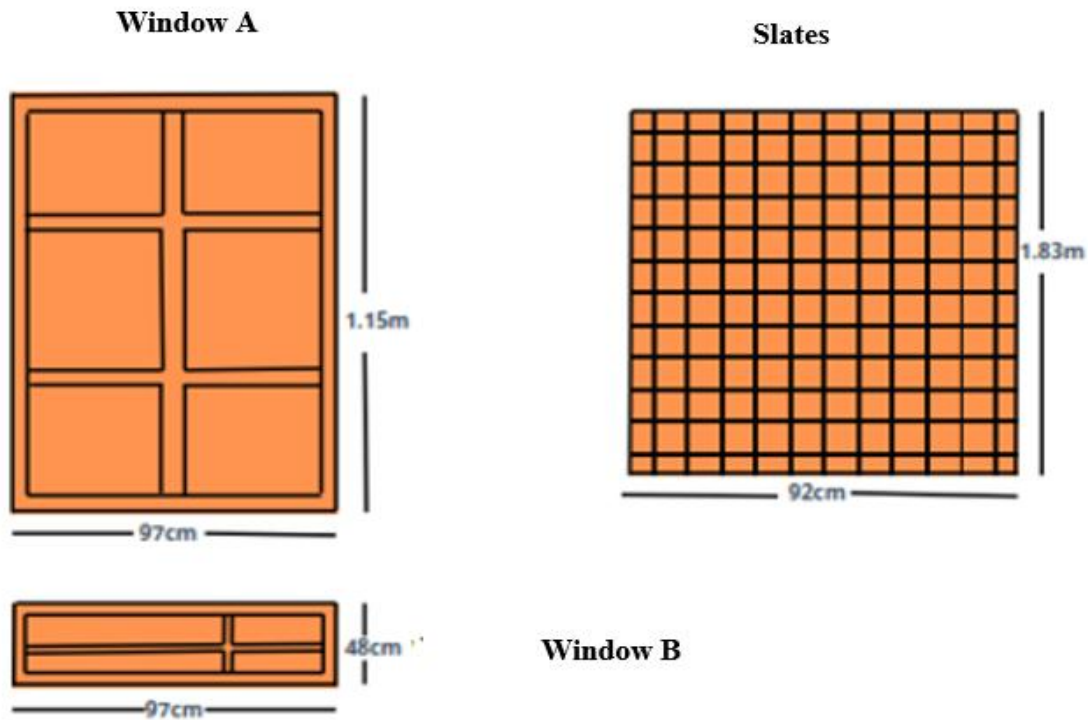


Figure 3. Geometry of the components of the modular residential building

The openings described have limited dimensions, which suggests a low window-to-wall ratio (WWR). Its effects on natural lighting will be investigated in later phases of the study. The light and energy behavior were simulated by comprehensively parameterizing the digital model, considering the exact geometry of the residential building and the environmental conditions characteristic of the study area. The input data for the model included: the three-dimensional configuration of the architecture, the properties of the materials used in the building envelope (precast concrete, lightweight roof, single glazing), the typical usage patterns for a residential building (time profiles of residential use), and the specific climate data for Bucaramanga, which was taken from the typical meteorological year (TMY) archive.

To perform the simulations, the Radiance and EnergyPlus engines integrated into the DesignBuilder platform were used to estimate the natural illuminance and electricity consumption for artificial lighting in the various WWR scenarios. The results of the process included illuminance distribution maps, daylight factors (DF), monthly electricity consumption in kilowatt hours, and projected energy savings rates for each simulated variant. This methodological approach facilitated the characterization of the com.

3.2. Digital model

A key component of the study was the creation of a high-resolution three-dimensional model using Design Builder software, a platform that integrates the Radiance and Energy Plus calculation modules and is recognized under the Colombian standard (RETILAP) for the verification of natural and artificial lighting conditions. This model served as the basis for investigating various alternatives for the window-wall ratio (WWR) and establishing a reference scenario. The modeling process began with the digitization of the architectural floor plan and geometric properties of the prefabricated elements, paying particular attention to the dimensions, spatial arrangement, and location of the openings as specified in the original technical documentation.

The four main rooms (two bedrooms, living room and kitchen) were represented together with the bathroom and circulation areas. The dimensions of each room, wall thickness, and the exact location of the doors and windows were reproduced to scale. (see the simulated model in Figure 4). The resulting model provided a consistent and reliable basis for comparative analysis. It also ensured that all evaluated scenarios were assessed under identical geometric conditions.

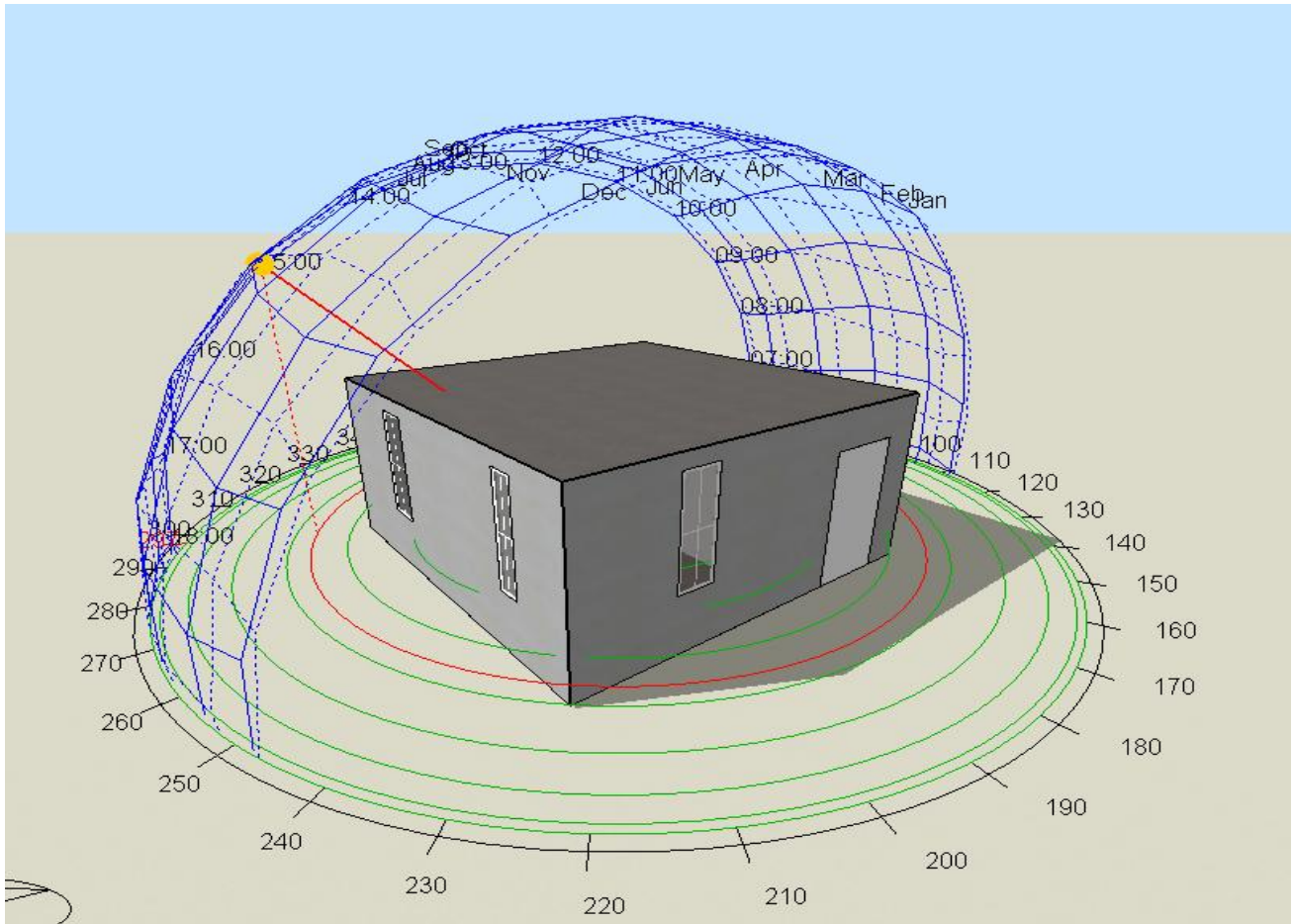


Figure 4. Energy model created in Design Builder

In order to accurately reflect the climatic conditions in Bucaramanga, the model was parameterized using the exact geographical location and weather station records from the typical meteorological year (TMY) file. The building envelope was characterized by prefabricated concrete walls, a lightweight flat roof, and aluminum windows with simple, colorless glazing. The house is arranged along the east-west axis, with the main façade facing east, resulting in direct sunlight in the morning and heat gains in the afternoon. This circumstance, as well as the small area of the existing openings, justify the relevance of evaluating WWR as a passive improvement strategy.

Figure 5 summarizes the climate variables extracted from EnergyPlus for the annual simulation cycle in Bucaramanga. Dry temperature and dew point values ranged between 9°C and 16°C, indicating a warm, humid climate with little temperature variation. Wind speed was predominantly between 1 m/s and 4 m/s, while wind direction was subject to fluctuations related to regional atmospheric dynamics. In terms of solar geometry, the elevation and azimuth angles reached their maximum values in the middle months of the year, indicating stronger radiation from the zenith direction. Air pressure remained largely constant at around 74,600 Pa and had significant influence on the natural lighting calculations. The average daily global radiation ranged between 4.2 and 5.6 kWh/m²-day, with peak values of normal direct radiation of 5 to 7 kWh/m² during dry periods (January, July, and December). Diffuse radiation, on the other hand, showed a more stable behavior of about 2.5 kWh/m², especially in months with higher cloud cover such as April and October.

These parameters enabled the model to be adjusted appropriately and ensured that the results in terms of energy consumption and light behavior corresponded to the actual solar conditions during the analyzed period. In addition, standard reflection coefficients were defined for the interior surfaces (ceiling: 70%, walls: 50%, floor: 20%), and the actual dimensions of the types A and type B windows were entered, from which the WWR for each façade of the reference model was automatically derived.

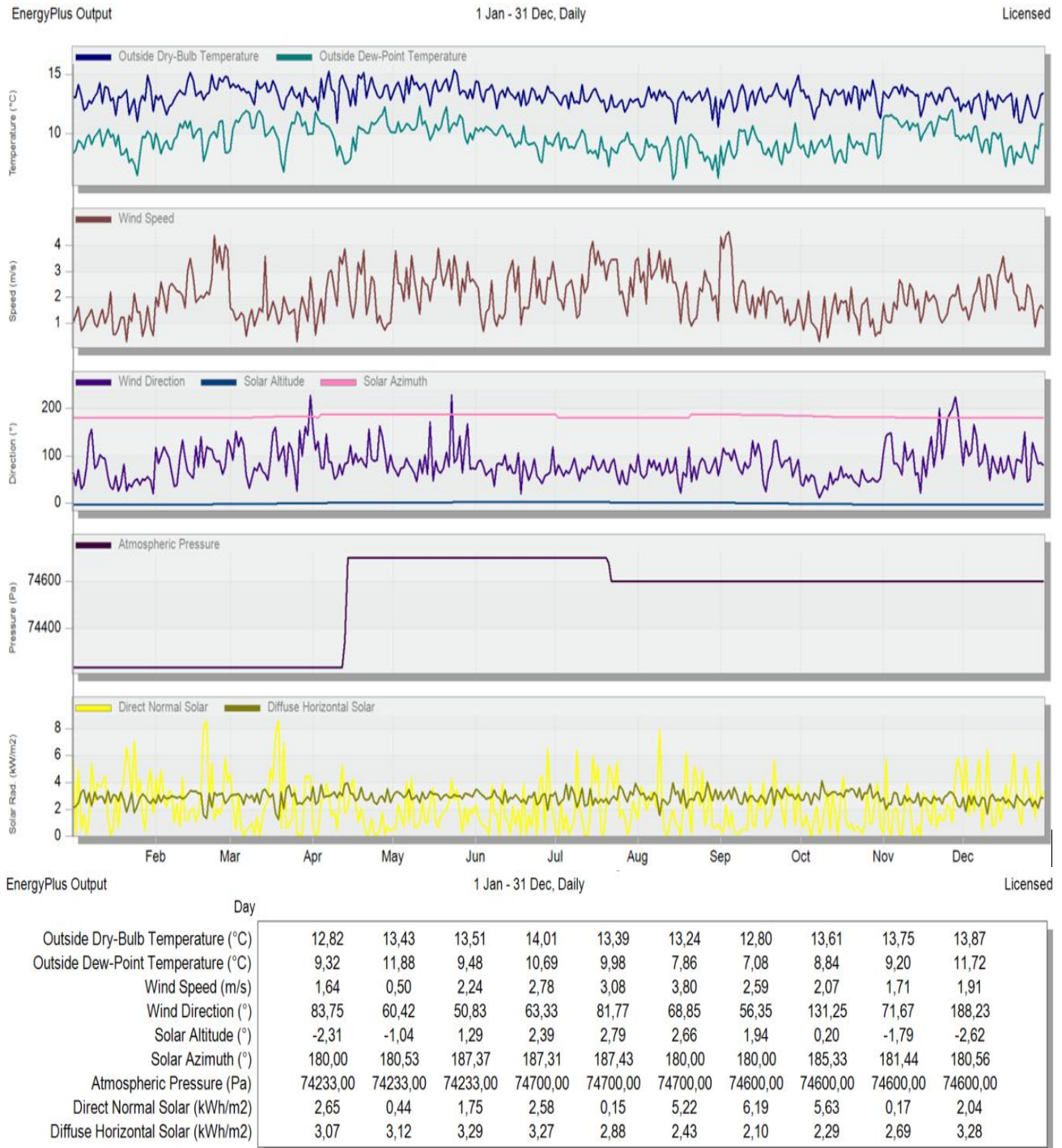


Figure 5. Climatic data from EnergyPlus

3.3. Evaluation of energy consumption due to lighting

In order to establish a baseline for the energy performance of the prefabricated house under investigation, an annual simulation of electricity consumption for general lighting was carried out, based on the original architectural model without considering design recommendations or optimized artificial lighting systems. This scenario represents a realistic situation for the operation of the house in its current state, which is characterized by low daylight utilization and the conventional use of luminaires. Figure 6 shows the monthly energy consumption for lighting, expressed in kilowatt-hours (kWh). The graph combines a bar chart with a trend line so that both the specific monthly values and the general annual pattern are visible. The graphical representation also facilitates the identification of seasonal variations in lighting demand throughout the year.

The months of January, May, July, and October have the highest consumption values at over 93 kWh, while February and June have the lowest values at just under 81 kWh. This fluctuation indicates a slight seasonal change in the availability of daylight, but it is not sufficient to significantly reduce the need for artificial lighting. During the rest of the year, consumption remains relatively constant between 85 and 89 kWh. This behavior confirms that the building's energy consumption in its current state remains high to ensure minimum levels. This underscores the need to implement passive optimization strategies such as adjusting the window-to-wall ratio (WWR), to improve visual comfort and reduce electricity consumption [22].

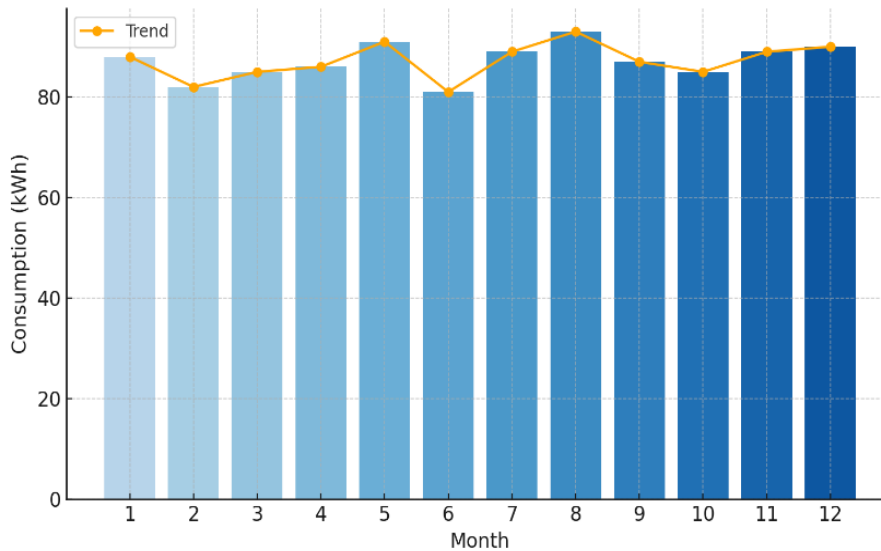


Figure 6. Monthly electricity consumption for artificial lighting

According to the Planning office for mining and energy (UPME), the average monthly electricity consumption of a Colombian household is approximately 157 kWh. Of this, between 14% and 15% is attributed to lighting, which corresponds to an average consumption of 22 to 24 kWh per month for this purpose. In contrast, the simulation results for the prefabricated house show lighting consumption between 81 and 94 kWh per month. This means that the energy required to maintain the illuminance levels in the current design is three to four times higher than the national average. This difference highlights the low efficiency of the base model and underscores the need to optimize daylighting strategies to achieve a more appropriate and sustainable energy demand that aligns with the conditions of an average household in Colombia [22].

3.4. Comparison models

Based on the digital reference model created in Design Builder, various experimental configurations were designed to evaluate the impact of window-to-wall ratio (WWR) on the natural illuminance inside the prefabricated house. To this end, ten alternative models were created, each corresponding to a 10% increase in WWR from the original condition (with a value below 10%) to an extreme case with a fully glazed facade with a WWR of 100%.

In order to isolate the effect of the variable under investigation, the other parameters of the model were kept unchanged: type of glazing, orientation of the building, exterior wall materials, geographical location, and climatic conditions. The change was limited exclusively to the glass area of the existing facades, whose dimensions were increased in proportion to the area of the corresponding wall, while maintaining both the number and relative position of the original openings. This procedure ensured comparability between different simulated scenarios and provides a clearer understanding of the relationship between WWR and the indoor visual performance of the prefabricated housing model.

The following table summarizes the models created and the corresponding WWR values expressed in % in graphical form (See Table 1).

Table 1. Simulation scenarios with different WWR proportions

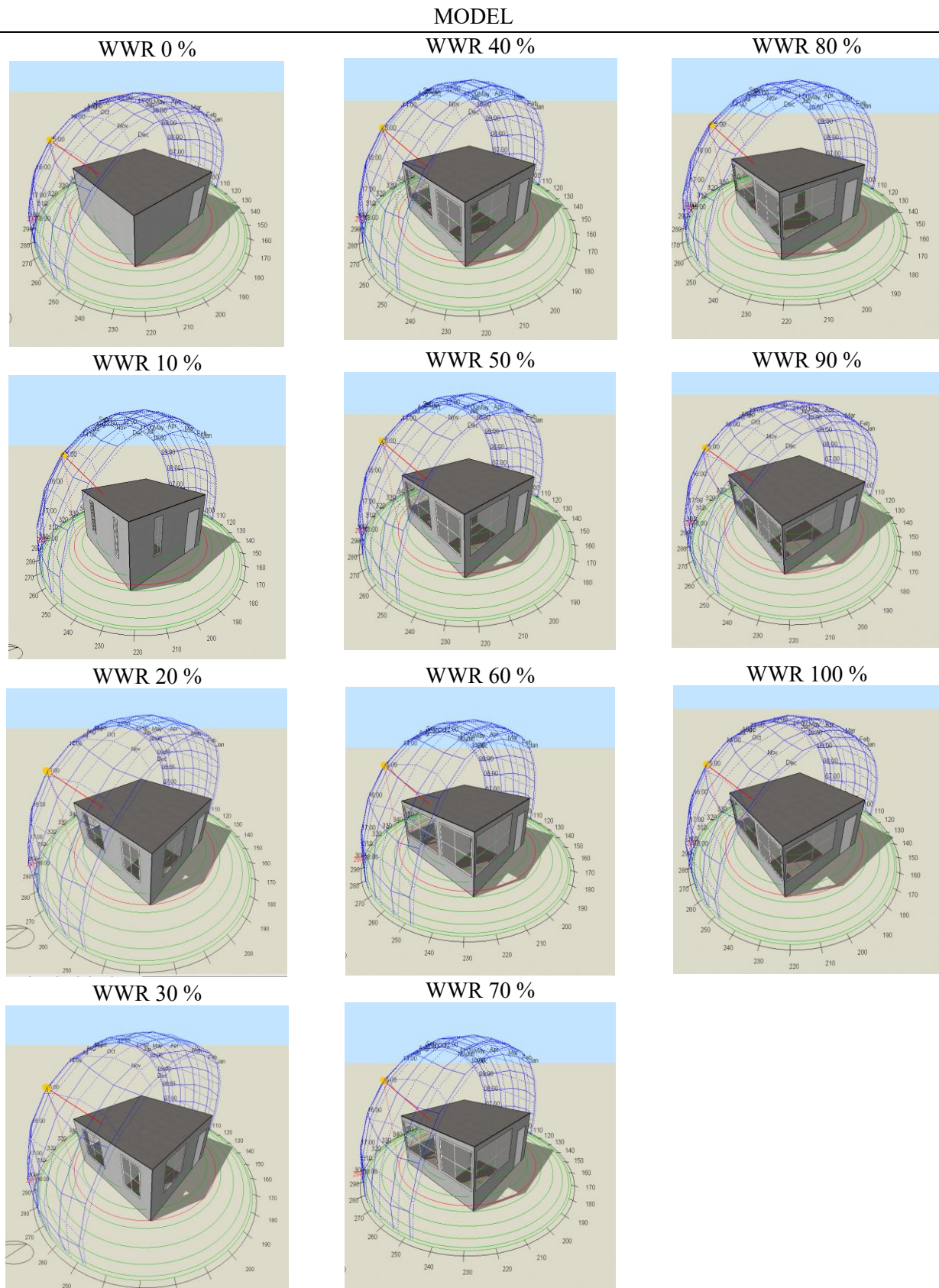


Figure 7 shows the development of the interior design model in DesignBuilder, with a gradual increase in the window-to-wall ratio (WWR). It clearly illustrates how the opening of the facade changes without altering the spatial layout of the interior of the apartment.

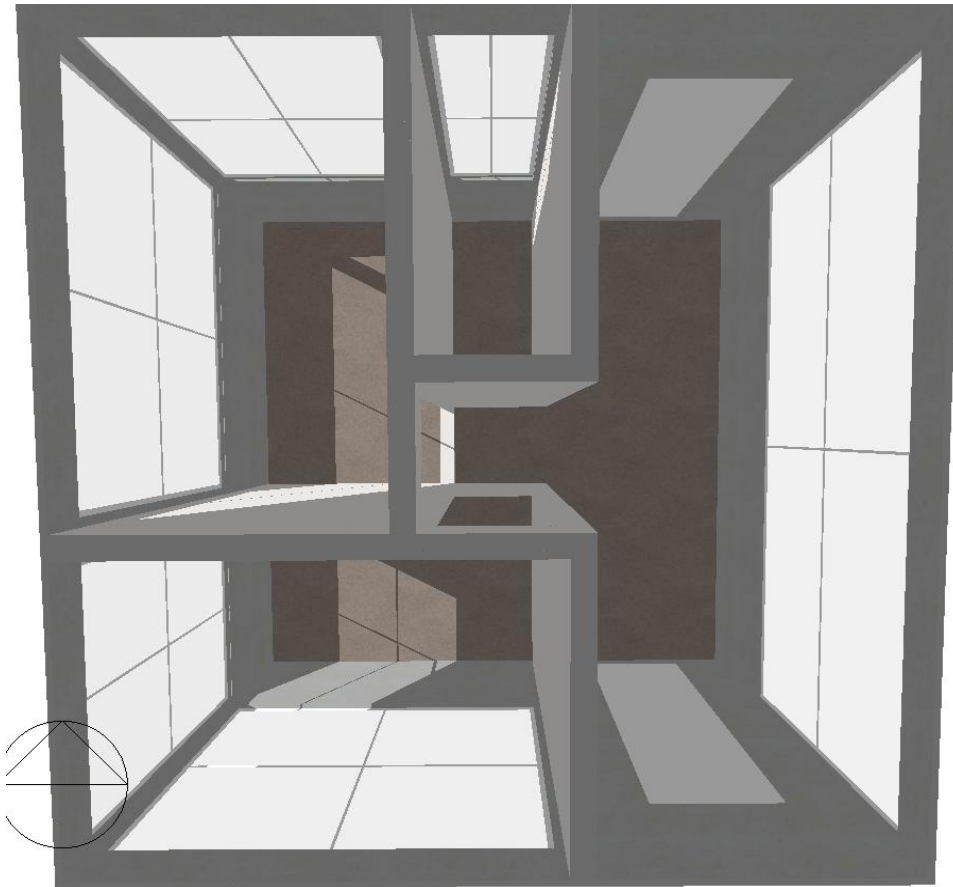


Figure 7. Interior design for different WWR proportions

The results of the various simulation scenarios defined in the basis of the variation in the WWR are presented in the following section.

3.5. Lighting simulation with spatial lux measurements

As expected, the model with a WWR of 0% delivers zero values for illuminance in all interior spaces. The simulation map created using DesignBuilder's daylight factor function shows a complete absence of daylight, represented by a uniform black color in all rooms (bedroom, living room, and kitchen). This result is consistent with the absence of openings to the outside, which prevents any direct or diffuse solar radiation from entering. Consequently, the daylight factor (DF) is zero at all measurement points, with no differences between the various rooms.

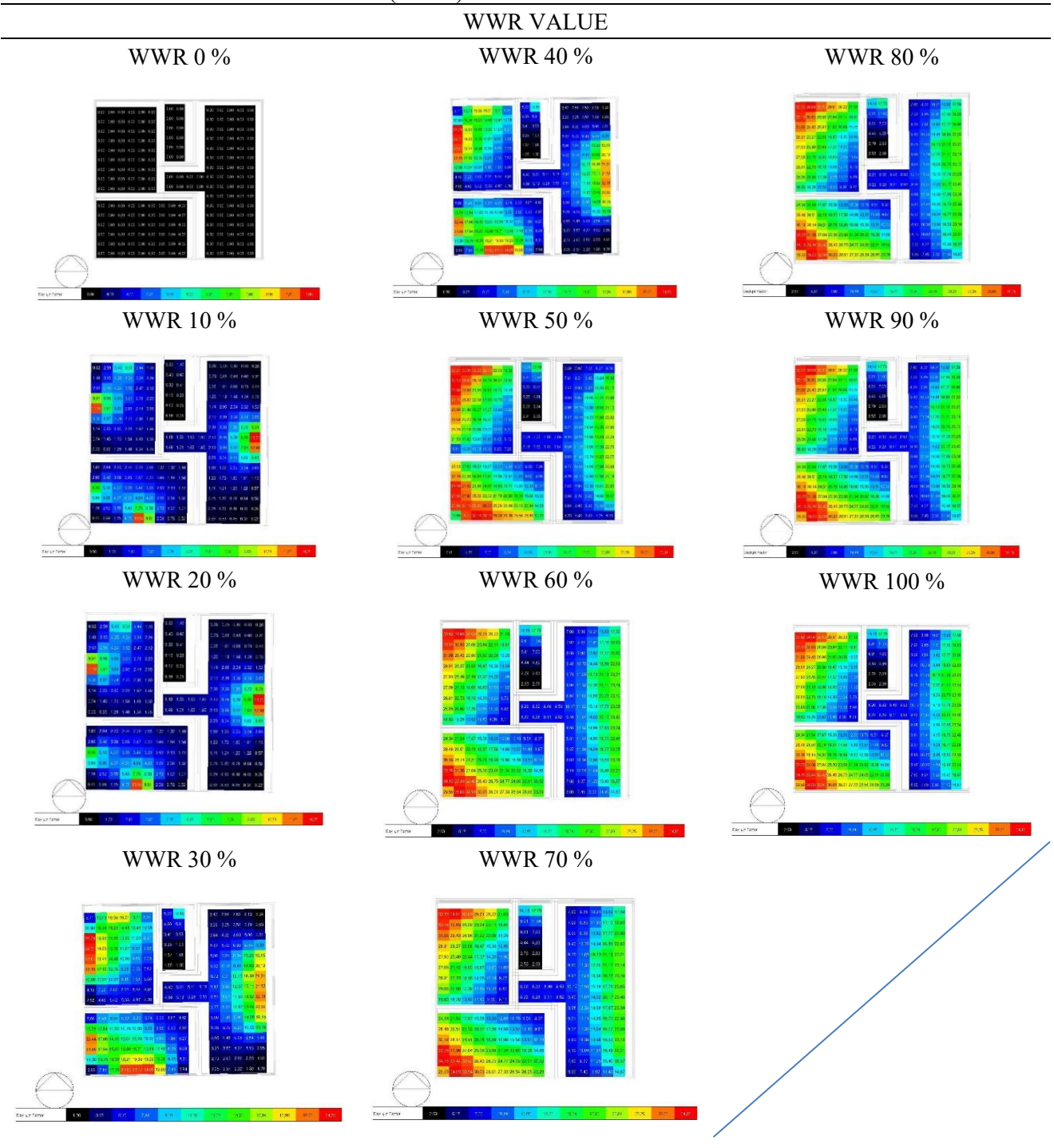
From a normative perspective, this configuration clearly violates the minimum requirements set by RETILAP, which stipulate basic natural illuminance levels in the various living spaces, even if supplementary artificial lighting is provided. In terms of energy efficiency, such design would mean absolute dependence on artificial lighting throughout the day, which would lead to an increase in electricity consumption and impair the visual comfort of the occupants. Therefore, this model forms the starting point for assessing the progressive effect of successive changes to the WWR allowing an evaluation of how lighting conditions improve as the glazing area increases.

Error! Reference source not found. 2 provides a summary of the results of the light simulations that were carried out for the various window-to-wall ratio (WWR) with values between 0% and 100% in 10% increments. The created illuminance maps show that models with low WWR (0% and 10%) have practically imperceptible illuminance levels, with average values below 50 lux, which is far below the minimum values below 300 lux required by RETILAP for living spaces. This situation confirms that it is impossible to achieve visual comfort conditions without openings, which results in complete dependence on artificial lighting systems.

With increasing WWR, a significant improvement in illuminance can be observed. In the middle scenarios (30% and 40%), the average values are between 280 and 420 lux, with some indoor areas being partially covered. Although rooms such as the living room and kitchen are approaching the normative standards, bedrooms continue to show deficits, with values close to the lower limit of the requirements.

The most favorable results are achieved in scenarios with WWR values between 50% and 60%. In this range, the average illuminance is above 500 lux, and the spatial uniformity improves significantly. More than 85% of the usable living space achieves adequate illuminance levels, reducing the use of artificial lighting by more than 40% compared to the base model. This behavior confirms that a medium WWR is the most effective passive strategy for optimizing the use of natural light without compromising visual comfort conditions.

Table 2. Results of the simulation of interior illuminance in prefabricated houses for various scenarios of the window-to-wall ratio (WWR) between 0% and 100% in increments 10%



In contrast, in scenarios with high WWR values (70% to 90%), the average illuminance levels are well above 1000 lux, but the peak values reach up to 2200 lux, especially on east-facing facades. These conditions lead to over-illumination and glare, which further reduce energy consumption but impair the habitability of the rooms. The extreme case of a WWR of 100% exacerbates this trend as excessive solar radiation leads to uneven light distribution and potential visual impairment, even if the electricity consumption for lighting is reduced to a minimum.

The comparative analysis between the base scenario (0% WWR) and the optimal scenario (50–60% WWR) shows that by installing appropriately sized openings, annual energy consumption for lighting can be reduced by up to 65%, from around 94 kWh/month in the closed model to 30–35 kWh/month in the optimized models. This reduction not only represents a gain in energy efficiency but also brings the behavior of the house closer to the national averages reported by UPME for Colombian households (22–24 kWh/month for lighting), confirming the relevance of adjusting the window-to-wall ratio as a strategy for increasing efficiency and sustainability.

In Colombia, the design of lighting systems in residential buildings is primarily governed by the technical regulations for lighting and public lighting (RETILAP), supplemented by the technical regulation for electrical installations (RETIE) and reference documents such as the Guide for interior lighting in residential buildings, which was produced by the UPME. These regulations establish minimum requirements in terms of illuminance, uniformity, glare control, and energy efficiency. Although RETILAP primarily deals with artificial lighting, it explicitly recognizes the importance of integrating daylight as a complementary strategy and allows the use of computer simulations based on international standards, such as the EnergyPlus and Radiance engines integrated into DesignBuilder, which are validated according to the EN 12464-1, CIE 140, and IESNA protocols.

Figure 9 shows the minimum illuminance values required by RETILAP for residential buildings. The highest requirements apply to areas intended for studying or reading (300 lux), followed by kitchens and dining rooms (200 lux). On the other hand, bedrooms and hallways require more moderate values (75 to 100 lux), which are sufficient for performing basic activities. This normative distribution is intended to ensure visual comfort, safety, and energy efficiency, aspects that are particularly important in the design of efficient residential solutions.



Figure 9. Minimum illuminance levels required by RETILAP depending on the type of room

Table 3 summarizes the illuminance levels in the WWR scenarios and provides information on compliance with regulations RETILAP and the most important technical observations. This identifies the areas that provide visual comfort and those that have negative effects (under-or-over-illumination).

Table 3. Summary of illuminance performance, RETILAP compliance, and technical observations

WWR (%)	General illuminance	RETILAP compliance	Observations
0	None	Does not comply	Total dependence on artificial lighting
10	None	Does not comply	Minimal, non-functional opening
20	Practically none	Does not comply	Insufficient illuminance
30	First appreciable levels	Partial, peripheral areas only	First visible impact of WWR
40	Adequate near windowed areas	Complies in most areas	Good distribution, some residual dark zones
50	High in most spaces	Fully compliant	Functional and uniform lighting
60	Very high, over-illumination near openings	Complies, but with excess light	Potential glare without solar control
70	Excessive, glare risk	Complies, but requires solar control	Intense light throughout the dwelling
80	Excessive, uncomfortable visual conditions	Complies, possible visual discomfort	Visual comfort compromised
90	Extremely high, generalized glare	Complies, but low comfort	Extreme visual conditions
100	Total over-illumination	Complies, but exceeds optimal limits	Model not recommended for daily comfort

Figure 10 shows a comparison of the illuminance levels measured in the apartment for the various WWR scenarios (0–100%). It can be seen that setting below 20% does not meet the minimum value for lighting comfort, while the range between 40% and 60% offers a satisfactory balance. Above 70%, there is a risk of glare, which confirms that the optimal range is between 40% and 60%.

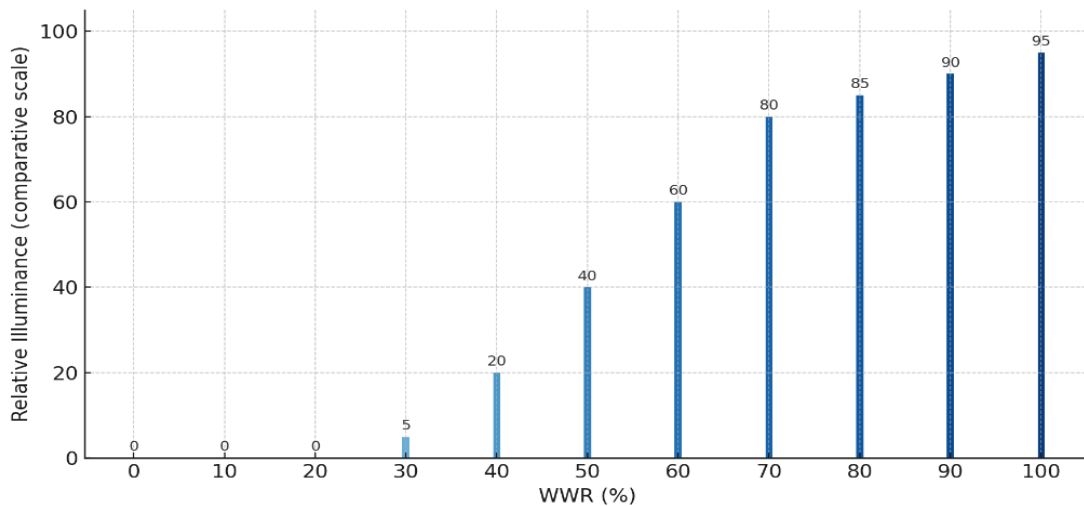


Figure 10. Relationship between the WWR percentage and the illuminance levels achieved

3.6. Energy consumption for lighting according to WWR

In order to determine the impact of passive optimization on the energy requirements of the prefabricated house, a comparative analysis was carried out between the various window-to-wall ratio (WWR) scenarios and the

base model (WWR = 0%), which represents a situation of absolute dependence on artificial lighting. The aim was to quantify the energy savings resulting from the gradual inclusion of daylight as the glass area increases.

The methodological approach was based on the maximum monthly consumption recorded in the model without openings (93.58 kWh/month), a value that was compared with the simulated lighting conditions in each WWR scenario. Using daylight maps and an assessment of compliance with normative standards, the percentage reductions in artificial lighting requirements were estimated and expressed as energy savings compared to the base model.

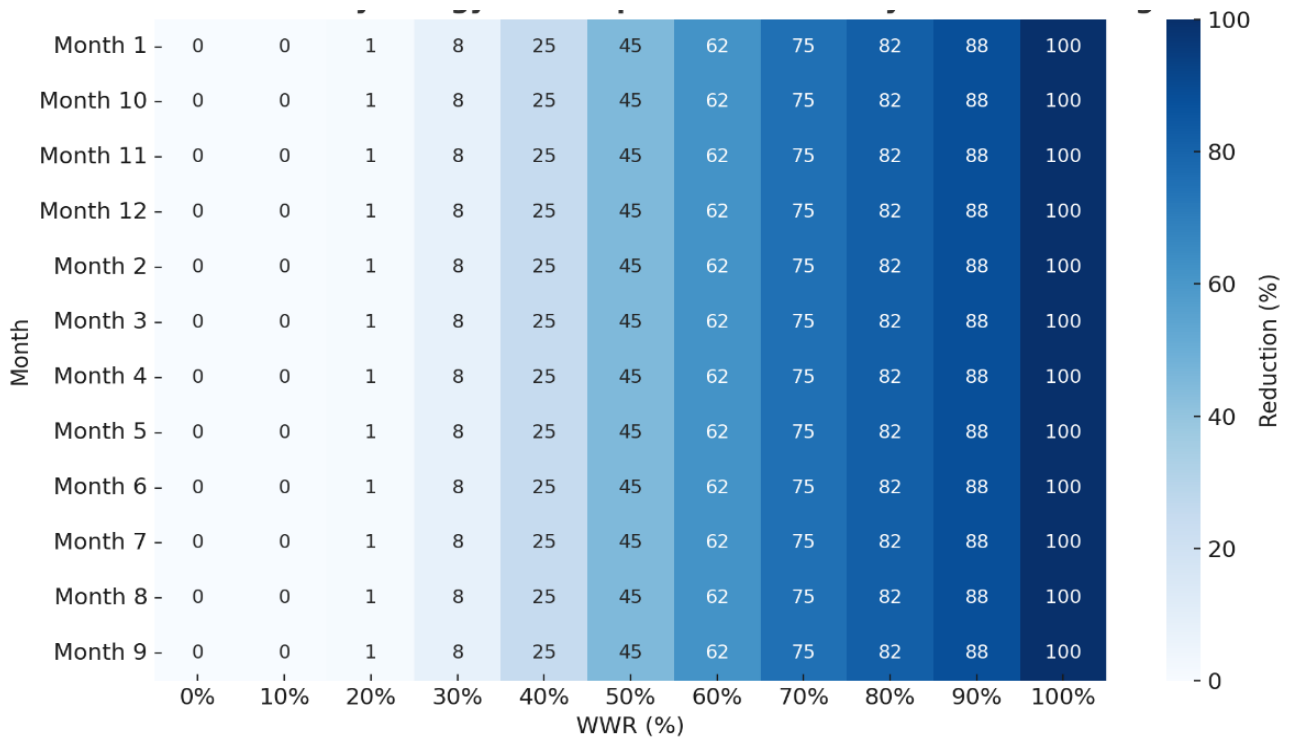


Figure 11. Estimated reduction in monthly electricity consumption associated with the change in WWR

The results show that with a WWR of 30%, energy consumption falls by around 18%. From 40% onwards, the savings exceed 35%, accompanied by functional natural illuminance levels in most rooms. In the middle range (50–60% WWR), savings are between 55% and 65%, making this range the most favorable for balancing energy savings and visual comfort. At WWR values above 70%, savings reach 80–90%, but then over-illumination and glare occur, which impair interior comfort. In the extreme case of a WWR of 100%, the theoretical savings are 100% because no artificial lighting is required during the day, although this configuration is not feasible from the point of view of visual comfort and solar control.

4. Discussion

Analysis of the prefabricated house that was studied showed that the window-to-wall ratio (WWR) has a decisive influence on the use of natural light and the reduction of electricity consumption for artificial lighting. In the base model with a WWR = 0%, monthly consumption was 93.58 kWh, which is three to four times the national average reported by UPME for lighting in Colombia households (22–24 kWh/month). This finding demonstrates the low efficiency of the original type and highlights the usefulness of passive design strategies that can be used to adjust the energy behavior of the house to more reasonable living parameters.

The results achieved show clear progression depending on the WWR. At a value of 30%, consumption fell by around 18% to 77 kWh/month. When 40% was achieved, the savings were over 35% with consumption of around 60 kWh/month, while the minimum lighting levels required by RETILAP were also maintained in the rooms intended for social purposes. The most balanced values were recorded in the middle range between 50%

and 60% WWR: consumption was between 32 and 40 kWh/month, which corresponds to a reduction of 55% to 65% compared to the base model. These values bring the apartment's performance closer to the national average and consolidate this range as the most efficient and balanced option.

At higher WWR values 70% and 90%, energy savings ranged from 80% to 90%, with residual consumption of only 9 to 18 kWh/month. However, these scenarios lead to excessive natural lighting with peak values of over 2000 lux near the facades, which leads to glare risks and impairs visual comfort. The extreme case of WWR of 100% would theoretically mean that there would be no need for artificial lighting during daylight hours (100% savings), but at the cost of inadequate light distribution and unacceptable comfort conditions. A comparison with studies conducted in other geographical contexts provides interesting insights. In China, earlier studies had determined optimal WWR values between 30% and 60%, depending on orientation of the facade and regional climatic conditions. In Saudi Arabia, due to the impact of glazing on thermal loads, was recommended that the WWR should be limited to a maximum of 20% in warm climates. On the other hand, in Algeria, it was found that a WWR of 30%, in combination with shading, reduces annual energy consumption. Against this background, the present study in Bucaramanga shows that, in the specific context of prefabricated social housing in hot climates, an average WWR range of 40–60% enables significantly higher energy savings (55–65%) and thus represents an important benchmark for the region.

From a normative perspective, RETILAP specifies minimum illuminance requirements of 200 to 300 lux for primarily used living spaces such as kitchens, living rooms, and studies. The simulations carried out confirm that scenarios with WWR values between 40% and 60% fully meet these requirements, while values below 20% are insufficient to ensure visual comfort and values above 70% impair the uniformity of lighting due to excessive illumination. These results are not only consistent with international literature but also provide new insights into the field of social housing, a typology that is rarely addressed in the studies available for the region. From a scientific point of view, the study confirms the usefulness of computer simulation methods for both verifying compliance with regulations and for determining optimal daylight areas in residential projects. Unlike most previous studies, which focused on typologies such as offices, schools, or institutional buildings, this study shows that relatively simple changes in the ratio of glass surfaces can reduce lighting requirements in low-cost prefabricated houses by more than 60%, bringing their performance closer to national efficiency standards. This paper fills a gap in the Latin American literature and highlights the relevance of considering passive design as an indispensable part of a policy aimed at truly sustainable living.

5. Conclusions

This study confirmed that the window-to-wall ratio (WWR) plays a crucial role in optimizing the use of natural light and reducing energy consumption for lighting in prefabricated social housing in warm climates. The base model without glazed openings had three to four times higher consumption than the national average for residential buildings, highlighting the inefficiency of the original type and the urgent need to incorporate passive design strategies.

Comparative analysis of the simulated scenarios showed that average WWR values between 40% and 60% provide the most effective balance, achieving energy savings of up to 65% while complying with the illuminance limits set by RETILAP. This range ensures adequate distribution of natural light in interior spaces, reduces dependence on artificial lighting, and brings the apartment's performance closer to national efficiency standards. In contrast, extreme values above 70%—although they could reduce consumption by more than 80%—led to over-illumination and glare, which impaired visual comfort and lighting uniformity.

Overall, the results confirm the relevance of WWR optimization as a practical and cost-effective strategy for improving the energy efficiency of prefabricated houses. Beyond its academic contribution, this research provides evidence-based guidelines for the design and regulation of social housing in Colombia and similar contexts in Latin America, thereby strengthening the role of passive design as a fundamental pillar of sustainable housing policy.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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Author contribution

The contribution to the article is as follows: Javier Ascanio-Villabona: conception and design of the study, methodology development, supervision, and drafting of the manuscript; Danna Vivas-Buitrago: development of the digital model, simulation setup, and data analysis; Orlando Palomino-Prieto: interpretation of results, validation of simulation outputs, and critical review of the manuscript; Brayan Eduardo Tarazona-Romero: data collection, analysis of energy performance, interpretation of results, and manuscript review; Miguel Duran-Sarmiento: support in data processing, graphical analysis, and technical revision of the manuscript; Karen Tatiana Jaimes-Quintero: literature review, organization of references, and support in the interpretation of visual comfort results. All authors reviewed, approved, and agreed to the published version of the manuscript.

References

- [1] [1] Q. Han, F. Wang, Y. Wang, and F. Guo, “How supply chain and digitalization are significant contributors to international trade? The role of renewable and energy intensity in global trade powerhouses’ economies,” *Energy Economics*, vol. 145, p. 108429, May 2025. [Online]. Available: <https://doi.org/10.1016/j.eneco.2025.108429>
- [2] H. I. Altintas, “Investigation of zero energy house design: Principles, concepts, opportunities and challenges,” *Heritage and Sustainable Development*, vol. 1, no. 1, pp. 21–32, Jun. 2019. [Online]. Available: <https://doi.org/10.37868/hsd.v1i1.8>
- [3] A. Furberg *et al.*, Guidelines for assessments of the global information and communication technology sector’s direct energy use and climate impact: Key aspects and future scenarios, *Renewable and Sustainable Energy Reviews*, vol. 226, p. 116176, ene. 2026, <https://doi.org/10.1016/j.rser.2025.116176>.
- [4] S. Grassi, F. Ravazzolo, J. Vespignani, and G. Vocalelli, “Global money supply and energy and non-energy commodity prices: A MS-TV-VAR approach,” *Journal of Commodity Markets*, vol. 40, p. 100502, Dec. 2025. [Online]. Available: <https://doi.org/10.1016/j.jcomm.2025.100502>
- [5] M. Adrian, E. P. Purnomo, A. Enrici, and T. Khairunnisa, “Energy transition towards renewable energy in Indonesia,” *Heritage and Sustainable Development*, vol. 5, no. 1, pp. 107–118, May 2023. [Online]. Available: <https://doi.org/10.37868/hsd.v5i1.108>
- [6] T. T. Bamgboye, T. Avellán, B. Klöve, and A. T. Haghghi, “Compounding impacts of climate change and urbanisation on water-energy-food nexus in global south countries: A systematic review,” *Environmental and Sustainability Indicators*, vol. 27, p. 100791, Sep. 2025. [Online]. Available: <https://doi.org/10.1016/j.indic.2025.100791>
- [7] M. Shahmoradi and M. Yeganeh, “A novel method for simulating dynamic facades to analyze and optimize daylight and visual comfort in office buildings,” *Results in Engineering*, vol. 27, p. 105608, Sep. 2025. [Online]. Available: <https://doi.org/10.1016/j.rineng.2025.105608>

-
- [8] B. Liu, Y. Liu, Q. Deng, and K. Hu, “A study on daylighting metrics related to the subjective evaluation of daylight and visual comfort of students in China,” *Energy and Buildings*, vol. 287, p. 113001, May 2023. [Online]. Available: <https://doi.org/10.1016/j.enbuild.2023.113001>
- [9] J. A. Villabona, J. T. Zubiaga, Y. A. M. Maldonado, O. L. Pérez, and L. A. D. P. Valdés, “Assessing the thermal performance of a conventional architecture in a dry warm climate,” *Heritage and Sustainable Development*, vol. 3, no. 2, pp. 173–182, Oct. 2021. [Online]. Available: <https://doi.org/10.37868/hsd.v3i2.66>
- [10] R. Ma, R. Ma, and E. Long, “Analysis of the rule of window-to-wall ratio on energy demand of residential buildings in different locations in China,” *Heliyon*, vol. 9, no. 1, p. e12803, Jan. 2023. [Online]. Available: <https://doi.org/10.1016/j.heliyon.2023.e12803>
- [11] M. Alwetaishi, “Investigation of the use of external insulation materials in domestic buildings in hot regions considering various window-to-wall ratios (WWR),” *Case Studies in Thermal Engineering*, vol. 74, p. 106900, Oct. 2025. [Online]. Available: <https://doi.org/10.1016/j.csite.2025.106900>
- [12] J. A. Villabona, N. O. Osorio, N. Y. C. Leon, B. E. T. Romero, and K. T. J. Quintero, “Thermal comfort evaluation using different glazing technologies in an energy model of rural housing in a cold climate,” *Heritage and Sustainable Development*, vol. 6, no. 2, pp. 735–748, Dec. 2024. [Online]. Available: <https://doi.org/10.37868/hsd.v6i2.922>
- [13] M. K. Cherier *et al.*, «Impact of glazing type, window-to-wall ratio, and orientation on building energy savings quality: A parametric analysis in Algerian climatic conditions», *Case Studies in Thermal Engineering*, vol. 61, p. 104902, sep. 2024, <https://doi.org/10.1016/j.csite.2024.104902>.
- [14] B. E. Tarazona-Romero, Y. A. M. Maldonado, A. C. Celador, y O. L. Pérez, «Optical performance assessment of a handmade prototype of linear Fresnel concentrator», *Periodicals of Engineering and Natural Sciences*, vol. 9, n.º 4, pp. 795-811, 2021.
- [15] P. Kishore, N. Selvam, S. Didwania, and G. Augenbroe, “Understanding BIPV performance with respect to WWR for energy efficient buildings,” *Energy Reports*, vol. 8, pp. 1073–1083, Nov. 2022. [Online]. Available: <https://doi.org/10.1016/j.egy.2022.10.371>
- [16] B. E. Tarazona-Romero, A. Campos-Celador, O. Lengerke-Perez, N. Y. Castillo-Leon, and A. D. Rincon-Quintero, “Appropriate technology for solar thermal desalination by concentration applied to the humidification-dehumidification method,” in *Applied Technologies*, M. Botto-Tobar, M. Zambrano Vizueté, S. Montes León, P. Torres-Carrión, and B. Durakovic, Eds. Cham: Springer Nature Switzerland, 2023, pp. 415–428. [Online]. Available: https://doi.org/10.1007/978-3-031-24971-6_30
- [17] Y. Tang, Z. Song, C. Zhang, X. Wang, and J. Ji, “Coupling ventilated semi-transparent photovoltaic windows with air-conditioning systems: Electrical, thermal, and daylight performance across diverse cooling-season climates in China for varying window-to-wall ratios,” *Energy*, vol. 332, p. 137167, Sep. 2025. [Online]. Available: <https://doi.org/10.1016/j.energy.2025.137167>
- [18] G. Miracco, F. Nicoletti, V. Ferraro, M. Muzzupappa, V. M. Mattanò, and F. Alberti, “Achieving nZEB goal through prefabricated buildings: Case study in Italy,” *Energy and Buildings*, vol. 329, p. 115301, Feb. 2025. [Online]. Available: <https://doi.org/10.1016/j.enbuild.2025.115301>
- [19] D. C. Fastofski, M. A. S. González, y A. P. Kern, «Sustainability analysis of housing developments through the Brazilian environmental rating system Selo Casa Azul», *Habitat International*, vol. 67, pp. 44-53, sep. 2017, <https://doi.org/10.1016/j.habitatint.2017.07.001>.
- [20] V. Rangasamy and J.-B. Yang, “AI-driven generative design and optimization in prefabricated construction,” *Automation in Construction*, vol. 177, p. 106350, Sep. 2025. [Online]. Available: <https://doi.org/10.1016/j.autcon.2025.106350>
-

- [21] “Towards a net-zero carbon economy: A sustainability performance assessment of innovative prefabricated construction methods for affordable housing in Southern Africa,” *ScienceDirect*, Accessed: Sep. 28, 2025. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S2210670723005188>
- [22] Unidad de Planeación Minero Energética (UPME) and Corpoema, *Primer balance de energía útil para Colombia y cuantificación de las pérdidas energéticas relacionadas y la brecha de eficiencia energética: Reporte final*. Bogotá, Colombia, 2019. [Online]. Disponible en: <https://bdigital.upme.gov.co/handle/001/1351>