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Comparative Analysis of Passive Thermal Solutions for Building Resilience Under Future Climate Scenarios

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Abstract

The intensification of thermal extremes increases the need for strategies that protect indoor comfort and reduce the energy demand of active systems. This study employs EnergyPlus dynamic simulations to evaluate how passive thermal design solutions for heating and cooling can minimize indoor temperature fluctuations. The analysis covers multiple locations to identify the most effective techniques for improving indoor thermal performance and energy efficiency. Results demonstrate that passive thermal strategies offer a sustainable and efficient approach to adapting buildings to extreme temperature variations, thereby reducing dependence on mechanical systems. The greatest reduction in energy demand is achieved by increasing the envelope's thermal mass, particularly in hot and temperate climates. Enhanced insulation and green roofs are more effective in cold and humid climates. In addition, solar control measures, such as external shading and reduced glazing areas, help lower indoor temperatures in high-thermal-radiation regions.

Keywords: passive thermal solutions; building energy performance; climate change adaptation; dynamic thermal simulation; thermal performance; EnergyPlus; modeling

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1. Introduction

Climate change plays a fundamental role in the sustainability of the construction sector, affecting the thermal and energy performance of buildings and their comfort [1]. The increasing occurrence of extreme phenomena such as heat waves and cold spells has demonstrated the fragility of buildings in meeting new thermal requirements [2–4]. There are phenomena, such as heat islands, which have caused maximum temperatures to rise in metropolitan areas and reduced the thermal performance of buildings [2]. As a result, energy consumption for heating and cooling has gradually increased, intensifying energy poverty, particularly among disadvantaged populations. The worsening of thermal conditions resulting from these thermal extremes has affected occupant health, operating costs, and international policies. Therefore, to use natural resources efficiently and reduce the use of active systems, the European Union has promoted directives on the use of passive solutions [5–8]. Passive solutions are characterised by architectural and design strategies that optimise the use of natural resources, such as shading, ventilation, thermal insulation, glazing area, or the use of materials with higher thermal mass. The adoption of these strategies is conditioned by their technical and economic variants, particularly when applied to existing buildings, due to their morphology and construction materials.

However, despite the growing interest in this topic, it remains a lack of integrated analyses evaluating the combined effects of multiple passive design solutions under projected future climate scenarios. Most previous research has addressed individual strategies or present-day climatic conditions, limiting the applicability of its results for long-term resilience and climate adaptation.

Thus, the research problem addressed in this study concerns the current lack of comprehensive and comparative analyses evaluating the performance of multiple passive design strategies across different climatic contexts, particularly when future thermal conditions are considered. Although numerous previous studies have analysed passive solutions individually or limited themselves to current climate scenarios, there remains a significant gap in understanding how the combination of these strategies affects the energy performance and thermal comfort of buildings across different climates. This study aims to fill this gap by developing an integrated, simulation-based framework that enables the systematic comparison of various passive thermal measures—such as increasing thermal mass, reinforcing insulation, using green roofs, shading, and varying the proportion of glazing—considering both current and future climate conditions. The originality of this study lies in its interclimatic and multi-strategic approach, which offers a more comprehensive and applicable understanding of passive solutions for designing resilient buildings and for energy-efficient adaptation to climate change.

Indoor thermal conditions in buildings have traditionally been maintained through active air conditioning systems, which, although highly effective, consume substantial energy and have a significant environmental impact. Thus, these strategies, when applied in future climate scenarios characterised by extreme phenomena, have proven unfeasible. As a result, alternative strategies have been used: passive solutions that help stabilize indoor temperatures through the exploitation of natural resources, reducing the need for electrical energy. The scientific literature cites several studies demonstrating the effectiveness of this type of solution across various scenarios [5,7,8]. Solutions such as shading, ventilation, efficient thermal insulation, reflective roofing, and phase change materials (PCMs) have demonstrated significant potential to improve the thermal and energy performance of buildings. Marcolini [9], in Palmas (Brazil), assessed the impact of natural ventilation combined with reflective coatings, finding that the latter significantly reduced indoor temperature. Toroxel and Silva [10] highlighted, through their studies, the fundamental role of Trombe walls and reflective roofs in minimising energy consumption. Zhang et al. [11] proposed a set of technical criteria for resilient passive cooling strategies, including thermal comfort metrics (operative temperature, PMV/PPD), energy-efficiency indicators, and resilience parameters such as adaptability to extreme weather and reliance on mechanical systems. These criteria emphasize early-stage architectural planning, material selection, and façade design to ensure thermal stability under future climate scenarios. Sakellariou et al. [12] conducted a comparative study between forced-circulation and thermosyphon solar systems, demonstrating that system configuration and climate conditions significantly affect energy efficiency. Mo et al. [13] demonstrated significant energy-saving potential of passive solar heating systems across varied climatic conditions, although their implementation may involve considerable initial costs. Sánchez et al. [14] presented innovative solutions, such as the solar chamber, which combines natural ventilation and solar heating to ensure thermal efficiency throughout the year. EnergyPlus software has been widely used for detailed simulations, allowing the evaluation of strategies such as shading, low-emissivity glazing, and natural ventilation, with studies reporting energy savings of up to 30%. Kokatnur et al. [15] emphasized that passive solutions must be tailored to specific climatic contexts to achieve optimal thermal efficiency across different regions. Xiao et al. [16] explored the potential of PCMs to switch between heating and cooling needs, demonstrating reductions in

energy consumption. Figueiredo et al. [17] found that integrating insulation, shading, and natural ventilation strategies can enable nearly zero-energy performance in Mediterranean buildings, in line with European sustainability goals. Brito-Coimbra et al. [18] addressed passive solar solutions for Mediterranean façades, confirming the effectiveness of efficient glazing and shading devices in reducing thermal loads and highlighting the importance of detailed economic feasibility analyses for widespread implementation.

Based on this context, the main objective of this study is to systematically evaluate the performance of multiple passive heating and cooling strategies under projected future climate extremes, across different climate zones and building types, using dynamic simulations with EnergyPlus. The specific goals are to (i) identify the most effective passive design combinations for each climate category, (ii) compare current and future thermal performance scenarios, and (iii) provide recommendations for climate-resilient building design and retrofitting.

Although the use of EnergyPlus, version 25.1.0 and OpenStudio, version SDK 3.10.0 is a common methodology for building performance analysis, this study applies these tools in a novel, integrated way. The research framework simultaneously evaluates multiple passive strategies, such as increased thermal mass, enhanced insulation, shading, green roofs, and reduced glazing, across diverse climate contexts and future emission scenarios. Unlike previous studies that typically focus on isolated measures or single climatic conditions, this approach enables direct cross-comparison of passive solutions under both present and projected climates. This integration provides new insights into the combined effects of passive strategies on energy demand and indoor thermal comfort, advancing methodological integration between simulation and practical application. The framework thus contributes to the development of resilient and energy-efficient buildings adapted to future environmental challenges, expanding the conventional use of EnergyPlus/OpenStudio beyond standard performance simulations.

This paper is organized into six main sections. Section 1 presents the introduction, providing background, objectives, and the research context for passive thermal design and climate change adaptation. Section 2 describes the materials and methods, including the simulation tools, the reference building, and the climatic characterization used in the study. Section 3 details the case studies, the selected cities, and the passive strategies analyzed. Section 4 presents and discusses the results obtained for different climates and passive solutions. Section 5 summarizes the main conclusions of the study, and Section 6 provides recommendations and future perspectives regarding the application of passive design strategies in buildings. This structure allows a clear understanding of the methodology, analysis, and main findings of the research.

2. Materials and Methods

Numerical modeling of the thermal behavior of buildings plays a fundamental role in evaluating solutions that enable the improvement of energy performance and thermal comfort. Thus, simulation software such as OpenStudio, version SDK 3.10.1, which provides a graphical interface to the EnergyPlus, version 25.1.0, simulation engine, is used. While the use of EnergyPlus and OpenStudio is a well-established methodology for building performance simulation, this study applies these tools to systematically evaluate multiple passive heating and cooling strategies under projected future climate extremes across different climate zones and building types. These software tools allow performing dynamic hourly simulations and analyzing various parameters, such as thermal gains and losses, from the adoption of different passive strategies. The numerical modeling in this work aims to evaluate how the adoption of passive heating and cooling solutions can influence the thermal performance of buildings in different climatic contexts, particularly

in situations of thermal extremes. Therefore, for an adequate implementation of solutions according to local characteristics, a proper climatic characterization must exist, such as the Köppen–Geiger classification [19,20]. This approach allows a systematic comparison with existing studies, which often focus on single passive strategies or current climatic conditions, highlighting the effectiveness and applicability of combined passive solutions for future thermal resilience. The Köppen–Geiger classification, developed by Wladimir Köppen and later revised by Geiger, characterizes climate zones by their temperature, precipitation, and vegetation types [19]. In 2006, Kottek and collaborators, based on new temperature and precipitation data and supported by databases from the Climatic Research Unit (CRU) and the Global Precipitation Climatology Centre (GPCC), developed a new map [20]. This system classifies the world into five main groups —equatorial zone (A), arid (B), temperate (C), snow (D), and polar (E)—based on the relationship between vegetation and climate, as shown in Figure 1.

2.1. Tools and Simulation Environment: OpenStudio + EnergyPlus

OpenStudio is a simulation software that serves as a graphical interface to the EnergyPlus simulation engine, enabling analyses of building energy performance and the identification and design of efficient solutions. The software is organized into several sections, each representing a modeling parameter. Within it, different aspects of the modeling can be defined, such as geographic location (Site), usage schedules (Schedule), materials and construction characteristics (Constructions), internal loads (Load), space types (Space Types), and geometry (Geometry).

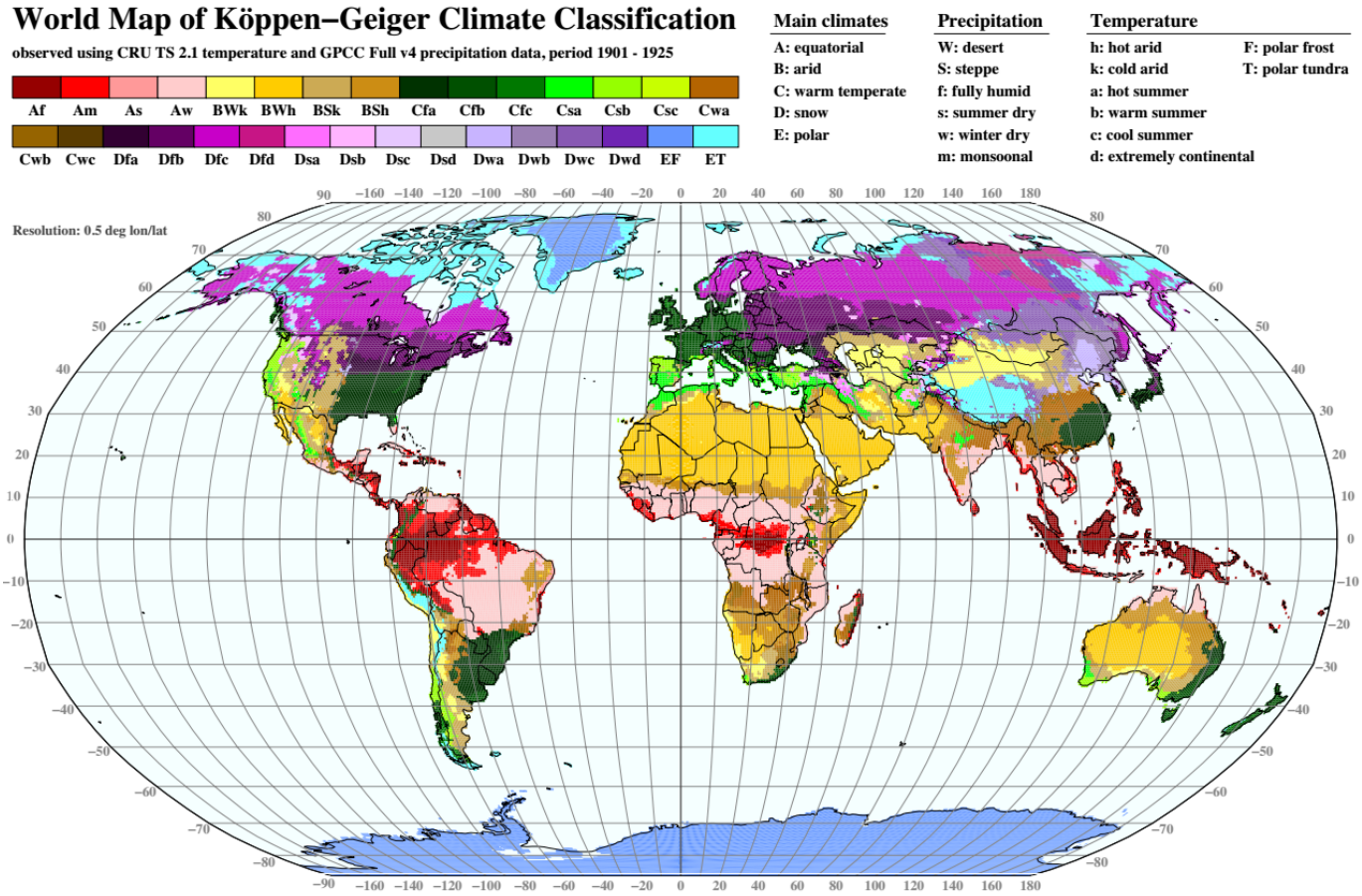


Figure 1. World Map of Köppen–Geiger climate classification (1901–1925). Source: adapted from [20].

In 2010, Rubel and Kottek [20] designed new climate maps for the period 1901 to 2100, indicating an increase in arid zones (B) and warm temperate zones (C), with a migration of cold (D) and polar (E) zones toward higher latitudes, as shown in Figure 2.

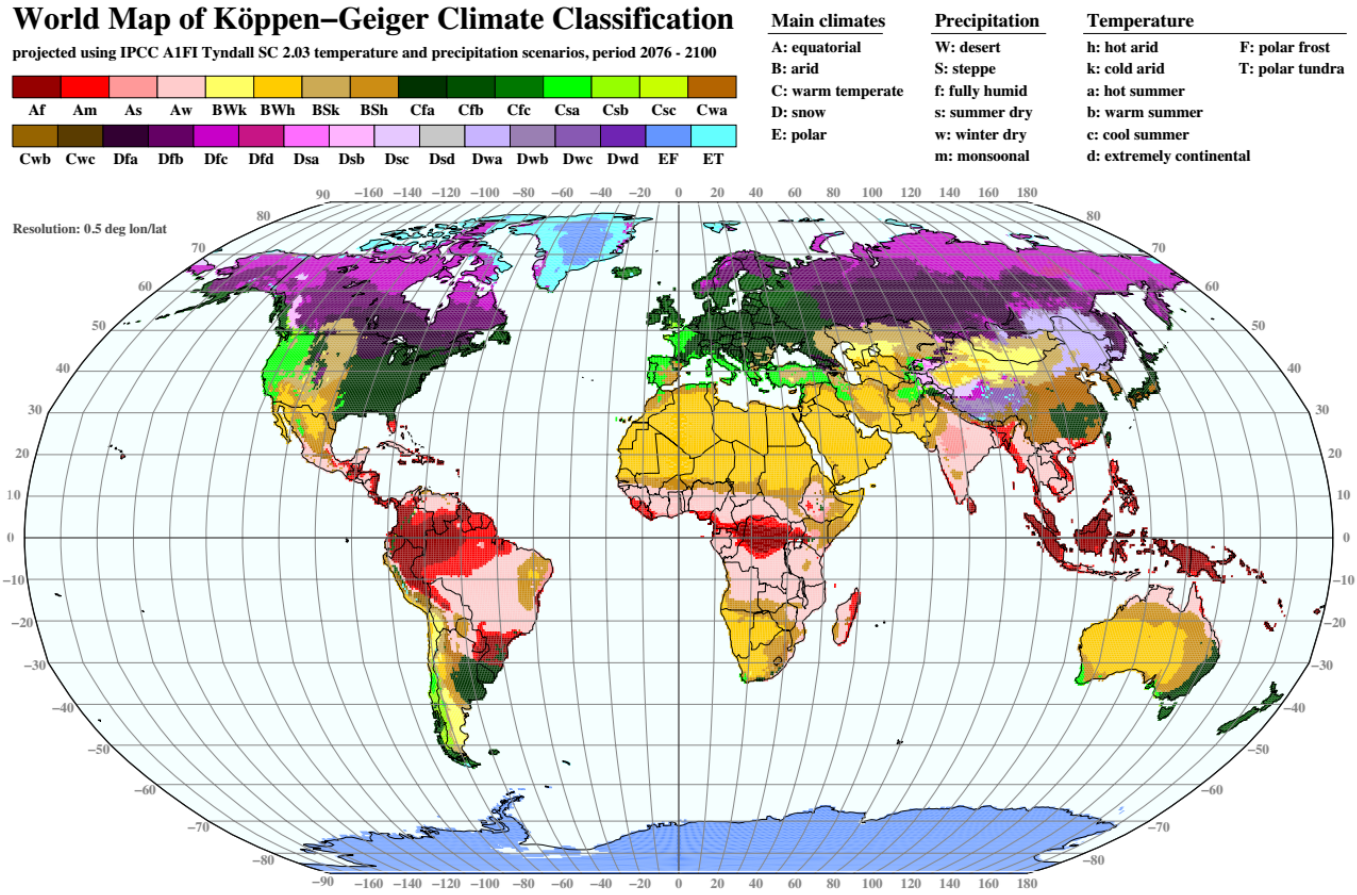


Figure 2. World Map of Köppen–Geiger climate classification (2076–2100, A1FI emission scenario). Source: adapted from [20].

In addition to these parameters, thermal zones, HVAC (heating, venting, and air conditioning) systems, and simulation settings can also be defined. After establishing all modeling parameters, the simulation is executed in the Run Simulation tab, and the data are presented in an organized manner in the Results Summary tab. OpenStudio is thus a tool that enables the design of efficient and sustainable buildings [21].

By integrating the detailed modeling capabilities of OpenStudio with the multi-strategy and multi-climate approach of this study, novel insights can be obtained regarding the design of thermally resilient and energy-efficient buildings under projected future climate extremes [21].

EnergyPlus is a software that allows the simulation of various parameters related to the thermal performance of walls, windows, and roofs, as well as the evaluation of passive heating and cooling solutions or heating, ventilation, and air conditioning (HVAC) systems. The software enables the analysis of the impact of weather conditions on building energy performance during simulations. Simulations use climate files in the EPW (EnergyPlus Weather-File) format, which contain characteristics of each location, such as radiation, outdoor temperature, and humidity.

EnergyPlus has a diverse library of materials and building components, allowing the modeling of buildings with different characteristics and the application of passive solutions [22,23].

This integration of EnergyPlus modeling with multiple passive strategies and climate scenarios provides a comprehensive framework to assess building performance beyond what is typically addressed in existing literature, offering both scientific and practical contributions.

2.2. Characteristics of the Model Building

In this study, to evaluate the performance and effectiveness of passive solutions and their ability to accommodate thermal extremes, a model with specific characteristics was developed. The building was designed using OpenStudio software, which configures the data required for the EnergyPlus simulation engine. The model was conceived as a flexible, adaptable prototype capable of analysis under a wide range of climatic conditions. This adaptability enables the evaluation of how different passive and active design strategies perform in distinct environmental contexts worldwide [3,15]. Accordingly, six representative cities were selected to reflect diverse climate zones and geographical regions, providing a comparative basis for analysing the building's energy performance and thermal comfort potential [19,20].

The model building is a single-story building with an interior area of 5 m^2 (2.5 m $\times$ 2.0 m) and a standard height of 2.3 m, as shown in Figure 3. Although simplified, this single-zone model was intentionally adopted to provide a controlled environment for studying thermal behaviour and validating simulation tools, minimising the influence of factors present in larger, more complex buildings. The building was designed to maximize solar gains through a south-facing orientation, which ensures better passive heating performance during the winter in temperate climates [13,24]. The building structure uses a Light Steel Framing (LSF) system, selected for its lightweight properties, structural efficiency, ease of assembly, and good thermal performance when combined with suitable insulating materials [25]. This also allows for high precision and reduced waste, making it suitable for small-scale energy performance models. The building envelope was designed to balance thermal insulation, airtightness, and durability. The exterior walls consist of an internal gypsum board panel with rock wool insulation sandwiched between metal profiles and an external oriented strand board (OSB) panel protected by a waterproofing membrane. Stone wool was selected for its low thermal conductivity, fire resistance, and acoustic insulation properties, while OSB offers structural rigidity and compatibility with lightweight systems [9,26]. The building's roof is completely flat and consists of a sandwich panel with stone wool insulation, an internal plaster covering, and an external OSB covering, protected by waterproofing and finishing layers. This configuration minimizes heat loss from the upper surface, which is one of the elements most exposed to solar radiation and precipitation [27,28]. The floor consists of a 10 cm-thick reinforced concrete slab, designed to increase the building's thermal mass. This material helps stabilize internal temperatures by absorbing and releasing heat throughout the day, which is particularly beneficial in climates with large diurnal temperature variations [17]. The choice of concrete also provides structural stability and represents a realistic boundary condition for heat transfer simulations [22,29].

In general, the selection of materials and construction systems aimed to represent a compact, energy-efficient, and economical building envelope, suitable for evaluating thermal performance and passive design strategies.

Regarding glazed surfaces, the building has one large window (1.30 m $\times$ 0.60 m) facing south and two smaller windows (0.60 m $\times$ 0.60 m) facing east and west, all with double glazing and aluminium frames. There are no glazed surfaces on the north façade, only an opaque aluminium door (0.90 m $\times$ 1.90 m).

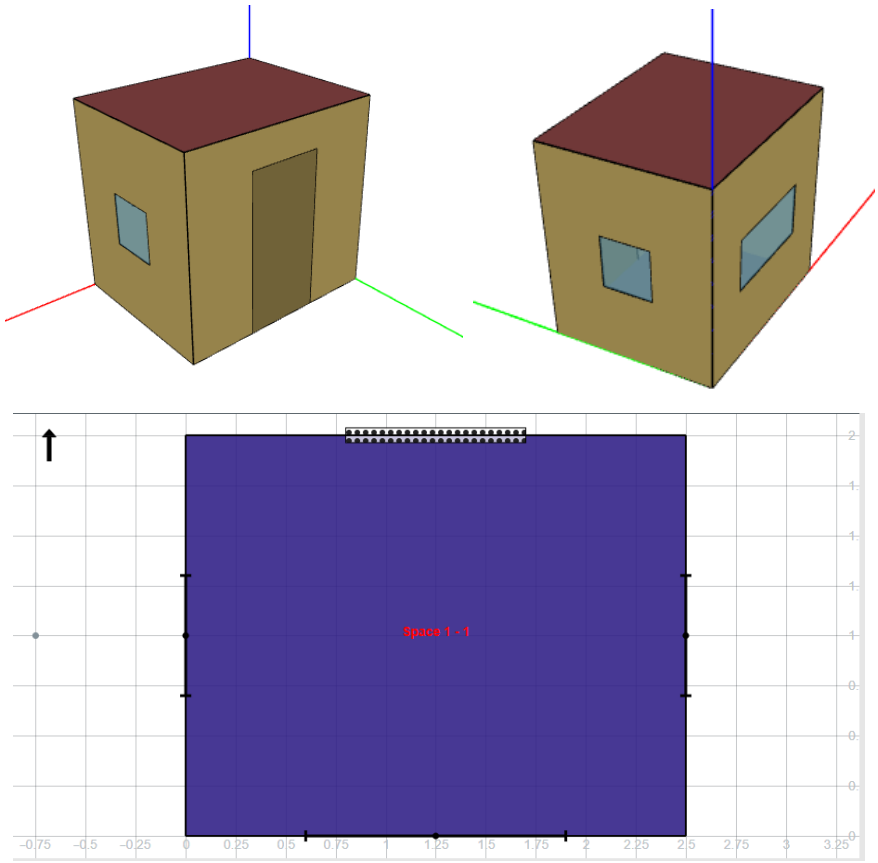


Figure 3. Three-dimensional representation of the model building used in the energy simulations.

No active heating, venting, and air conditioning (HVAC) systems were installed in the reference building. Ventilation is provided by natural ventilation, with 0.5 air changes per hour [23].

The indoor reference conditions adopted for the simulation followed the adaptive criteria of ASHRAE 55 [30] and fixed limits of EN 16798-1 [31], considering comfort temperatures between 18 °C and 25 °C to measure hours of thermal discomfort throughout the year. This simulation model enables the evaluation of passive solutions across various climates, demonstrating the potential and limitations of bioclimatic architecture in adapting buildings to local conditions [32]. The detailed characteristics of the building, namely the composition of the walls, windows, door, roof, and floor, are presented in Tables A1–A3.

2.3. Model Validation and Reliability Assessment

To ensure the highest reliability of the simulation results, the model was approved based on empirical studies and recognised benchmarks. Various thermal performance study data, such as energy requirements for cooling and heating, indoor temperatures, and hours of thermal discomfort, were compared with published data for small-scale buildings in similar climate zones.

The validation process followed procedures established by the American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers, in accordance with ASHRAE Standard 140 [29], which defines comparative test cases for evaluating building energy simulation programs. This standard enables benchmarking EnergyPlus results against reference analytical and empirical data, ensuring that model performance is within the expected accuracy range. The simulated energy requirements were also compared with results from previous empirical and simulation-based studies of small-scale buildings in similar climatic conditions, such as those by Im

et al. [33] and Palacios Mackay [34]. The good agreement observed between the present model and these validated studies confirms that the numerical framework provides reliable, consistent results, in line with international standards and the published literature.

Although the study is based on a simplified building model, this reference geometry was intentionally adopted to enable consistent comparison of passive design strategies across multiple climatic contexts, minimizing the variability caused by differences in architectural form or regional construction practices. The methodology and validation steps, therefore, provide confidence that the trends observed for passive strategies across various climatic conditions are reliable. This approach isolates the influence of climate and passive measures from morphological effects, ensuring that the comparative analysis reflects regional climatic diversity rather than geometric variation. Empirical validation, as described in studies such as that conducted by Im et al. [33], is essential to ensure the accuracy of building energy models, especially in projected climate change scenarios. Other studies, such as Palacios Mackay's [34], have demonstrated the effectiveness of simplified, validated models for evaluating adaptive façade strategies, reinforcing the applicability of a similar perspective across diverse contexts. Future work will expand this framework to include representative regional building typologies, thereby further enhancing the model's contextual adaptation.

3. Case Studies: Evaluating the Performance of Passive Strategies in Different Climatic Contexts

The study aims to evaluate the effectiveness of passive strategies for thermal performance in buildings across various climate zones through computational modelling and dynamic energy simulations. Seven passive strategies were applied to a standard building model in six cities selected based on the Köppen–Geiger climate classification. While architectural geometry and materials remain constant, this uniform model enables direct comparison of climatic influences and passive strategy performance across distinct regional contexts. The approach ensures that variations in results are attributable to climate diversity rather than differences in building form or design complexity.

Future climate data were determined using climate analogue mapping, a methodology that compares projected conditions for a city with the current climates of other locations. This makes it possible to estimate, in a simple way, what the climate conditions of a region will be like. In the study conducted by Fitzpatrick and Dunn [35], the technique was applied to approximately 540 urban areas in North America, analysing two scenarios: emissions mitigation (Representative Concentration Pathway (RCP) 4.5) and high uncontrolled emissions (RCP8.5).

The study showed that by 2080, several cities will experience climatic conditions similar to those in regions hundreds of kilometres to the south. For example, cities in the north-east of the United States will experience conditions similar to those in the south-west of the country, becoming warmer and more humid [35].

The authors developed a tool that allows the climate analogues of each city and different scenarios to be observed, proving effective for predicting climate change. The study shows that cities will face unprecedented conditions, requiring the implementation of adaptation policies, urban infrastructure prepared for uncertain scenarios, and resilience strategies capable of addressing not only gradual changes but also new climatic conditions [35].

3.1. Modelling Methodology and Strategy

The model building underwent four types of thermal simulations to assess the performance of passive strategies in both current and future scenarios, such as the potential

thermal performance (without control) and realistic performance (with control) of the building, as described below:

- Present scenario without temperature control—Simulation that allows verification of the natural thermal behaviour of the building, without the use of active air conditioning systems, thus evaluating passive performance.
- Present scenario with temperature control—Simulation that allows the thermal behaviour of the building to be verified, with the use of active air conditioning systems, through defined heating and cooling setpoints (18 °C and 25 °C).
- Future scenario without temperature control—Simulation that allows the passive thermal performance of the building to be projected in future climate scenarios, without the use of active air conditioning systems.
- Future scenario with temperature control—Simulation that allows the passive thermal performance of the building to be projected in future climate scenarios, with active air conditioning systems, using setpoints (18 °C and 25 °C). This scenario is the only one in which passive strategies are applied, allowing the evaluation of how thermal loads will evolve in the future to promote thermal comfort.

3.2. Selection of Cities and Climate Justification

The six selected cities present diverse climate scenarios across different latitudes and regions of the globe, allowing for a comparative analysis of strategies. According to the Köppen–Geiger classification, cities are classified as shown in Table 1.

Table 1. Köppen–Geiger climate classification for the six selected cities, including country, latitude, and climate type.

City	Country	Latitude	Classification Köppen–Geiger	Climate Type
Lisbon	Portugal	38° N	Csa [1]	Mediterranean
Berlin	Germany	52° N	Cfb [1]	Temperate oceanic
Östersund	Sweden	63° N	Dfc [1]	Cold subarctic
Montreal	Canada	45° N	Dfb [1]	Humid continental
Riyadh	Saudi Arabia	24° N	BWh [1]	Hot and dry (desert)
Bangkok	Thailand	13° N	Aw [1]	Tropical with dry season

[1] Köppen–Geiger codes: first letter = main climate type (A = tropical, B = arid, C = temperate, D = cold); second letter = seasonal precipitation pattern (s = savanna-dry summer, w = savanna-dry winter, f = no dry season, W = Arid desert); third letter = temperature intensity (a = hot summer, b = warm summer, c = cold summer, h = hot).

The city of Lisbon has experienced hot, dry summers, with average temperatures above 30 °C, frequent tropical nights, and mild, humid winters. Therefore, due to these records, passive strategies should be used to minimise heat gains, such as shading or ventilation [17,36].

The city of Berlin has experienced moderate summers and cold winters, with temperatures ranging from −1 °C to 24 °C, and an increase in summer temperatures and precipitation over the last few years. Thus, there has been a need to implement strategies to control solar gains and promote natural ventilation [37].

The city of Östersund has long, harsh winters, with temperatures often below −15 °C, and short, mild summers. Based on these records, energy expenditure is mainly for heating, requiring strategies that promote heat conservation, such as improved thermal insulation and maximising solar gains [38].

The city of Montreal has high annual temperature variability, with severe winters (down to −20 °C) and hot summers (>30 °C). The main energy expenditure is for heating;

however, the use of electronic equipment and glazed areas has led to an increase in demand for cooling, implying a combined use of strategies (heating and cooling) [39].

The city of Riyadh has experienced extremely high summer temperatures, often above 45 °C, and low relative humidity (<20%). The city has a high building density and low vegetation, which contribute to increased local temperatures. Thus, there has been a need for solutions such as high-reflectance surfaces, horizontal shading, and reduced exposure of paved areas [40].

The city of Bangkok has experienced high average temperatures throughout the year (~29 °C) and relative humidity often above 80%, with periods of heavy rainfall and high humidity (monsoon season). The use of night ventilation, solar protection, low-thermal-absorption materials, and internal humidity control has proven highly effective in this scenario [41].

3.3. Passive Strategies Adopted in Sustainable Construction

Sustainable construction refers to the design, construction, and operation of buildings that reduce environmental impact, promote energy efficiency, and improve occupant well-being. This approach encompasses the use of environmentally friendly materials, efficient resource management, waste and emissions reduction, and the incorporation of strategies that minimise energy consumption while ensuring indoor comfort. In this context, passive strategies play a crucial role by leveraging the environment's natural resources to maintain thermal comfort, thereby reducing reliance on mechanical systems. The choice and application of solutions depend on factors such as the local climate, the building's solar orientation, construction characteristics, and thermal inertia. The study under analysis considers seven passive strategies: increasing thermal mass, night ventilation, increasing thermal insulation thickness (wall/roof), green roofing, shading, and reducing glazing area.

Increased Thermal Mass (SP1)—This strategy involves using materials with higher thermal capacity in the internal cladding, which store heat during the day and release it at night, reducing internal temperature fluctuations. As materials with higher thermal capacity can significantly reduce energy consumption [27,42], four types of interior panels were tested in the simulation (see Table A4): plasterboard panel (Case 1), with lower thermal mass; lightweight concrete panel (Case 2); stucco panel (Case 3); and normal concrete panel (Case 4), with higher thermal mass.

Natural Night Ventilation—'Free Cooling' (SP2)—The solution is characterized by the renewal of indoor air through the entry of cooler outdoor air during the night (from 4 a.m. to 8 a.m., between June and September), allowing heat to dissipate from the building. Increasing the ventilation rate can reduce cooling energy consumption by around 30%, depending on the outside temperature [26,42]. To assess the potential of this technique, different air changes per hour (h^{-1}) values ranging from mild to very intense were chosen in the form of four scenarios (see Table A5): case 1–0.5 h^{-1}; case 2–7.8 h^{-1}; case 3–15.6 h^{-1}; and case 4–23.5 h^{-1}. These rates represent the number of times the indoor air is completely renewed per hour.

Increased Roof/Wall Thickness (SP3/SP6)—The strategy involves increasing the thickness of roofs or walls to improve thermal insulation and reduce heat loss in winter and heat gain in summer. This strategy could lead to a 20% to 47% reduction in energy consumption [25,43]. In the simulation, four scenarios were tested (see Tables A6 and A9) with different insulation thicknesses for the roof (0.05 m to 0.0875 m) and the wall (0.05 m to 0.08 m).

Green Roof (SP4)—The strategy is characterised by the use of a green roof composed of several layers: vegetation, substrate, drainage, and waterproofing, ensuring natural

shading, evapotranspiration, and thermal insulation. Implementing this solution helps reduce external temperatures, thereby decreasing heat transfer into the building [11,27]. In the simulation, four scenarios were defined and tested with variable values in the constituent properties that characterize the solution: vegetation, substrate, drainage, and waterproofing (see Table A7).

Exterior Shading Devices (SP5)—The strategy is characterized by using shading elements that block direct solar radiation on glazed surfaces, and factors such as solar radiation intensity and climatic conditions could influence the effectiveness of this solution [11,42]. Four scenarios were simulated (see Table A8). Case 1 corresponds to the initial condition, without any active shading elements. In the remaining cases, three shading solutions were evaluated: external blinds (Case 2), opaque internal blinds (Case 3), and external blinds with slats (Case 4), all capable of directly blocking solar radiation on the building's glazed surfaces.

Reduction of Glazed Area (SP7)—The strategy involves reducing the glazed area, resulting in a considerable decrease in heat gains and losses [44]. In the simulation, four different scenarios were considered (see Table A10): Case 1, corresponding to the initial scenario, with no reduction in glazed area; Case 2, with a 10% reduction; Case 3, with a 20% reduction; and Case 4, with a 30% reduction in relation to the initial glazing measurements.

The characteristics of each case for each passive solution tested can be found in more detail in Tables A4–A10.

3.4. Climate Data

The current data was obtained from EPW (EnergyPlus Weather) files, which provide temporal data on meteorological variables for different locations [22].

Future data were obtained from contemporary climate analogues, using a methodology described by Fitzpatrick and Dunn [35]. This approach identifies current regions with climates like those of other locations in the future, using forecasts for the 2080s under two emission scenarios (RCP4.5 and RCP8.5). However, the Fitzpatrick & Dunn study indicates that this method cannot provide forecasts for cities with extreme climates, such as Riyadh and Bangkok, due to their unique climatic conditions [35].

It is important to point out that, due to this limitation in the adopted methodology, no future climate data are available for Riyadh and Bangkok. However, these two cities were retained, given their extreme climatic characteristics (arid and tropical), which are important for the performance of buildings in different climatic contexts. The inclusion of these cities aims to highlight gaps in available future climate data and to reinforce the need to develop alternative modelling methods capable of addressing these unique climatic conditions. Thus, the comparative analysis of future climate scenarios focuses only on the four remaining cities for which data is available. In Riyadh and Bangkok, simulations are conducted only in the current scenario.

3.4.1. Outdoor Temperature

The evolution of outdoor temperatures for current and future climate scenarios across six distinct climate zones—Lisbon, Berlin, Östersund, Montreal, Riyadh, and Bangkok—is shown in Figure 4.

The temperature difference between the present and future scenarios shows an increase in the average temperature and the maximum values recorded, by 1.5 °C to 3.3 °C. These values allow us to identify possible scenarios of global warming and how they will affect the thermal and energy performance of buildings.

In Lisbon, the maximum annual temperature increased from 35.8 °C in the current scenario to 36.8 °C in the future, while minimum temperatures remained stable around 4 °C,

leading to an increase in the frequency of summer overheating. In Berlin, the minimum annual temperature drops from −8.9 °C in the present to −14.3 °C in the future, while maximum temperatures remain stable at 32.6 °C to 33.3 °C, resulting in harsher winters. In Östersund, the annual minimum temperature has decreased from −25.5 °C at present to −22.4 °C in the future, while maximum temperatures have remained stable at 26.4 °C to −26.8 °C, resulting in winters with shorter periods of extreme cold. In Montreal, the annual minimum temperature rises from −26.2 °C at present to −24.9 °C in the future, while maximum temperatures remain stable between 31.8 °C and 32.6 °C, resulting in winters with fewer periods of extreme cold and warmer summers. For Riyadh and Bangkok, future climate data were unavailable because the applied climate-analogue methodology does not provide equivalents for extreme arid and tropical-humid climates. Nevertheless, both cities were included to represent these critical climatic contexts, which are relevant to assessing the performance of passive strategies under hot, humid conditions. Thus, only present-day data are used for Riyadh and Bangkok, while future projections are applied to the remaining four cities.

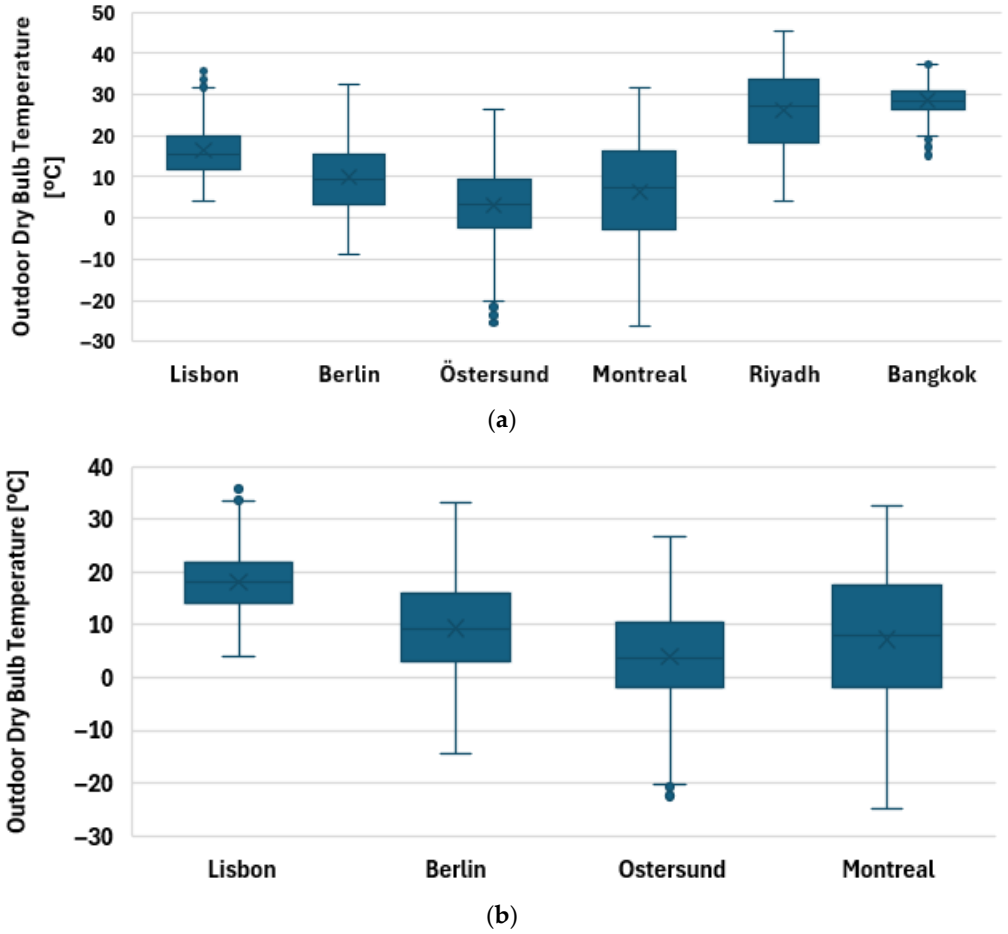


Figure 4. Annual variation of outdoor air temperature under current (**a**) and future (**b**) climate scenarios for the six selected cities, (**a**) Outdoor dry bulb temperature [°C]—Current scenario, (**b**) Outdoor dry bulb temperature [°C]—Future scenario.

3.4.2. Solar Radiation

Direct solar radiation (direct normal irradiance) for current and future climate scenarios across the six distinct climate zones—Lisbon, Berlin, Östersund, Montreal, Riyadh, and Bangkok—is shown in Figure 5.

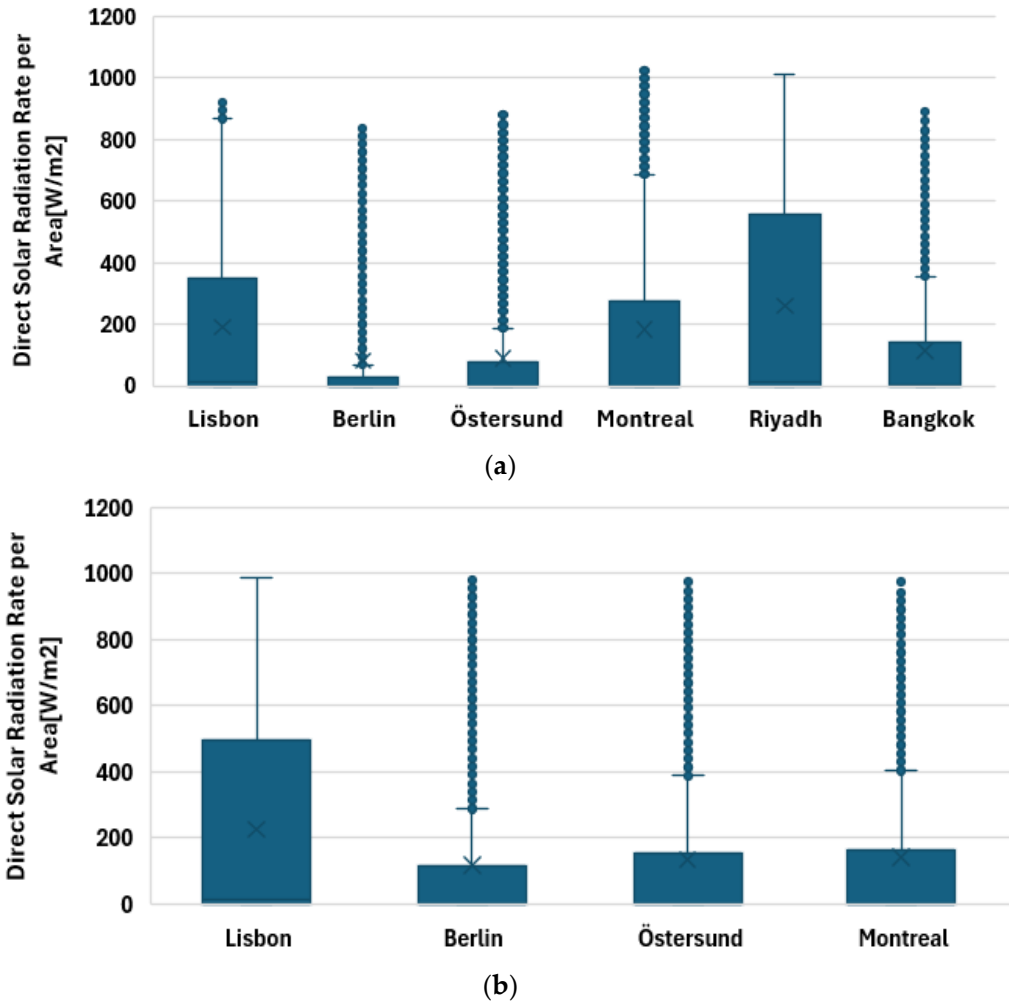


Figure 5. Annual variation of direct solar radiation under current (**a**) and future (**b**) climate scenarios for the six selected cities, (**a**) Solar radiation [W/m^2]—Current scenario, (**b**) Solar radiation [W/m^2]—Future scenario.

The analysis shows an increase in average annual radiation in various cities. In Lisbon, average annual solar radiation and maximum radiation increase from 191 W/m^2 to 225 W/m^2 and from 941 W/m^2 to 988 W/m^2, respectively, demonstrating longer periods of solar radiation. In Berlin, the average annual solar radiation and maximum radiation increase from 80 W/m^2 to 118 W/m^2 and from 856 W/m^2 to 983 W/m^2, respectively, demonstrating longer periods of solar radiation. In the city of Östersund, the average annual solar radiation and maximum radiation increase from 89 W/m^2 to 135 W/m^2 and from 903 W/m^2 to 976 W/m^2, respectively, demonstrating longer periods of solar radiation in the summer. In Montreal, the average annual solar radiation and maximum radiation decrease from 182 W/m^2 to 142 W/m^2 and from 1029 W/m^2 to 997 W/m^2, respectively, indicating longer periods of cloud cover. In Riyadh and Bangkok, where no data are available for future scenarios, it is not possible to assess climate change for these locations, as there is only data for the present situation. Thus, in the present scenario, Riyadh has a maximum radiation of 1013 W/m^2 and an average of 258 W/m^2, while Bangkok has a maximum of 889 W/m^2 and an average of 115 W/m^2. Based on this data, some cities show an increase in solar radiation, leading to overheating, which in turn promotes the use of architectural solutions to cool buildings.

4. Results and Discussion

This study investigated energy consumption per unit area for heating and cooling, and the overall energy balance, for a model building in different climate zones, using graphs to show thermal loads under different conditions.

Initially, current energy needs (heating and cooling) were analysed to characterize indoor thermal conditions for each climate region. Next, the percentage energy variation for future climatic conditions was analysed, first without the use of passive solutions (case 1) and then with different passive strategies (cases 2, 3, 4), to evaluate the impact of each solution on energy efficiency. However, as the methodology adopted by Fitzpatrick & Dunn [35] was not suitable for extreme climates such as those of Riyadh and Bangkok, the climate analogue failed to provide accurate future projections. Therefore, in these locations, the effects with and without passive solutions are analysed only in the current scenario. Finally, to adopt a systematic, comparative approach, an energy-impact analysis is conducted to demonstrate the effects of each passive solution across the various climate zones.

4.1. Present Energy Diagram

Figure 6 shows variations in heating and cooling energy requirements across cities with different climates. In regions with cold climates, such as Östersund, Montreal and Berlin, heating loads prevail, underscoring the importance of maintaining comfortable environments during extended periods of low temperatures with minimal cooling requirements. The predominance of heating demand indicates high conductive losses through the envelope, emphasizing the importance of insulation-based strategies.

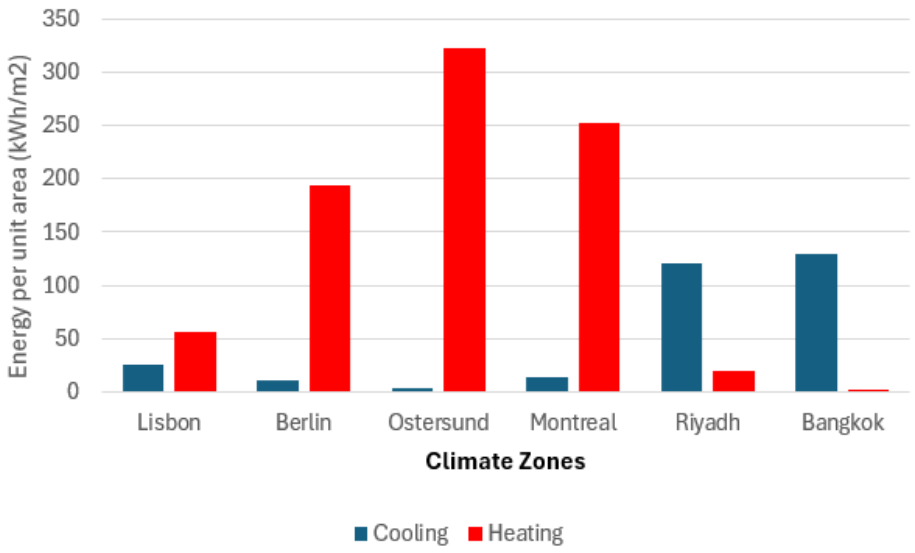


Figure 6. Annual heating and cooling loads per unit area (kWh/m^2) for the base case (present scenario without passive solutions) in each climate zone.

On the other hand, in hot climates such as Bangkok and Riyadh, cooling accounts for the largest energy demand, with very low heating loads. Cooling energy needs dominate due to solar radiation and latent heat gains, making solar control and ventilation essential priorities. In climates with intermediate conditions (heat and cold), such as Lisbon, heating and cooling energy needs are balanced. The balanced pattern observed in Lisbon highlights its transitional nature, where both heating and cooling loads are significant, underscoring the need for a mix of passive strategies. This enables understanding how thermal behaviour evolves across different regions and thus defines the best passive strategies and solutions suited to each climate.

4.2. Present/Future Energy Consumption

Figure 7 shows the evolution of thermal loads per unit area (kWh/m^2) for cooling and heating between the present and future scenarios without passive solutions. In Lisbon, as temperatures rise, the cooling load increases from 25.6 to 36.1 kWh/m^2, while the heating load decreases from 55.9 to 33.2 kWh/m^2, promoting the adoption of cooling solutions. In Berlin, cooling demand increases from 10.3 to 12.8 kWh/m^2, while heating demand remains practically unchanged, rising from 193.3 to 191.4 kWh/m^2. The cities of Östersund and Montreal exhibit similar behavior, with a reduction in heating loads—from 322.7 to 296.5 kWh/m^2 in Östersund and from 252.0 to 249.3 kWh/m^2 in Montreal. In terms of cooling needs, Östersund decreases slightly from 3.6 to 3.1 kWh/m^2, while Montreal increases from 13.7 to 16.6 kWh/m^2.

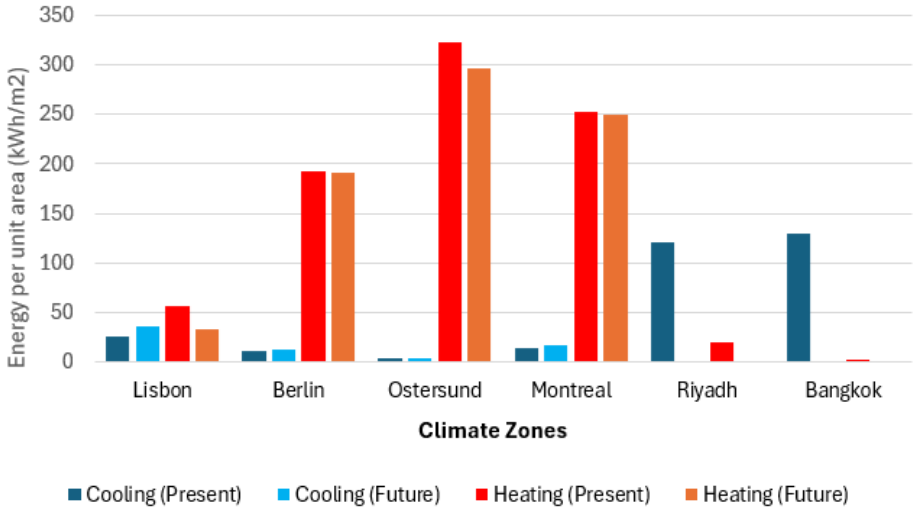


Figure 7. Comparison of heating and cooling energy needs per unit area (kWh/m^2) between present and future scenarios, without passive solutions.

The reduction in heating and simultaneous increase in cooling demand across most cities demonstrates the projected impact of climate change on building thermal performance. These trends indicate that passive design must adapt dynamically, enhancing shading and natural ventilation in warmer regions, while maintaining good insulation efficiency to prevent overheating. The graphical results thus serve not only as quantitative outcomes but as visual evidence of the changing thermal balance that motivates the adoption of adaptive passive measures.

4.3. Energy Consumption with the Application of Passive Solutions (Increased Thermal Mass)

Figure 8 shows the evolution of thermal loads per unit area (kWh/m^2) for cooling and heating in the future scenario (except for Riyadh and Bangkok, which are carried out in the present scenario), using the passive solution of increasing thermal mass. The passive solution of increasing thermal mass reduces energy loads for both cooling and heating. In Lisbon and Berlin, the solution implementation results in a gradual decrease in cooling load, reaching approximately 85% (from 36.1 to 5.5 kWh/m^2) in Lisbon and 96% (from 12.8 to 0.6 kWh/m^2) in Berlin, respectively. This demonstrates that increasing thermal mass helps to reduce heat peaks. Heating energy requirements show the same behavior, although less pronounced in Berlin, decreasing from 33.2 to 9.6 kWh/m^2 in Lisbon and from 191.4 to 165.4 kWh/m^2 in Berlin. In Östersund and Montreal, the solution also allows for a significant reduction in cooling loads, from 3.1 to 0.0 kWh/m^2 and from 16.6 to 1.0 kWh/m^2, respectively. In terms of heating energy requirements, there is also a decrease, although smaller, from 296.5 to 274.5 kWh/m^2 in Östersund and from 249.3 to 225.7 kWh/m^2 in

Montreal. In Riyadh and Bangkok, the solution also demonstrates high efficiency, reducing cooling loads from 120.8 to 76.1 kWh/m^2 and from 129.3 to 62.9 kWh/m^2, respectively. In heating loads, reductions from 20.1 to 2.8 kWh/m^2 are observed in Riyadh and from 0.118 to 0.0 kWh/m^2 in Bangkok, confirming that increasing the thermal mass delays heat transfer.

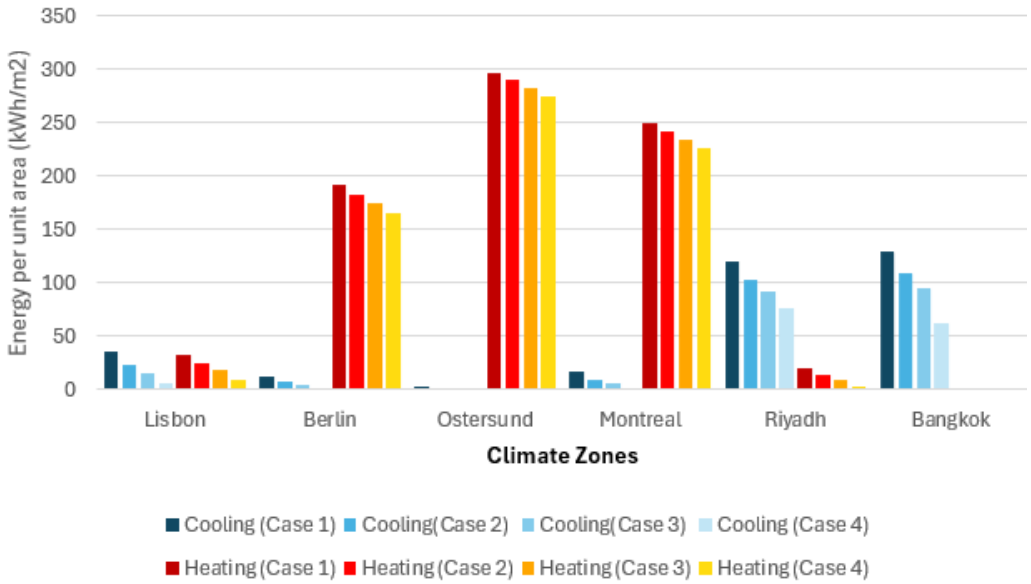


Figure 8. Heating and cooling energy needs (kWh/m^2) under the future scenario with passive solution—increased thermal mass.

As shown in Figure 8, the effect of thermal mass is particularly relevant in climates with high diurnal temperature amplitude. In Lisbon and Berlin, the enhanced inertia delays heat transfer through walls and floors, thereby reducing temperature peaks and stabilizing indoor comfort conditions. This buffering effect explains the sharp reductions in cooling energy seen in both temperate climates. In contrast, in colder regions such as Östersund and Montreal, the lower external temperature oscillation limits the benefit of stored heat, resulting in smaller improvements for heating loads. In hot climates (Riyadh, Bangkok), the performance gain results from the time lag between peak solar radiation and indoor heat release, which helps reduce overheating during daytime hours. These interactions demonstrate how the physical properties of materials directly influence the numerical trends observed in Figure 8, reinforcing the scientific connection between the graphical data and the building's thermal behaviour.

4.4. Energy Consumption with the Application of Passive Solutions (Free Cooling)

The evolution of thermal loads per unit area (kWh/m^2) for cooling and heating, in the future scenario (except for Riyadh and Bangkok, which are carried out in the present scenario), using the passive solution, night ventilation, is shown in Figure 9. In Lisbon, the results show a slight variation between cases, with cooling loads (36.1–36.4 kWh/m^2) and heating loads (33.2–34.0 kWh/m^2) varying slightly. In Berlin and Montreal, the effects of the solution show the cooling loads remaining practically unchanged (around 12.8 to 12.7 kWh/m^2 in Berlin and 16.6 kWh/m^2 in Montreal), while heating loads increase from 191.4 to 230.0 kWh/m^2 in Berlin and from 249.3 to 273.1 kWh/m^2 in Montreal. In Östersund, cooling loads remain nearly constant (3.1–3.0 kWh/m^2), while heating demand increases from 296.5 to 359.5 kWh/m^2. In areas such as Riyadh and Bangkok, there is an increase in cooling load, from 120.8 to 149.2 kWh/m^2 in Riyadh and from 129.3 to 145.9 kWh/m^2 in Bangkok, while heating loads remain practically constant (around 20.1 kWh/m^2 in Riyadh

and 0.118 kWh/m^2 in Bangkok), a result explained by the small temperature difference between day and night, which limits the effectiveness of night cooling.

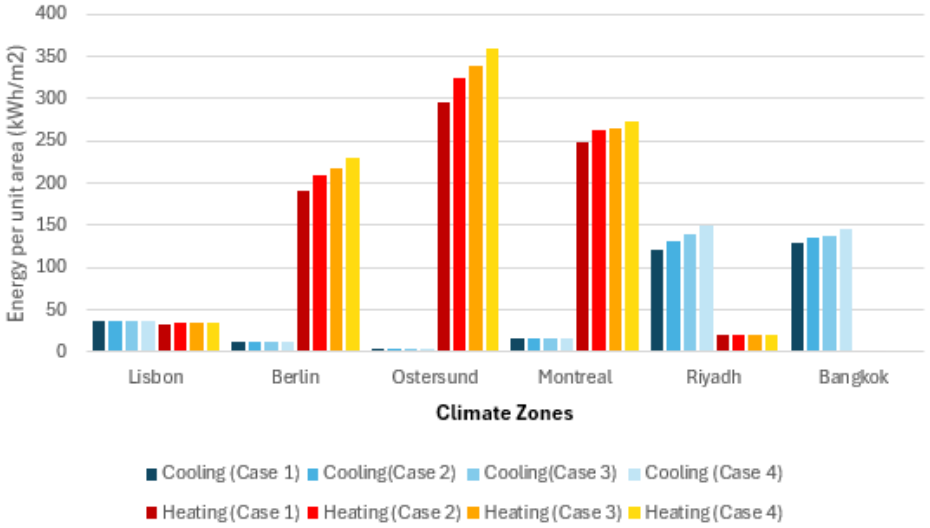


Figure 9. Heating and cooling energy needs (kWh/m^2) under the future scenario with passive solution—night ventilation (free cooling).

As illustrated, the performance of the night ventilation strategy (free cooling) depends strongly on the daily temperature range. In cold climates, this strategy proves less effective, as the infiltration of colder outside air can increase heat loss, compromising the building's energy performance. In temperate regions, the impact remains low, as the potential for night-time cooling is limited by the small temperature difference. On the other hand, in hot arid regions, the low humidity and high nighttime temperatures reduce the effectiveness of natural cooling.

4.5. Energy Consumption with the Application of Passive Solutions (Increased Roof Thickness)

Figure 10 shows the evolution of thermal loads per unit area (kWh/m^2) for cooling and heating in the future scenario (except for Riyadh and Bangkok, which are carried out in the present scenario), using the passive solution of increasing roof thickness. In Lisbon, cooling loads decrease from 36.1 to 31.1 kWh/m^2, and heating loads decrease from 33.2 to 30.3 kWh/m^2, indicating that the increase in roof thickness improves thermal stability. In areas such as Berlin, similar behaviour is observed, with cooling loads decreasing from 12.8 to 10.9 kWh/m^2 and heating loads decreasing from 191.4 to 180.1 kWh/m^2. In colder climate regions such as Östersund and Montreal, implementing the solution results in more obvious reductions: cooling loads decrease from 3.1 to 2.5 kWh/m^2 and from 16.6 to 14.1 kWh/m^2, respectively, while economical heating loads decrease from 296.5 to 279.9 kWh/m^2 and from 249.3 to 234.8 kWh/m^2, respectively.

In hot climates (Riyadh and Bangkok), increasing roof thickness leads to a notable reduction in cooling loads: from 120.8 to 109.1 kWh/m^2 and from 129.3 to 117.7 kWh/m^2, respectively. On the other hand, heating energy needs fall from 20.1 to 17.9 kWh/m^2 in Riyadh and are virtually non-existent in Bangkok, demonstrating that the increased thickness of thermal insulation helps to reduce energy requirements in these regions.

Figure 10 highlights the stabilizing role of improved roof thickness in moderating internal temperature variations. The decrease in cooling and heating loads is mainly due to a reduction in heat conduction through the upper surface of the envelope, which is most exposed to solar radiation. In temperate and cold climates, thicker insulation layers help prevent heat loss during winter, while in hot climates, such as Riyadh and

Bangkok, they reduce solar heat gain through the roof during periods of peak radiation. The results confirm that improved roof insulation offers a universal benefit across climates, though its relative efficiency depends on the balance between conductive and radiative heat transfer mechanisms.

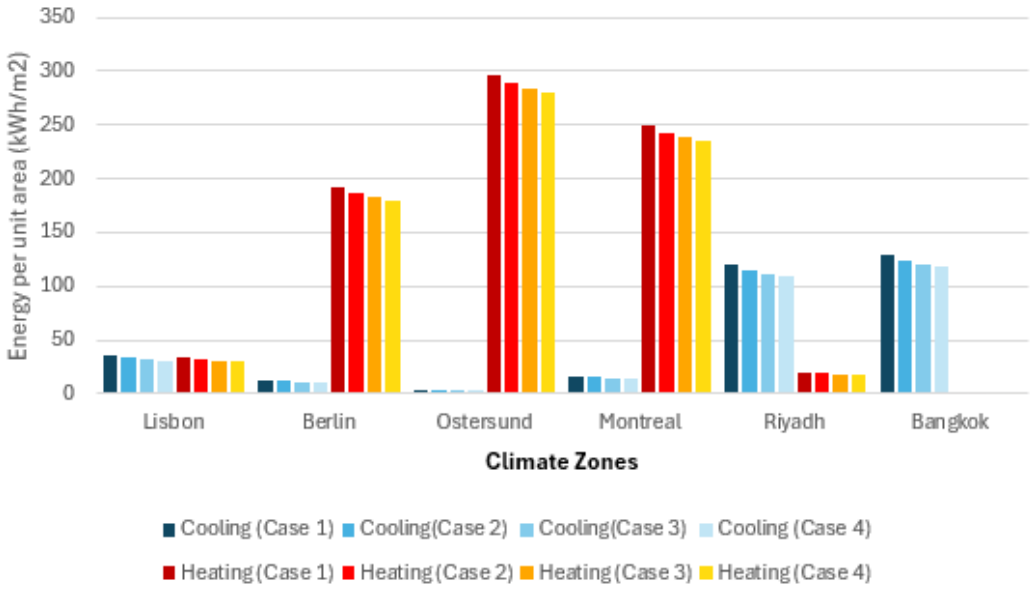


Figure 10. Heating and cooling energy needs (kWh/m^2) under the future scenario with passive solution—increased roof thermal insulation.

4.6. Energy Consumption with the Application of Passive Solutions (Green Roof)

Figure 11 shows the evolution of thermal loads per unit area (kWh/m^2) for cooling and heating in the future scenario (except for Riyadh and Bangkok, which are carried out in the present scenario), using the passive solution of a green roof. Across cities, results show that cooling and heating loads decrease in all cases, demonstrating the high efficiency of this passive strategy. In Lisbon, the cooling load drops from 36.1 to approximately 23.9 kWh/m^2, while the heating load decreases from 33.2 to 24.7 kWh/m^2. In Berlin, the cooling load is reduced from 12.8 to 7.2 kWh/m^2, and the heating load from 191.4 to 167.7 kWh/m^2. In colder climates such as Östersund and Montreal, cooling loads decrease by about 57% (3.1 to 1.3 kWh/m^2) and 41% (16.6 to 9.8 kWh/m^2), respectively. In these cities, the energy needs for heating, with the implementation of the solution, also show a decrease from 296.5 to 267.0 kWh/m^2 and from 249.3 to 223.3 kWh/m^2, respectively. In hot climates such as Riyadh and Bangkok, green roofing can lead to significant reductions in cooling and heating loads. In cities with hot or temperate climates (Lisbon, Riyadh, and Bangkok), cooling demand remains higher than heating demand, whereas in cities with cold climates (Östersund, Berlin, and Montreal), the opposite trend is observed.

As shown in Figure 11, green roofs significantly contribute to thermal regulation of buildings through shading, evapotranspiration, and additional layers of insulation. The marked reduction in cooling demand across most climates confirms that vegetated surfaces effectively mitigate solar heat gain, especially in cities such as Lisbon and Berlin. In cold climates, its function becomes thermal regulation, acting as a barrier that reduces heat loss throughout the winter. In hot, humid regions such as Bangkok, the combination of evapotranspiration and substrate insulation more effectively delays heat transfer, increasing thermal performance and reducing reliance on air conditioning.

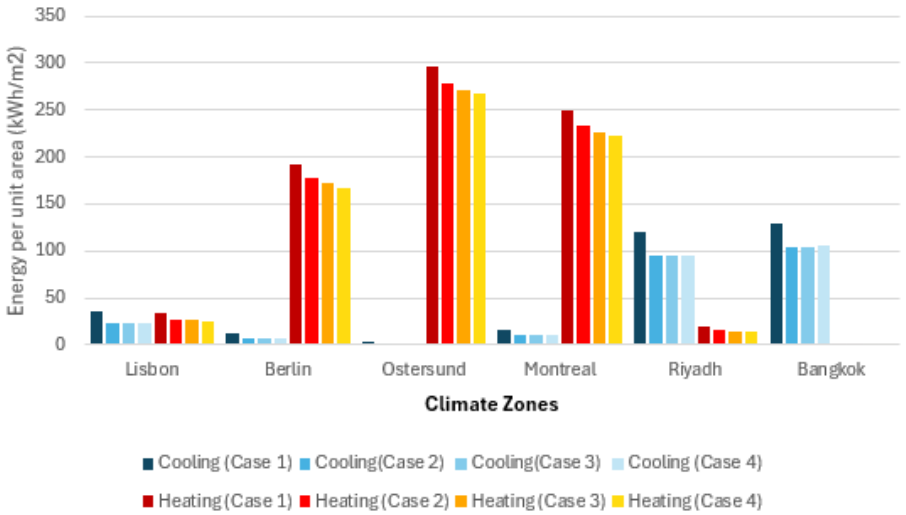


Figure 11. Heating and cooling energy needs (kWh/m^2) under the future scenario with passive solution—green roof.

4.7. Energy Consumption with the Application of Passive Solutions (Shading)

Figure 12 shows the evolution of thermal loads per unit area (kWh/m^2) for cooling and heating, in the future scenario (except for Riyadh and Bangkok, which are carried out in the present scenario), with the implementation of a passive shading device solution. In Lisbon, the results show a reduction in cooling energy in all cases, from 36.1 kWh/m^2 (without passive solutions) to 31.3, 14.7, and 13.8 kWh/m^2 (with passive solutions), while heating loads vary slightly, from 33.2 to 31.1, 32.5, and 35.2 kWh/m^2, showing a small decrease in the intermediate cases (Case 2—Roller Blind, Case 3—External Shutter (PVC)) and a slight increase with External Slat Blinds-Case 4. In Berlin, cooling and heating loads are significantly reduced by implementing shading solutions. In Östersund, there is a sharp reduction in cooling loads—from 3.1 to 2.7, 0.08, and 0.17 kWh/m^2—while heating loads remain nearly stable—from 296.5 to 286.2, 301.3, and 302.6 kWh/m^2. In Montreal, cooling loads decrease while heating loads vary slightly. In hot zones such as Riyadh and Bangkok, the cooling and heating loads decrease consistently, confirming that excessive shading may limit heat dissipation.

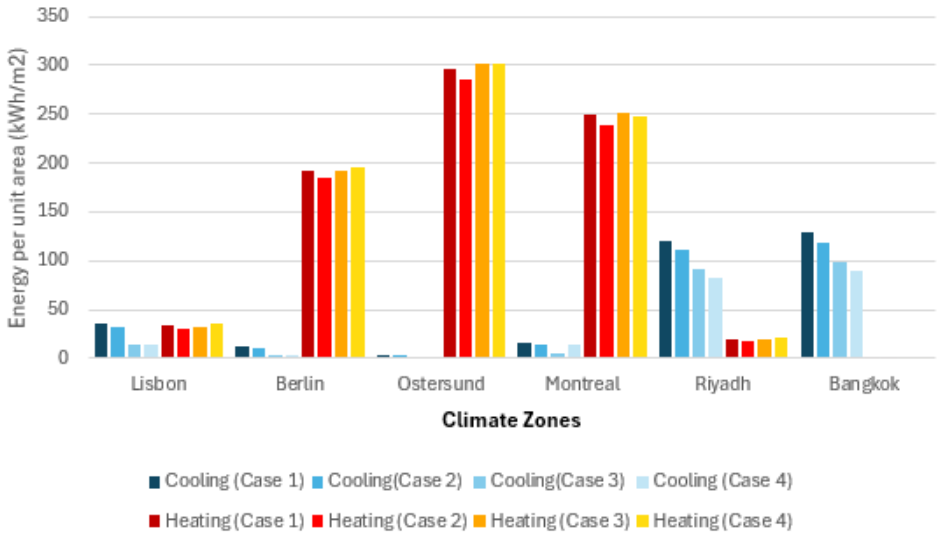


Figure 12. Heating and cooling energy needs (kWh/m^2) under the future scenario with passive solution—solar shading.

As shown in Figure 12, solar shading significantly affects cooling performance, especially in hot and temperate climates. The reduction in cooling loads by up to 60–70% demonstrates the effectiveness of external shading devices in reducing direct solar gains through glazed surfaces. However, the slight increase in heating requirements in some cold regions underscores the importance of adopting adjustable or seasonal shading solutions to balance energy performance year-round. This observed behaviour reinforces the principle that the design of shading systems must align with local latitude, the sun's path, and façade orientation to optimise thermal performance and energy efficiency.

4.8. Energy Consumption with Passive Solutions (Increased Wall Thickness)

Figure 13 shows the evolution of thermal loads per unit area (kWh/m^2) for cooling and heating in the future scenario (except for Riyadh and Bangkok, which are carried out in the present scenario) with increased wall thickness. In Lisbon, cooling loads decrease from 36.1 to 24.8 kWh/m^2 and heating loads from 33.2 to 25.5 kWh/m^2, demonstrating the effectiveness of increased thermal insulation.

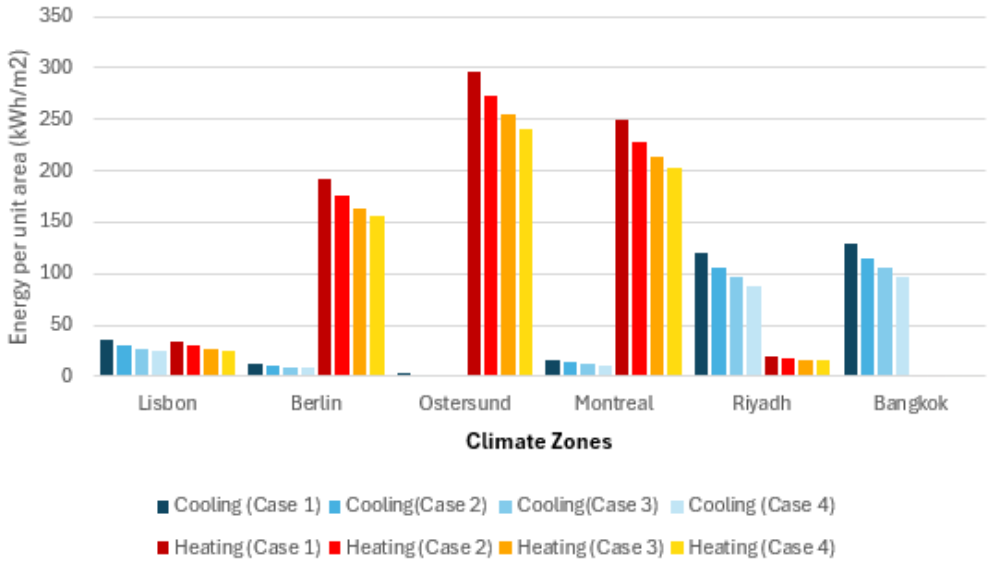


Figure 13. Heating and cooling energy needs (kWh/m^2) under the future scenario with the passive solution—increased wall thermal insulation.

In colder areas such as Berlin, Östersund, and Montreal, increasing the wall thickness results in progressive reductions in cooling loads and heating loads.

In this way, increasing the thickness of the walls' thermal insulation reduces heat transfer in winter, reduces thermal losses, and helps limit excessive heating of indoor spaces during summer. In hot climates, such as Riyadh and Bangkok, the loads for cooling decrease by up to around 27% (120.8 to 88.5 kWh/m^2) and 25% (129.3 to 97.0 kWh/m^2), respectively, while the heating loads show notable reductions of up to about 24% (20.1 to 15.3 kWh/m^2) and 39% (0.118 to 0.072 kWh/m^2), confirming that the increase of the thermal insulation of the walls contributes to lower energy needs in these climates.

Figure 13 further demonstrates that wall insulation directly governs the building's conductive heat exchange. The improvement observed in all climates shows that this measure offers a double benefit: it reduces the need for heating in cold regions and helps to mitigate overheating in hot regions. The graphical data show that thicker walls increase the thermal time lag, promoting indoor temperature stability. This confirms that structural envelope improvements remain one of the most universally effective passive strategies.

4.9. Energy Consumption with the Application of Passive Solutions (Reduction of the Glazed Area)

Figure 14 shows the evolution of thermal loads per unit area (kWh/m^2) for cooling and heating in the future scenario (except for Riyadh and Bangkok, which are carried out in the present scenario), using the passive solution of reducing the glazing area. In Lisbon, reducing the glazing area leads to a progressive reduction in both cooling and heating energy needs, with cooling loads decreasing from 36.1 to 24.3 kWh/m^2 and heating loads decreasing slightly from 33.2 to 32.8 kWh/m^2. In cities such as Berlin, Östersund, and Montreal, implementing the solution results in consistent reductions in both heating and cooling energy loads. This demonstrates that controlling the glazing area allows for effective energy management in colder climates by reducing both heating and cooling demands.

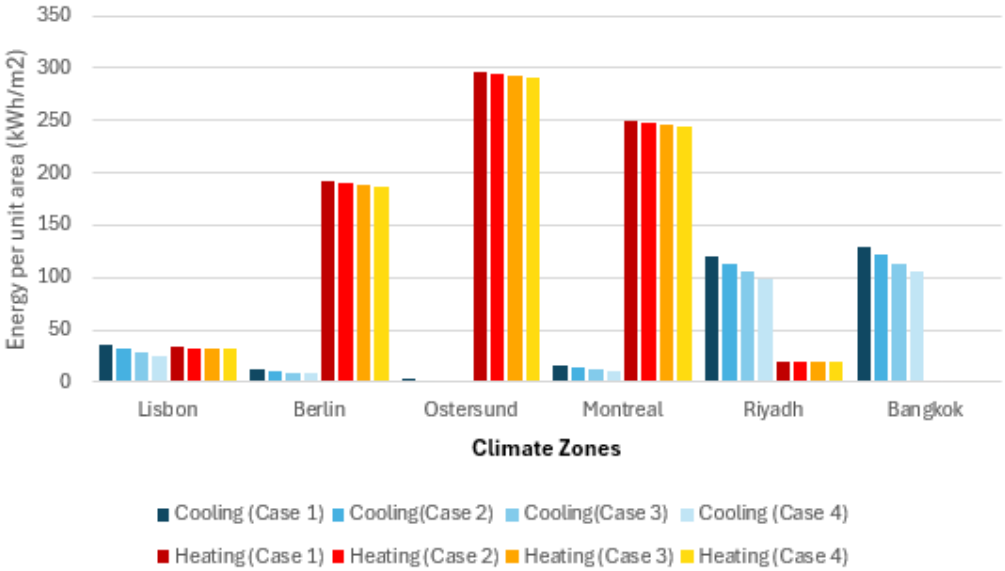


Figure 14. Heating and cooling energy needs (kWh/m^2) under the future scenario with passive solution SP7—reduced window-to-wall ratio.

The results shown in Figure 14 demonstrate that optimising the window-to-wall ratio is a simple but highly effective design tool. The consistent reduction in cooling and heating requirements demonstrates that solar and conduction heat gains through glazed surfaces can be controlled efficiently. However, it is essential that designers maintain a balance between natural lighting and ventilation requirements, as excessive reduction of these elements can compromise occupant comfort. The relationship between the results presented and the design principles underscores the importance of an integrated façade design approach to promote thermal efficiency.

4.10. Global Analysis of Passive Solutions—Energy Consumption

Table 2 shows the energy impact of the various passive solutions implemented (SP1-SP7) across the six climatic locations considered: Lisbon, Berlin, Östersund, Montreal, Riyadh, and Bangkok. The energy impact is evaluated using symbols to assess energy reduction (>40%, 20–40%, <20%) or energy increase.

In hot climates such as Ride and Bangkok, the energy performance improves with increasing thermal mass (SP1), from case 2 (★) to case 4 (★★★). This is attributed to thermal inertia, which delays heat propagation and reduces indoor temperature peaks. On the other hand, in cold climates, the implementation of the solution (SP1) shows a lower energy performance (★) because heating dominates and temperature fluctuations are slower, limiting the benefit of thermal storage. In moderate climates like Lisbon, the energy performance remains high (★★★) in all cases. Thus, the adoption of thermal

mass increases in these climates demonstrates their effectiveness in improving energy efficiency [28,42].

Table 2. Energy impact of the various passive solutions implemented (SP1 to SP7) in the different climatic locations.

City	Case	SP1	SP2	SP3	SP4	SP5	SP6	SP7
Lisbon	Case 2	★★★	★	★	★★	★★	★★	★★
Lisbon	Case 3	★★★	★	★★	★★	★★★	★★	★★
Lisbon	Case 4	★★★	★	★★	★★★	★★	★★	★★
Berlin	Case 2	★	•	★	★	★	★	★
Berlin	Case 3	★	•	★	★	★	★	★
Berlin	Case 4	★	•	★	★	★	★	★
Ostersund	Case 2	★	•	★	★	★	★	★
Ostersund	Case 3	★	•	★	★	★	★★	★
Ostersund	Case 4	★	•	★	★	★	★★	★
Montreal	Case 2	★	•	★	★	★	★	★
Montreal	Case 3	★	•	★	★	★	★	★
Montreal	Case 4	★	•	★	★	★	★	★
Riyadh	Case 2	★	•	★	★★	★	★	★
Riyadh	Case 3	★★	•	★	★★	★★	★	★
Riyadh	Case 4	★★★	•	★	★★	★★	★★	★
Bangkok	Case 2	★	•	★	★	★	★	★
Bangkok	Case 3	★★	•	★	★	★★	★	★
Bangkok	Case 4	★★★	•	★	★	★★	★★	★

The implementation of the SP2 solution (free cooling) shows a negative impact in almost all cases and climate zones, with an increase in energy, except in Lisbon, which shows an energy reduction (13%). This underscores the importance of sufficient diurnal temperature amplitude for effective free cooling, requiring a climatic and architectural analysis for its implementation [42].

The implementation of the SP3 solution (increased roof thickness) shows moderate performance (★) in all cases and climate zones, with maximum performance (★★) in case 4 in Lisbon. The results show the stability and reliability of this solution as a complementary strategy. This results from reduced conductive heat transfer through the roof, moderating both heating and cooling loads [15].

The use of the SP4 solution (green roof) shows satisfactory results in improving energy efficiency in the various cases and locations. In hot and moderate climates, such as Lisbon and Riyadh, it shows maximum performance (★★★) and (★★★) in case 4, respectively, demonstrating the solution's effectiveness in promoting thermal regulation [28]. This phenomenon occurs due to evapotranspiration and shading, which reduces roof surface temperatures and decreases cooling loads. In colder climates, the performance is more modest (★), as heating dominates energy demand.

The SP5 solution (shading devices) has moderate performance, achieving its best results in hot climates such as Bangkok and Riyadh and in moderate climates such as Lisbon. The use of various shading techniques reduces the retention of direct solar gains, lowers cooling demand, and maintains indoor comfort [24,45].

The SP6 solution (increased wall thickness) has a positive impact on reducing energy needs for heating in cold climates such as Östersund and Montreal (★★). However, in warmer climates (★), the results obtained are more moderate. Thus, increasing the wall thickness increases the opaque envelope's thermal resistance, limiting winter heat losses and summer solar gains [15].

The SP7 solution (reduced glazing area) performs uniformly in all cases and zones, with maximum performance in temperate climates such as Lisbon (★★). Reducing the area of glazing can reduce thermal fluxes through radiation and conduction, but it also affects natural lighting and ventilation. However, despite modest results, reducing the glazing area has proven consistent and reliable [46].

4.11. Summary of Results

The results clearly demonstrate that the effectiveness of passive design strategies depends heavily on the climatic context.

In hot climates (Riyadh and Bangkok), strategies such as increasing thermal mass, incorporating shading devices, and implementing green roofs yielded the greatest reductions in cooling demand. These effects result from thermal inertia, shading, and evapotranspiration [46].

In temperate climates (Lisbon), a combination of enhanced thermal mass, improved wall insulation, and green roof systems provided balanced improvements in both heating and cooling efficiency, leveraging thermal storage, conductive resistance, and surface cooling mechanisms.

In cold climates (Östersund, Montreal, and Berlin), increasing the insulation of walls and roofs, coupled with a reduction in glazing area, proved most effective in minimizing heating energy consumption by limiting conductive and radiative heat losses [15].

Based on the data, it can be concluded that there is no universally ideal passive strategy and that a combination of strategies is needed to achieve the greatest potential for energy efficiency and thermal performance. The results highlight the importance of implementing design strategies that consider the climate when designing energy-efficient buildings, both for current and future climate scenarios [24,28].

The results obtained in this study are consistent with the trends reported in previous research. For instance, the energy savings achieved through enhanced thermal mass (up to 85–96% reduction in cooling demand in temperate climates) are comparable to those found by Kokatnur et al. [15], who reported 80–90% improvement in thermal stability with high-inertia materials. Similarly, the effectiveness of green roofs in reducing cooling loads (up to 44% in Berlin and 34–36% in Lisbon) aligns with the findings of Zhang et al. [11] and Jia et al. et al. [28], who observed cooling reductions between 30–45% in comparable climates. In hot climates, the performance of shading devices observed in Riyadh and Bangkok (up to 32% reduction in cooling energy) agrees with Palmero-Marrero & Oliveira [24], emphasizing the relevance of solar control in tropical regions. Conversely, the limited efficiency of night ventilation (SP2) in most cities is consistent with Artmann et al. [45], who noted that the potential for free cooling is highly dependent on large diurnal temperature ranges. Overall, the comparison demonstrates that the simulated passive strategies exhibit comprehensive performance levels and, in certain cases, are superior to those described in the literature, confirming the robustness of the modeling framework. This integrated analysis shows that passive thermal design is an efficient climate-adaptation solution for buildings facing future environmental conditions.

5. Conclusions

This article evaluates the performance of seven passive solutions through dynamic simulations using the OpenStudio and EnergyPlus simulation engines. The analysis includes the evaluation of solutions in a model building, in various climate and time scenarios, making it possible to recognize which strategies are best suited to reducing the effects of thermal extremes and reducing energy consumption. The main conclusions of the study are summarized below for greater clarity and emphasis:

1. The results showed that implementing the solution of increasing the thermal mass leads to the best performance, making it possible to reduce energy loads for heating and cooling in various contexts, particularly in hot and temperate climates.
2. The natural ventilation solution, SP2, on the other hand, had a negative impact in the various contexts, essentially when there is a reduced temperature range between day and night.
3. The solutions for improving thermal insulation, increasing the thickness of the roof (SP3) and walls (SP6), have shown considerable performance, especially in cold climates such as Östersund and Montreal.
4. The implementation of the green roof solution (SP4) has shown maximum effectiveness in hot and humid climates such as Riyadh and Bangkok, where it reduces energy needs for cooling due to the shading and evapotranspiration effect.
5. On the other hand, the implementation of solutions that promote solar control, such as external shading (SP5) and reducing the glazing area (SP7), makes it possible to reduce temperatures in climates with high radiation. The effectiveness of this type of solution varies according to solar radiation intensity and climatic conditions.

In short, the results obtained show that the effectiveness of passive solutions depends on the climatic context and the time scenario considered, and that it is possible to combine different solutions to maximize thermal benefits. A rigorous approach must therefore be taken at the design stage to significantly increase buildings' thermal resilience, mitigating the impacts of heat waves and intense cold. This study, therefore, enables the evaluation of the use of passive solutions to adapt buildings to the thermal extremes caused by climate change, thereby promoting energy-efficient, sustainable environments. The method used demonstrates the functionalities of energy simulation tools, providing an approach for energy renovation policies, climate adaptation strategies, and bioclimatic architecture practices. Future studies could examine buildings with different uses and configurations and explore how different passive strategies affect their energy performance.

6. Recommendations

In future work, it is advisable to explore integrated solutions that combine economic and environmental variables, apply them to different building types (e.g., offices, schools, and hospitals), and investigate other technologies. The inclusion of both economic and environmental factors is also essential for assessing the cost–benefit ratio and the sustainability of each approach. Future studies should also conduct detailed economic feasibility and cost–benefit analysis of the most effective passive strategy combinations identified in this work, to evaluate their practical applicability and support evidence-based decision-making for policymakers and practitioners.

Furthermore, research on integrating passive and active technologies can provide valuable insights to achieve higher energy efficiency and improved thermal performance. In the future, given the various climate uncertainties, the adoption of passive solutions will represent a fundamental strategy for enhancing the thermal and energy performance of buildings.

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Appendix A

Table A1. Construction Parameters of Walls/Roof.

Parameter (Walls)	Interior Panel—Gypsum	Metal Structure (LSF)	Insulation—Rock Wool	Exterior Panel—OSB
Roughness	Smooth	Very Smooth	Very Smooth	Medium Rough
Thickness (m)	0.012	0.001	0.04	0.015
Thermal Conductivity (W/m·K)	0.25	50	0.032	0.13
Density (kg/m^3)	800	7850	80	600
Specific Heat (J/kg·K)	800	500	800	1200
Thermal Absorptance	0.9	0.9	0.9	0.9
Solar Absorptance	0.7	0.7	0.7	0.7
Visible Absorptance	0.7	0.7	0.7	0.7
Parameter(Roof)	Interior Panel—Gypsum	Metal Structure (LSF)	Insulation—Rock Wool	Exterior Panel—OSB
Roughness	Smooth	Very Smooth	Very Smooth	Medium Rough
Thickness (m)	0.012	0.001	0.04	0.015
Thermal Conductivity (W/m·K)	0.25	50	0.032	0.13
Density (kg/m^3)	800	7850	80	600
Specific Heat (J/kg·K)	800	500	800	1200
Thermal Absorptance	0.9	0.9	0.9	0.9
Solar Absorptance	0.7	0.7	0.7	0.7
Visible Absorptance	0.7	0.7	0.7	0.7

Table A2. Construction Parameters of Floor/Door.

Property (Floor)	**Reinforced Concrete Floor**		
Roughness	Medium Smooth		
Thickness (m)	0.10		
Conductivity (W/m·K)	1.4		
Density (kg/m^3)	2200		
Specific Heat (J/kg·K)	840		
Thermal Absorptance	0.9		
Solar Absorptance	0.7		
Visible Absorptance	0.7		
Property (Door)	Aluminium (opaque)	Thermal Insulation (PU ~3 cm)	Aluminium (opaque)
Roughness	Smooth	Smooth	Smooth
Thickness (m)	0.025	0.030	0.025
Conductivity (W/m·K)	200	0.022	200
Density (kg/m^3)	2700	40	2700
Specific Heat (J/kg·K)	900	1500	900
Thermal Absorptance	0.5	0.15	0.5
Solar Absorptance	0.4	0.15	0.4
Visible Absorptance	0.4	0.15	0.4

Table A3. Construction Parameters of Window.

Parameter	**CLEAR 4 MM**	**AIR 12 MM**	**CLEAR 4 MM**
Material Type	Glass	Air	Glass
Thickness (m)	0.004	0.0127	0.004
Solar Transmittance at Normal Incidence	0.775	-	0.775
Solar Reflectance (Front) at Normal Incidence	0.071	-	0.071
Solar Reflectance (Back) at Normal Incidence	0.071	-	0.071
Visible Transmittance at Normal Incidence	0.881	-	0.881
Visible Reflectance (Front)	0.080	-	0.080
Visible Reflectance (Back)	0.080	-	0.080
Infrared Transmittance	0.000	-	0.000
Infrared Emissivity (Front)	0.840	-	0.840
Infrared Emissivity (Back)	0.840	-	0.840
Thermal Conductivity (W/m·K)	0.900	-	0.900
Dirt Correction Factor (Solar/Visible Transmission)	1.000	-	1.000

Table A4. Thermal Mass Increase Cases (SP1).

Characteristic	Case 1—Gypsum Interior Panel	Case 2—M11 Lightweight Concrete (100 mm)	Case 3—1IN Stucco Interior Panel	Case 4—Normalweight Concrete (100 mm)
Thickness (m)	0.012	0.2544	0.3321	0.1109
Thermal Conductivity (W/m·K)	0.25	0.53	0.6918	2.3105
Density (kg/m^3)	800	1280	1858	2322
Specific Heat (J/kg·K)	800	840	837	833
Thermal Absorptance	0.9	0.9	0.9	0.9
Solar Absorptance	0.7	0.5	0.92	0.7
Visible Absorptance	0.7	0.5	0.92	0.7
Roughness	Smooth	Medium Rough	Smooth	Medium Rough

Table A5. Night Ventilation Cases (SP2).

Characteristic	Case 1	Case 2	Case 3	Case 4
Design Flow Rate (m^3/s)	0.5	7.826	15.652	23.478
Flow per Space Floor Area (m^3/s·m^2)	0.0016	0.025	0.05	0.075
Flow per Space Floor Area (alternative) (m^3/s·m^2)	0.00032	0.005	0.01	0.015
Flow per Exterior Surface Area (m^3/s·m^2)	0.000052	0.000814	0.001629	0.002443

Table A6. Insulation Thickness Variation in Roof (SP3).

Characteristic	Case 1 (0.05 m)	Case 2 (0.0625 m)	Case 3 (0.075 m)	Case 4 (0.0875 m)
Thickness (m)	0.05	0.0625	0.075	0.0875
Thermal Conductivity (W/m·K)	0.032	0.032	0.032	0.032
Density (kg/m^3)	80	80	80	80
Specific Heat (J/kg·K)	800	800	800	800
Thermal Absorptance	0.9	0.9	0.9	0.9
Solar Absorptance	0.7	0.7	0.7	0.7
Visible Absorptance	0.7	0.7	0.7	0.7
Roughness	Very Smooth	Very Smooth	Very Smooth	Very Smooth

Table A7. Green Roof Properties (SP4).

Vegetation Layer				
Property	Case 1—No Green Roof	Case 2—Light	Case 3—Intermediate	Case 4—Robust
Thickness (m)	0.05	0.05	0.25	0.40
Thermal Conductivity (W/m·K)	0.032	0.1	0.18	0.25
Density (kg/m^3)	80	300	700	1000

Table A7. *Cont.*

Vegetation Layer				
Specific Heat (J/kg·K)	800	900	1200	2000
Thermal Absorptance	0.9	0.8	0.9	0.95
Solar Absorptance	0.7	0.4	0.6	0.75
Visible Absorptance	0.7	0.4	0.6	0.75
Roughness	Very Smooth	Smooth	Smooth	Smooth
Substrate Layer				
Property		Case 2—Light	Case 3—Intermediate	Case 4—Robust
Thickness (m)		0.05	0.3	0.5
Thermal Conductivity (W/m·K)		0.1	0.6	1.5
Density (kg/m^3)		800	1600	2700
Specific Heat (J/kg·K)		600	1400	2200
Thermal Absorptance		0.85	0.9	0.95
Solar Absorptance		0.3	0.5	0.7
Visible Absorptance		0.3	0.5	0.7
Roughness		Medium Smooth	Medium Rough	Medium Rough
Drainage/Filter Layer				
Property		Case 2	Case 3	Case 4
Thickness (m)		0.02	0.02	0.02
Thermal Conductivity (W/m·K)		0.3	0.3	0.3
Density (kg/m^3)		1000	1000	1000
Specific Heat (J/kg·K)		1500	1500	1500
Thermal Absorptance		0.85	0.85	0.85
Solar Absorptance		0.4	0.4	0.4
Visible Absorptance		0.4	0.4	0.4
Roughness		Medium Rough	Medium Rough	Medium Rough
Waterproofing/Anti-root Layer				
Property		Case 2	Case 3	Case 4
Thickness (m)		0.005	0.005	0.005
Thermal Conductivity (W/m·K)		0.2	0.2	0.2
Density (kg/m^3)		900	900	900
Specific Heat (J/kg·K)		1400	1400	1400
Thermal Absorptance		0.9	0.9	0.9
Solar Absorptance		0.5	0.5	0.5
Visible Absorptance		0.5	0.5	0.5
Roughness		Smooth	Smooth	Smooth

Table A8. Shading Systems Properties (SP5).

Material Properties	Case 1—No Shading	Case 2—Roller Blind	Case 3—External Shutter (PVC)	Case 4—External Slatted Blind (Aluminium)
Material	None	Fabric	PVC	Aluminium
Slat Orientation	-	-	Horizontal (E/W)	Horizontal (South)
Slat Width (m)	-	-	0.04	0.09
Slat Separation (m)	-	-	0.045	0.07
Slat Thickness (m)	-	0.005	0.005	0.005
Slat Angle (deg)	-	0	0	60/90
Slat Conductivity (W/m·K)	-	0.17	0.17	205
Slat Beam Solar Transmittance	-	0	0	0
Front Side Beam Solar Reflectance	-	0.6	0.6	0.7
Back Side Beam Solar Reflectance	-	0.5	0.5	0.6
Diffuse Solar Transmittance	-	0	0	0
Front Side Diffuse Solar Reflectance	-	0.6	0.6	0.7
Back Side Diffuse Solar Reflectance	-	0.5	0.5	0.6
Beam Visible Transmittance	-	0	0	0
Front Side Beam Visible Reflectance	-	0.6	0.6	0.7
Back Side Beam Visible Reflectance	-	0.5	0.5	0.6
Diffuse Visible Transmittance	-	0	0	0
Front Side Diffuse Visible Reflectance	-	0.6	0.6	0.7
Back Side Diffuse Visible Reflectance	-	0.5	0.5	0.6
Infrared Hemispherical Transmittance	-	0	0	0
Front Side Infrared Hemispherical Emissivity	-	0.9	0.9	0.05
Back Side Infrared Hemispherical Emissivity	-	0.9	0.9	0.05
Blind to Glass Distance (m)	-	0.07	0.1	0.05
Blind Top Opening Multiplier	-	0.5	0.5	0
Blind Bottom Opening Multiplier	-	0	0	0
Blind Left Side Opening Multiplier	-	0.5	0.5	0
Blind Right Side Opening Multiplier	-	0.5	0.5	0
Minimum Slat Angle (deg)	-	0	0	0
Maximum Slat Angle (deg)	-	180	180	90
Thermal Transmittance	-	-	-	0
Shade Thickness (m)	-	-	-	0.005
Shade to Glass Distance (m)	-	-	-	0.05
Top Opening Multiplier	-	-	-	0
Bottom Opening Multiplier	-	-	-	0
Left Side Opening Multiplier	-	-	-	0
Right Side Opening Multiplier	-	-	-	0
Airflow Permeability	-	-	-	0

Table A9. Insulation Thickness Variation in Walls (SP6).

Characteristic	Case 1	Case 2	Case 3	Case 4
Thickness (m)	0.04	0.05	0.06	0.07
Thermal Conductivity (W/m·K)	0.032	0.032	0.032	0.032
Density (kg/m^3)	80	80	80	80
Specific Heat (J/kg·K)	800	800	800	800
Thermal Absorptance	0.9	0.9	0.9	0.9
Solar Absorptance	0.7	0.7	0.7	0.7
Visible Absorptance	0.7	0.7	0.7	0.7
Roughness	Very Smooth	Very Smooth	Very Smooth	Very Smooth

Table A10. Window Dimension Variation (SP7).

Dimension	Initial—Case 1	Case 2—10% Reduction	Case 3—20% Reduction	Case 4—30% Reduction
East/West Window Height (m)	0.6	0.5692	0.5367	0.5020
East/West Window Width (m)	0.6	0.5692	0.5367	0.5020
South Window Height (m)	0.6	0.5692	0.5367	0.5020
South Window Width (m)	1.3	1.2333	1.1628	1.0877

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