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ENERGETIC ANALYSIS IN THE APPLICATION OF PASSIVE SOLAR STRATEGIES IN RESIDENTIAL BUILDING USING *ENERGYPLUS*

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Agora que o silêncio é um mar sem ondas,
E que nele posso navegar sem rumo,
Não respondas
Às urgentes perguntas
Que te fiz.
Deixa-me ser feliz
Assim,
Já tão longe de ti como de mim.

Miguel Torga

Agradecimentos

A Ti, que me colocas vírgulas enquanto vou em narração pelo que sinto meu, sou Teu eternamente, Ámen.

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Obrigado!

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Abstract

This study evaluates passive solar strategies to enhance thermal comfort and reduce energy demand in residential buildings in three Portuguese cities (Lisbon, Évora, and Bragança) each representing different Mediterranean climate profiles. Simulations were conducted using the *EnergyPlus* engine via *OpenStudio*, enabling detailed analysis of thermal behaviour and energy consumption under various passive design scenarios. The strategies assessed include building orientation, shading devices, window-to-wall ratio adjustments, natural ventilation rates, and improvements to wall and roof insulation.

In the context of climate change, which is increasing average temperatures and intensifying heatwaves, the demand for cooling energy is rising, placing added pressure on building energy performance. The results show that reducing the U-value of opaque elements consistently lowers energy loads, reinforcing the importance of an efficient thermal envelope. Among the strategies tested, natural ventilation and optimized glazing ratios had the most substantial impact on reducing the energy loads.

A final combined model, incorporating the best-performing measures, demonstrated major reductions in energy demand: 60% in Lisbon, 62% in Évora, and 37% in Bragança, relative to their respective base cases. These findings highlight the effectiveness of a comprehensive passive design approach in reducing mechanical energy use and promoting energy-efficient, climate-resilient residential architecture.

Keywords: Passive solar systems, thermal comfort, *EnergyPlus*, energy efficiency, U-value, mediterranean climate, climate change, residential simulation.

Resumo

Este estudo avalia estratégias solares passivas para melhorar o conforto térmico e reduzir a procura energética em edifícios residenciais em três cidades portuguesas (Lisboa, Évora e Bragança), cada uma representando diferentes perfis climáticos. As simulações foram realizadas com o software *EnergyPlus* através do *OpenStudio*, permitindo uma análise detalhada do comportamento térmico e do consumo de energia sob diversos cenários de conceção passiva. As estratégias avaliadas incluem a orientação do edifício em relação ao norte, dispositivos de sombreamento, ajustes na relação de percentagem de envidraçado nas fachadas, taxas de ventilação natural e melhorias no isolamento de paredes e coberturas.

No contexto das alterações climáticas, que estão a aumentar as temperaturas médias e a intensificar as ondas de calor, a procura por energia para arrefecimento tem vindo a crescer, exercendo maior pressão sobre o desempenho energético dos edifícios. Os resultados mostram que a redução do valor de U dos elementos opacos (paredes e cobertura) reduz consistentemente as cargas energéticas, reforçando a importância de uma envolvente térmica eficiente. Entre as estratégias testadas, a ventilação natural e a otimização da área envidraçada revelaram-se as mais impactantes no valor energético final.

Um modelo final combinado, incorporando as soluções com melhor desempenho, demonstrou reduções significativas na carga energética: 60% em Lisboa, 62% em Évora e 37% em Bragança, relativamente aos respetivos modelos base. Estes resultados evidenciam a eficácia de uma abordagem integrada da utilização de estratégias solares passivas na redução do uso de energia mecânica e na promoção de uma arquitetura residencial eficiente e resiliente ao clima.

Palavras-chave: Sistemas solares passivos, conforto térmico, *EnergyPlus*, eficiência energética, valor de U, clima mediterrânico, alterações climáticas, simulação residencial.

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Nomenclature

Acronyms

ACH	Air changes per hour
ASHRAE	American society of heating, refrigerating and air conditioning engineers
DDY	Design Day file
EPS	Expanded polystyrene
EPW	*EnergyPlus* Weather format
HVAC	Heating, ventilation and air conditioning
NZEB	Nearly zero energy building
WWR	Window-to-wall Ratio

Latin Symbols

R	Thermal resistance
U	Overall heat transfer coefficient
k	Thermal conductivity
t	Thickness

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1 Introduction

Climate change represents one of the challenges of our time, with global warming leading to more intense, frequent, and prolonged heatwaves. This growing climatic pressure significantly affects the thermal performance of buildings and energy consumption patterns, especially in regions characterized by hot summers and large temperature variations. In this context, ensuring thermal comfort inside dwellings without over-reliance on mechanical systems has become both an environmental necessity and a public health concern as pointed by (Z. Y. Chen et al., 2025).

Portugal, like many Mediterranean countries, is experiencing a gradual increase in average temperatures and a growing number of extreme weather events (Espinosa & Portela, 2025). These shifts amplify issues such as urban overheating and energy poverty, particularly in older building stocks that lack modern thermal insulation or climate-responsive design. In Mediterranean climates, thermal discomfort is often aggravated by poor building envelope performance, inadequate ventilation, and high dependence on active cooling systems, especially in summer (Semprini et al., 2017).

The European Green Deal and national regulations have increasingly emphasized the transition toward energy-efficient building practices. Within this framework, passive solar design offers a promising path forward, leveraging climate-responsive strategies such as building orientation, window sizing, thermal insulation, shading, and natural ventilation to reduce mechanical energy needs while maintaining acceptable indoor conditions (European Union, 2024).

With this setting in mind, this work focuses on evaluating the energetic and thermal performance of passive solar strategies in single-family residential buildings located in three distinct Portuguese cities – Lisbon, Bragança and Évora - each representing a different climate zone. Using *EnergyPlus* through the *OpenStudio* interface, dynamic simulations were conducted to analyse the heating and cooling loads and indoor temperature behaviour under various design scenarios. The results were analysed and discussed to check their reliability and effectiveness.

The general objective of this study is to understand how passive solar strategies can optimize the thermal behaviour of dwellings and reduce energy loads, especially for air conditioning. More specifically, the work aims to:

- Simulate typical single-family residential buildings under current climatic conditions in Portugal;
- Test the impact of passive design strategies individually, such as building orientation, shading devices, wall and roof improvements, natural ventilation, and window-to-wall ratio (WWR);
- Develop a combined optimized model for each location by integrating the best-performing solutions;
- Quantify the reduction in mechanical energy demand achieved through passive strategies;
- Reflect on the applicability and limitations of these solutions in the reduction of energy and achieving thermal comfort dwellings.

Firstly, an extensive literature review was carried out to establish the foundation for this research, as presented in Chapter 2. It explores core concepts of thermal comfort, passive solar

strategies, and energy efficiency in residential buildings, with particular focus on the building sector's energy impact. A historical overview of passive solutions is provided, alongside their evolution and practical application. The review also considers the European and Portuguese regulatory contexts.

The methodology, presented in Chapter 3, outlines the full approach used to conduct this study. It begins with the characterization of climatic conditions for the three selected Portuguese cities. This is followed by the definition of the base case models, including architectural layouts, construction materials, and thermal properties. The chapter also details the simulation setup using *EnergyPlus* via *OpenStudio*, along with the internal load definitions and boundary conditions. Finally, it introduces the different passive solar strategies tested - such as orientation, shading, ventilation, and wall and roof modifications, as well as the different alternatives within them.

The results, presented in Chapter 4, include the thermal characterization of the base buildings in each location and assess the performance of the passive solutions tested individually. Simulations evaluate both heating and cooling energy needs, showing how passive strategies impact the building's ability to maintain thermal comfort. A final combined model integrates the most effective parameters for each location, highlighting the overall energy savings potential. This chapter offers a comparative perspective on the efficiency of each solution, providing practical insights for improving building performance through passive design.

Finally, Chapter 5 presents the main conclusions of the study, summarizing the key findings regarding the effectiveness of passive solar strategies in improving energy performance in residential buildings. It also outlines potential areas for future research, suggesting ways the study could be expanded or refined to support more efficient and climate-responsive building design.

United Nations' Sustainable Development Goals (SDGs)

The 2030 Agenda for Sustainable Development, adopted unanimously by all United Nations Member States in 2015, outlines a comprehensive framework aimed at addressing global challenges and fostering sustainable development worldwide. At the heart of this agenda are the 17 Sustainable Development Goals (SDGs), which serve as a universal call to action to end poverty, protect the planet, and ensure prosperity for all by 2030.

This research contributes to several of these goals by promoting energy-efficient residential design through passive solar strategies. By reducing reliance on mechanical heating and cooling systems, the study supports sustainable energy consumption, responsible construction practices, and climate action. The optimization of building elements such as orientation, insulation, window-to-wall ratio, and natural ventilation aims to reduce energy demand and improve thermal comfort, particularly in response to climate change.

The following table outlines the specific SDG targets supported by this study, demonstrating its role in advancing sustainable development through energy-conscious design and climate-adaptive building practices.

SDG	Target	How this project impacts:
7	3	Improves energy efficiency in buildings by applying passive solar solutions, reducing reliance on non-renewable energy sources.
7	A	Supports the transition to sustainable energy systems by promoting low-energy building strategies.
11	6	Contributes to reducing the environmental impact of urban housing by optimizing thermal performance through design.
11	b	Strengthens local planning capacity by demonstrating climate-resilient design strategies applicable to Portuguese regions.
12	2	Encourages sustainable use of construction materials by promoting envelope design improvements that reduce energy waste.
12	8	Promotes awareness of sustainable building practices by showcasing passive design strategies that reduce energy consumption and environmental impact in residential buildings.
13	1	Supports climate change mitigation by promoting building designs that enhance thermal comfort and energy efficiency in response to rising temperatures.
13	3	Enhances education and awareness on climate-resilient design by demonstrating the impact of passive solutions in reducing energy demand and improving indoor comfort under climate stress.

2 Literature Review

2.1 Energy in Buildings

2.1.1 Energy Consumption

The building sector is one of the largest consumers of energy worldwide, with residential buildings alone accounting for 40% of global energy consumption (Kaloop et al., 2025). Given the long lifespan of buildings and their extensive energy needs in form of heating, ventilation, and air conditioning (HVAC), researchers have increasingly focused on improving energy performance (Kaloop et al., 2025). To minimize energy losses in future buildings, innovative and sustainable design strategies must be integrated from the early stages of construction, emphasizing passive energy solutions to enhance efficiency and reduce environmental impact.

According to the International Renewable Energy Agency (IRENA, 2022), building-related energy use accounts for nearly half of global energy-related carbon dioxide emissions, surpassing electricity generation (20%) and transportation (30%). Fossil fuels, including coal, oil, and natural gas, remain the primary contributors, alongside the unsustainable use of biomass. The demand for energy in buildings, particularly for cooling, is expected to rise significantly in the coming decades. Currently, only one-third of the population in hot climates has access to mechanical cooling systems, but this number is projected to grow rapidly (IRENA, 2022). Additionally, rising global temperatures, with expected increases of 1.5°C or more by 2035, will further drive the expansion of cooling demand (Scoccimarro et al., 2023).

However, the growing reliance on mechanical cooling systems poses a major challenge to European decarbonization goals. Since most of these systems are powered by electricity, as it can be seen in figure 2.1, they increase greenhouse gas emissions, creating a vicious cycle (European Union, 2024). These electrified systems are not only environmentally detrimental but also economically burdensome for consumers (IEA, 2023).

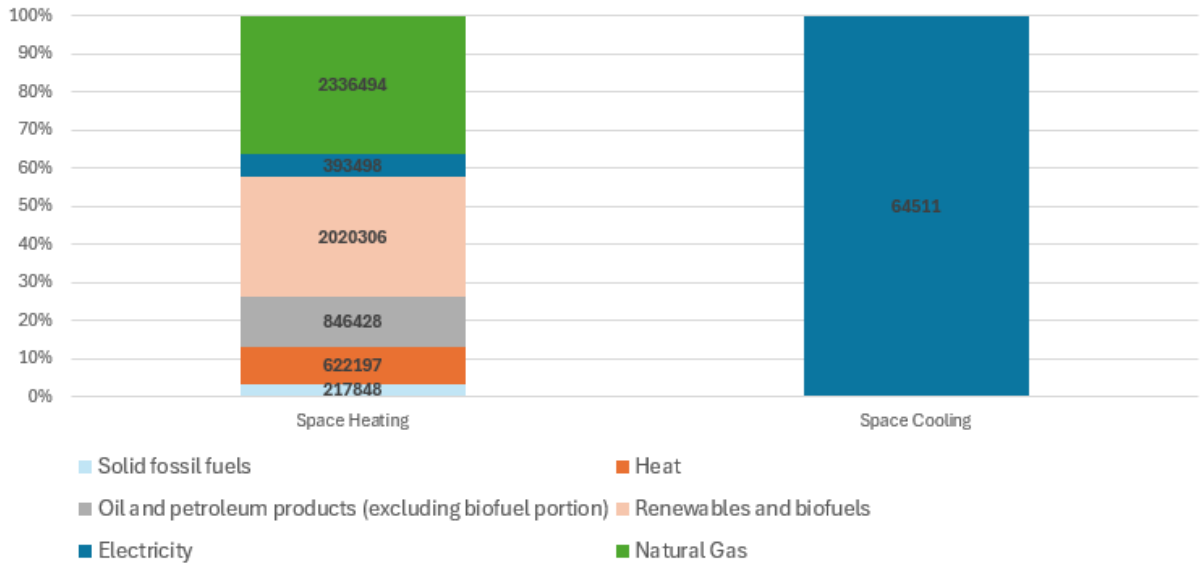


Figure 2.1 - Final energy consumption in the residential sector by use, in terajoules, EU, 2022.

(Adapted from: Eurostat, 2024, "Energy Consumption in households", https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_consumption_in_households)

2.1.2 Energy Policies and the European Green Deal

The European Green Deal has set ambitious targets to decarbonize the building sector, recognizing that more than 75% of EU buildings are not energy efficient (European Commission, 2020). To address this, the European Commission has introduced policies such as:

- Energy Performance of Buildings Directive – Encourages energy efficiency improvements and the use of renewable energy in buildings.
- Renewable Energy Directive – Supports the transition to cleaner energy sources in residential and commercial buildings.
- Renovation Wave Strategy – Aims to modernize and decarbonize the EU's building stock by increasing renovation rates and phasing out fossil fuels in heating and cooling.

By 2030, all new buildings must be zero-emission, and by 2050, fossil fuels in heating and cooling must be fully phased out (European Commission, 2020). However, the continued reliance on electrified cooling systems presents a challenge to achieving these goals. While mechanical cooling is expected to increase globally (Scoccimarro et al., 2023), Europe must prioritize passive cooling strategies and renewable energy integration to reduce energy consumption and emissions (European Commission, 2020).

2.1.3 Nearly Zero-Energy Buildings (NZEB) and the Challenge of Existing Buildings

A Nearly Zero-Energy Building (NZEB) is a building with very high energy performance, where the small amount of energy required is covered mostly by renewable sources produced on-site or nearby (European Union, 2024). The European policy goal is to minimize energy consumption through high-efficiency design, insulation, and passive strategies while integrating renewable energy sources such as solar, wind, or biomass. This standard is crucial for achieving climate neutrality by 2050 (European Union, 2024).

However, a significant challenge remains: the majority of existing buildings were constructed before energy efficiency regulations were in place. Approximately 60% of buildings in Europe were built between the 1950s and 1980s, right after the World War II, and in Mediterranean regions (Portugal, Spain, Greece, Cyprus, etc.), this number increases to 70-75% (Semprini et al., 2017), as it can be seen in figure 2.2. Since energy-efficient design was not a priority during this period, these buildings are highly inefficient, leading to higher energy consumption for heating and cooling (Semprini et al., 2017).

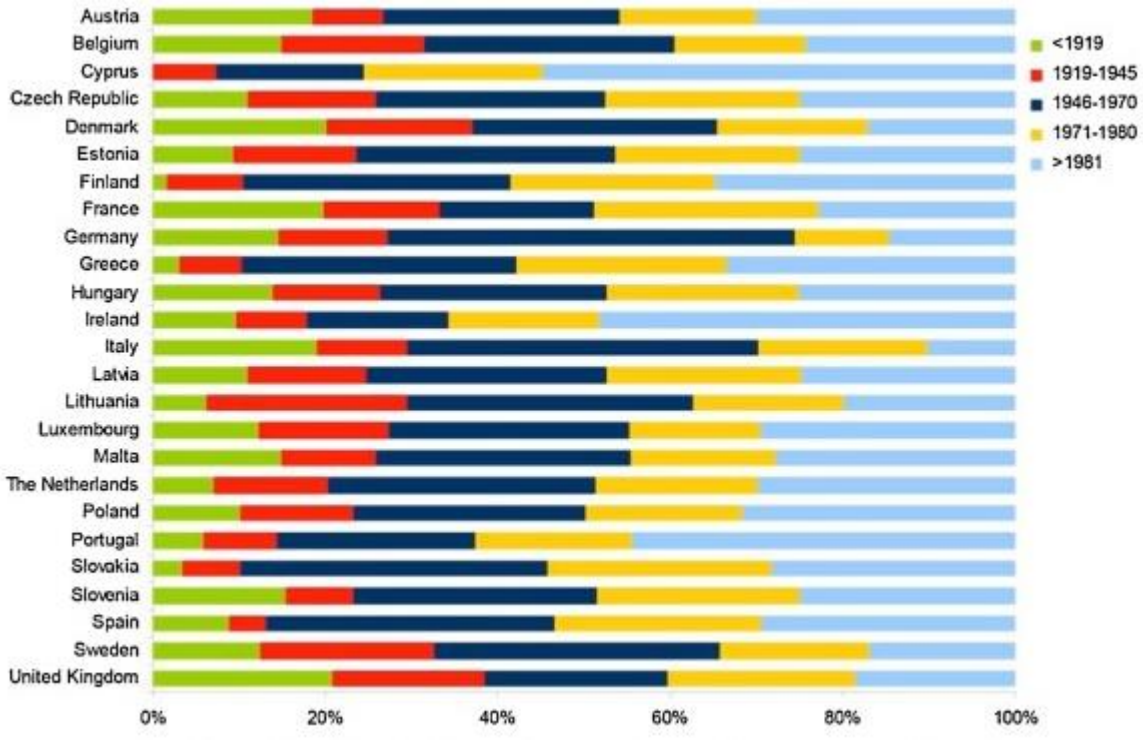


Figure 2.2 - Age distribution of housing stock.

(Giovanni Semprini, Riccardo Gulli, Annarita Ferrante, Deep regeneration vs shallow renovation to achieve nearly Zero Energy in existing buildings: Energy saving and economic impact of design solutions in the housing stock of Bologna, Energy and Buildings, Volume 156, 2017, Pages 327-342, ISSN 0378-7788, https://doi.org/10.1016/j.enbuild.2017.09.044

2.1.4. Energy Poverty and Its Impact on Thermal Comfort

The inefficiency of aging buildings directly impacts the well-being of residents, particularly in mediterranean climate regions. Winters are generally mild, yet poorly insulated buildings remain cold indoors, making heating costly and inefficient. Conversely, the harsh summer heat leads to high air conditioning demand, requiring systems to run for long hours to maintain comfort (Alba-Rodríguez et al., 2021).

Additionally, this type of construction contributes to energy poverty in these regions (Alba-Rodríguez et al., 2021). Energy poverty refers to the inability of a household to afford sufficient energy to meet basic needs such as heating, cooling, and lighting. This issue arises due to high energy costs, low household incomes, and inefficient buildings, preventing residents from maintaining adequate thermal comfort. Beyond physical discomfort, energy poverty has broader consequences, including negative impacts on health, well-being, and social exclusion. Exposure to cold or excessive heat can lead to respiratory and cardiovascular diseases, while high energy bills create financial stress and social exclusion (Guevara et al., 2023).

Portugal ranks as the fifth worst country in the European Union in terms of households unable to afford adequate heating, with approximately 18% of the population affected by energy poverty (European Commission, 2023), as it can be seen in figure 2.3. Recognizing the severity of this issue, the European Union's energy policies, particularly the Internal Market for Electricity Directive (2019/944), require all member states to assess and address energy poverty through their National Energy and Climate Plans (NECPs). The Energy Efficiency Directive further emphasizes the need for building renovations and the transition to NZEB, aligning with the Paris Agreement's long-term climate goals (United Nations, 2025).

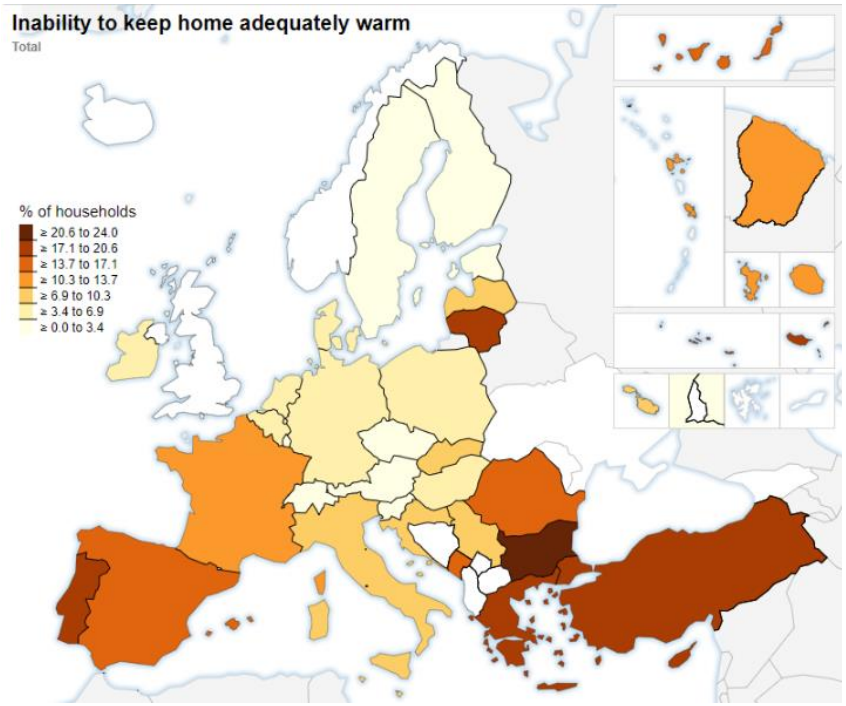


Figure 2.3 - Percentage of the population that cannot afford to keep thermal comfort.

(European Commission, 2021, The ''Inability to keep home adequately warm'' indicator: Is it enough to measure energy poverty? https://energy-poverty.ec.europa.eu/newsroom/news/inability-keep-home-adequately-warm-indicator-it-enough-measure-energy-poverty)

2.1.5 The Energy in Portuguese Households

In Portugal, electricity is the primary energy source for households, accounting for 46.4% of total residential energy consumption (INE, 2020). Other sources include biomass (18.4%), natural gas (12.4%), liquefied petroleum gas (LPG) (16.6%), heating oil (4.1%), and solar thermal energy (2.1%), as it can be seen in figure 2.4.

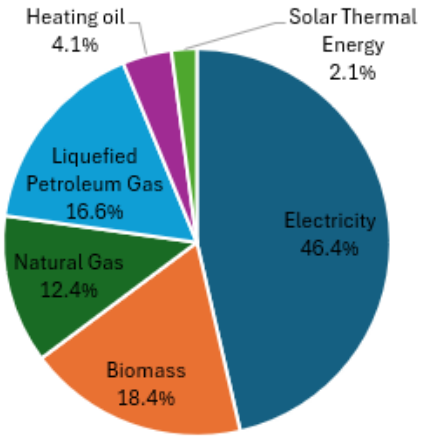


Figure 2.4 - Distribution of energy consumption in household by type of energy, in Portugal.

(Adapted from: INE. (2020). *Inquérito ao Consumo de Energia no setor doméstico* (2021st ed.). www.ine.pt)

Within household consumption, different end-uses contribute to overall energy demand, as can be seen in figure 2.5.

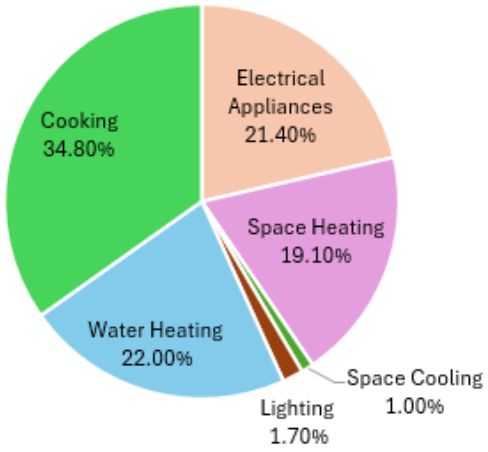


Figure 2.5 - Distribution of energy consumption in household by final use, in Portugal.

(Adapted from: INE. (2020). *Inquérito ao Consumo de Energia no setor doméstico* (2021st ed.). www.ine.pt)

The largest share is allocated to cooking (34.8%), followed by water heating (22.0%) and electrical appliances (21.4%). Space heating accounts for 19.1% of total consumption. Among heating equipment, the electric heater is the most used device, present in 64.8% of households, with an average of 1.6 units per dwelling (INE, 2020). The distribution of domestic energy consumption in households by final use and by type of energy can be seen in the figure 2.6.

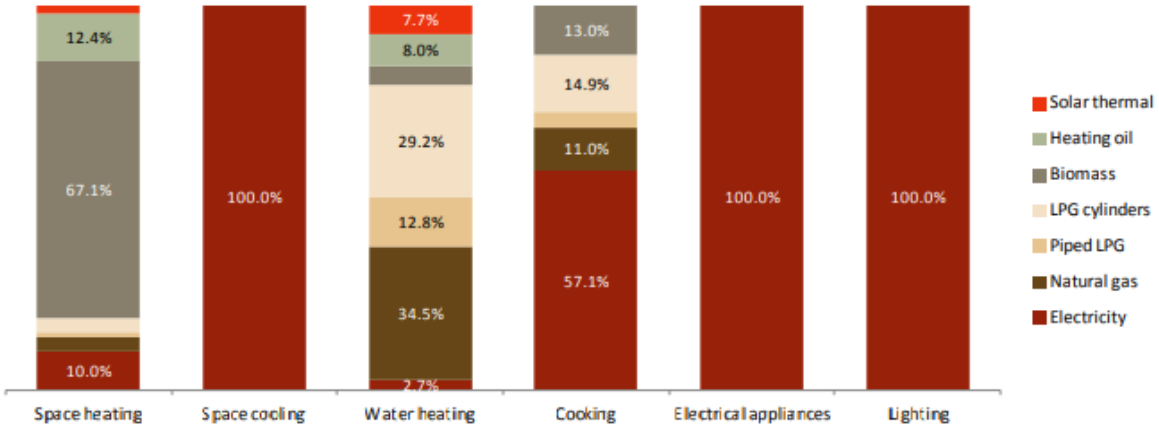


Figure 2.6 - Distribution of Energy consumption in household by final use and by type of energy.

(INE. (2020). *Inquérito ao Consumo de Energia no setor doméstico* (2021st ed.). www.ine.pt)

Despite significant energy use for cooling and heating, many Portuguese households struggle with energy poverty. Addressing this issue requires a focus on building efficiency improvements, sustainable design solutions, and the integration of passive solar strategies, which will be the focus of the next section.

2.2 The Passive Solar Approach

2.2.1 Historic overview

In 1859 a theory was published that revolutionized the way biology is viewed today. In that year, the most well-known biologist of all time, Charles Darwin, gave to the world his most important work, the book "The Origin of Species", where he theorized that the better-adapted individuals are more likely to survive and reproduce (Darwin, 1859). In 2017, Anh Tuan Nguyen made the parallelism of the basic theory to the bioclimatic architecture. Since forever, people have improved their residencies and buildings to the climatic zone they are in, with adaptable architecture. The buildings have been evolving just like biology, where the most efficient techniques were applied to achieve the desired results in each unique climatic condition (Nguyen & Reiter, 2017).

From the caves in Cappadocia, Turkey, to the Russian shelters in Alaska or the Japanese well known "Ryokans", all of them have their own characteristics to deal with their own climate adversities. These types of cultural housing techniques are defined as vernacular architecture which is developed by local builders who draw on traditional techniques and locally available materials. Notably, both low-tech and vernacular approaches exhibit a high degree of sustainability and a strong connection to nature, stemming from long-established methods of adapting to the local climate (Widera, 2021).

Allen G. Noble, 2007, pointed a similar vision in his book "Traditional Buildings" where he approached the vernacular architecture evolution and characteristics from different places around the world. Architecture evolved to be as comfortable as possible and for that conserving heat in the cold regions or months in structure was as important as creating heat in first place with fire, as well as getting the interiors as ventilated and colder in hot zones and harsh summers.

In the same book, Allen G. Noble, highlights some of the characteristics considered in diverse climates and zones in the globe. In the log houses of north America, the location of the fireplace and stove served two purposes. Placing the heat source near the door ensured that warmth was delivered right where the greatest heat loss occurred. In addition, positioning the stove by the door minimized the distance needed to carry heavy firewood.

The location of the kitchen withing the dwelling was also a factor. The book makes the case that the kitchen in hot climates was a source of unwanted heat and for that reason was built far from the south part of the house (in the northern hemisphere), to prevent overheating of the other divisions. For cold climates the contrary was verified, the kitchen was normally built in the centre of the house, so every division could take advantage of the heat during the preparation of the meals (Allen G. Noble, 2007). In the figure 2.7, it can be seen a typical 60's house plan from Germany, with the kitchen in the centre.

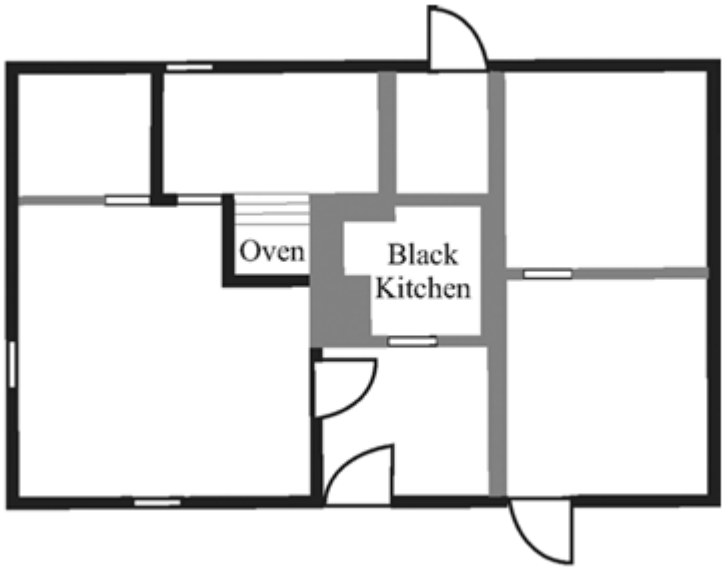


Figure 2.7 - Plan of a black kitchen house from Furstenwald, Germany.

(Allen G. Noble, 2007, "Traditional Buildings")

The ceiling's height often explains its role in temperature regulation. When a ceiling is absent or very high, it permits warm air to rise and accumulate near the roof; conversely, a lower ceiling helps to retain heat. In contrast, Russian settlers in Alaska, facing prolonged cold, insulated their dwellings by filling the space between the ground-floor ceiling and the upper floor of their log houses with sand. For instance, in Turkey, rooms designated for summer use were strategically placed at building corners and arranged in single rows with large windows, thin partitions, high ceilings, and spacious dimensions to maximize cooling ventilation. Conversely, to protect against winter winds and low temperatures, other rooms in the same dwellings were located on upper floors in interior positions, featuring thick, insulating construction and low ceilings. The same is verified in the vernacular architecture of Japan more to southwest zone where the typical Ryokans (figure 2.8) have big movable doors and windows to have a desired ventilation to cope with the hot season (Allen G. Noble, 2007).



Figure 2.8 - Typical "ryokan", the traditional housing from Japan with its big façades for easier ventilation.

(Stefanie Akkerman, 2024, "Unique Features of a Traditional Japanese House", https://blog.japanwondertravel.com/features-of-a-traditional-japanese-house-36728)

For insulation, vernacular architecture has its methods also. Ancient cultures recognized that earth materials - including ice - offered superior insulation compared to wood or metal. For instance, American Plains Indians would pile earth and stones around the base of their tipis to

block cold drafts and anchor the structure against winter winds. In colonial Connecticut, houses were often banked with turf, leaves, or seaweed to conserve warmth, a practice that persists today in rural northern United States, where low bales of hay are used around foundations (Isham & Brown, 1900). Similarly, traditional farmhouses in southern Norway featured low stone walls on the windward side to break the force of prevailing winds and reduce moisture penetration. These early methods underscore the importance of sealing even the smallest openings to effectively retain heat, a principle that remains central in modern insulation practices (Allen G. Noble, 2007).

The ventilation is another vernacular solution applied for a long time. This solution, as far as it is known it has been around since pharaonic era about 5000 years ago and has been perpetuated until today. In the figure 2.9 it can be seen a copy of a papyrus dated from 1583-1292 BC from the *Book of the Dead*, where a possible house with what it is most likely a wind catcher (Nessim et al., 2023).

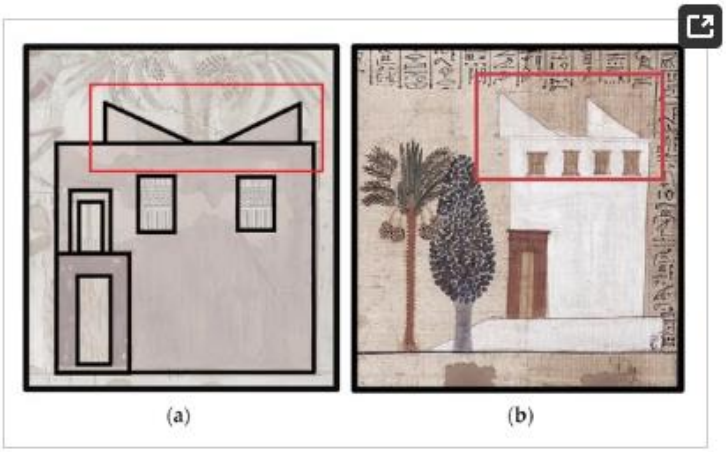


Figure 2.9 - (a) Windcatcher of Pharaonic house of Neb-Amun, (b) *Book of the Dead* showing a building with a wind tower.

(Allen G. Noble, 2007, “Traditional Buildings”)

The contribution of ventilation as a solution as well as the flow of air within the house for hot climates can be demonstrated by the principles of aerodynamics. By perforating the back wall with several high-placed ventilation holes, to minimize dust, and maintaining a large opening facing the prevailing wind, the low pressure inside draws air in through the holes, generating a continuous breeze. Furthermore, the larger the downwind opening, the stronger the resulting airflow (Saadatian et al., 2012).

Across the Middle East, ingenious devices have evolved to harness the cooling power of the wind. Among these, the wind tower is well used, see figure 2.10, as well as the porous water jar system, that are incredible in its use. In rural Upper Egypt, for example, the porous water jar, locally known as the maziara, is placed in a windward opening. Testing has shown that even when outside temperatures range from 19°C to 36°C, the water inside remains nearly constant at about 20°C. This effect is attributed to the fact that as outside temperatures rise, the relative humidity drops, which in turn increases the rate of evaporation and the cooling effect. With this technique it was observed that comfort in Egypt is maintained only within the narrow range of 21°C to 26°C (Cain et al., 1976). When combined with a wind catcher, these systems become even more effective. A simpler variation of this principle is the use of a loosely woven, thick mat, which is hung across a door or window opening and regularly doused with water, a method that has been employed from northern India to Iran (Allen G. Noble, 2007).



Figure 2.10 - Wind towers in Yazd, Iran

(ArchDaily, 2021, "What is a Traditional Windcatcher?", https://www.archdaily.com/971216/what-is-a-traditional-windcatcher)

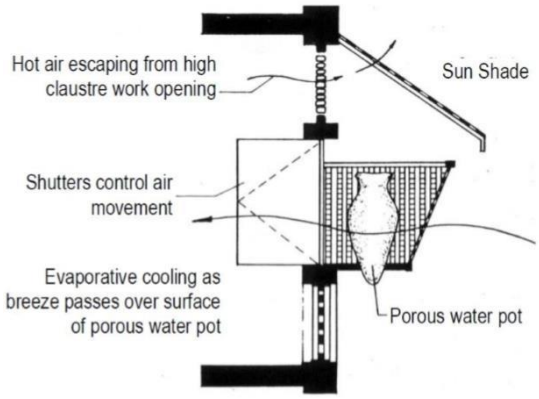


Figure 2.11 - Typical technique for cooling the inside using the evaporation of water from the porous jar known as Miazara, used in Egypt and middle east.

(Faggal, Ahmed, (2015), "Using Ecooler technique to enhance thermal comfort in hot desert arid climate in Egypt", 10.13140/RG.2.2.13135.48803)

A modern example of the use of ventilation as passive cooling system is the Basuna Mosque, in Sohag, Egypt, design by Dar Arafa Architects (figure 2.12). The architects that design it were asked to make it as low maintenance as possible and so the roof is covered with 108 pendentive domes that function as windcatchers and skylights.

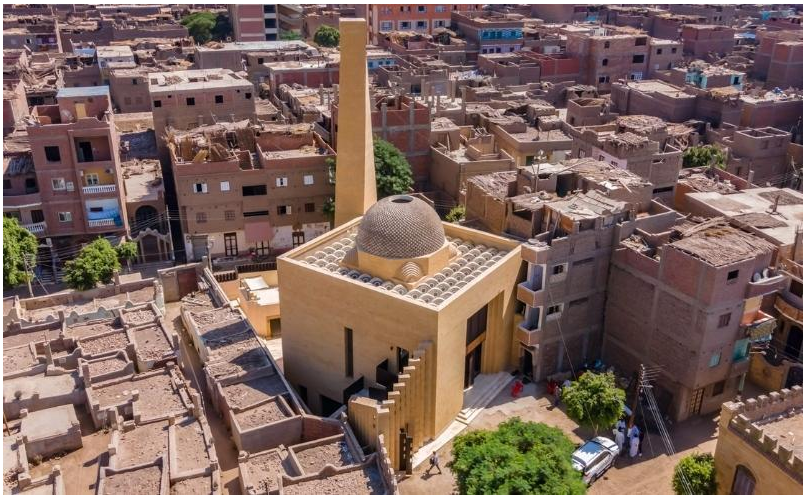


Figure 2.12 - Basuna Mosque, in Sohag, Egypt, with its roof characteristics for passive cooling. Design by Dar Arafa Architects.

(Karim Abdullatif, 2024, "The Brilliance of Basuna Mosque by Dar Arafa Architecture", https://scenehome.com/Architecture/The-Brilliance-of-Basuna-Mosque-by-Dar-Arafa-Architecture)

As humans moved out of cave dwellings, they faced the critical challenge of coping with pronounced seasonal temperature changes. In high latitudes, the primary issue was the bitter cold of long winters, while in tropical regions, it was the intense heat of extended summers. In the middle latitudes, both extremes presented significant challenges and so, over time, traditional societies, working with limited technology, gradually developed and refined a range of techniques to address these climatic variations.

2.2.2 Solar Passive Solutions

Passive solar design uses the sun's natural energy to help regulate indoor temperatures by thoughtfully considering a building's location, orientation, materials, and layout. When sunlight strikes a structure, its materials reflect, transmit, or absorb solar radiation, setting off predictable heat responses that can be applied to warm or cool a space. Additionally, the heat from the sun can drive natural air movement, further contributing to thermal comfort. Unlike active systems that rely on mechanical and electrical components such as pumps or fans, passive solar solutions are inherently simple and integrated into the building's design, offering a sustainable way to reduce energy consumption for heating and cooling. I this chapter it will be presented different techniques used for these results (US Energy Department, 2025).

- **Building orientation**

The relative orientation of a dwelling through north is a well know design parameter that affects the thermal comfort in it. As Helena Nbéu et al. (2024) pointed out, this type of solution, when applied in certain context, can increase solar heat gain by up to 25% in winter and reduce energy needs by up to 75% in mechanical equipment's to achieve a comfortable living place.

This design solution uses the radiation of the sun to generate or avoid heat inside the building, making the orientation of the building as well as the type of materials that are oriented for that radiation crucial for the good energy performance. The optimal orientation varies based on geographical location, climatic conditions, and building materials (Karimi et al., 2024).

Nogueira S. et al. (2024) pointed the same crucial factor in building orientation for passive solar design which is the changing path of the sun throughout the day and across the seasons, driven by the tilt of the Earth's axis. In the Northern Hemisphere, the sun follows a higher and steeper path during summer, resulting in longer daylight hours and increased solar gains, particularly for south-facing buildings. Conversely, in winter, the sun's lower and shorter trajectory reduces direct solar radiation, which can limit passive heating potential, the illustration of different sun path can be seen in figure 2.13. Additionally, the east and west facades play a significant role in thermal comfort, as they receive intense sunlight—in the morning for east-facing orientations and in the afternoon for west-facing ones—which can contribute to peak energy consumption if not properly accounted for in the design.

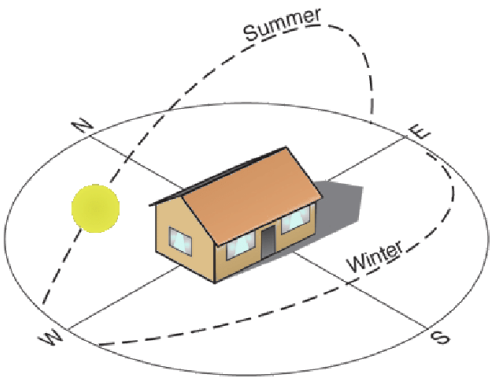


Figure 2.13 - Illustration of the sun path difference on summer and winter in the northern hemisphere.

(Tahouri, Ali. (2015). Evaluation of Windows and Energy Performance Case-Study: Colored Building, Faculty of Architecture (EMU). 10.13140/RG.2.1.3946.3444)

Another way in which the radiation is affected and consequently the thermal performance, is the geography of the place in study. Different hemispheres and latitudes contribute for a different sun path, similar to the different seasons, and in that way the radiation of the sun hits different zones of a building (Nogueira et al., 2024). Quantitative values can be taken from the coordinates of a specific location as well as the angle of the sun, observable in the sun path of that specific location. In figure 2.14 it can be seen the sun path for 36 degrees north latitude, near Portugal.

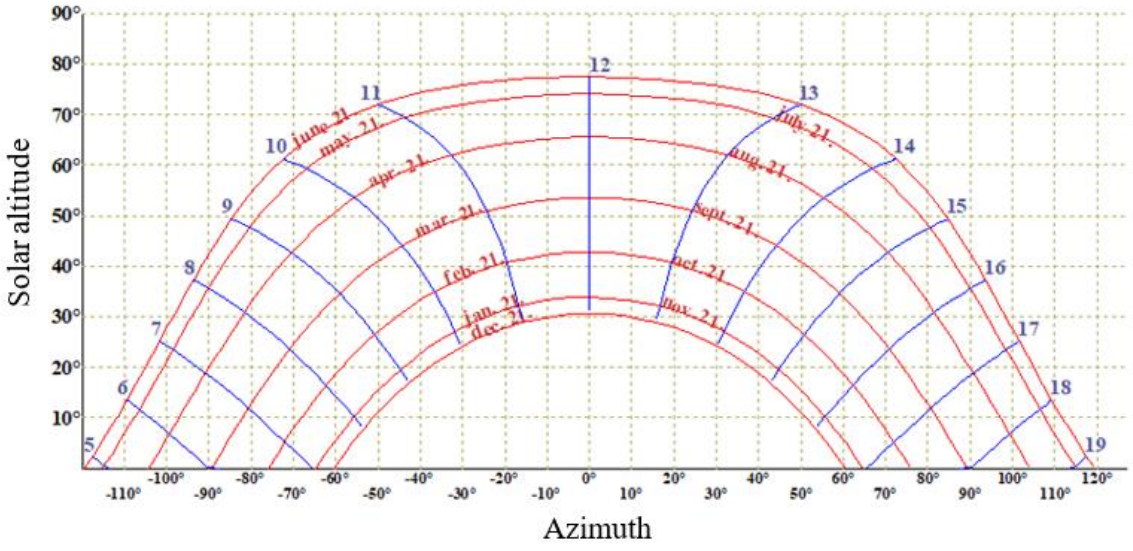


Figure 2.14 - Sun path diagram for 36 degrees north latitude.

(Source: Bonapoz Software)

In this type of plots, the azimuth is also described which is an angle that is important for the ideal orientation of a building. Azimuth is the angle of a celestial object relative to the observer's horizon, measured from the north and increasing in the eastward direction (European Space Agency, 2025). Using the sun as the celestial object, the azimuth can be measured and in the sun plot, when facing south, azimuth is 180º, and when facing north azimuth is 0º. For a more detailed and illustrative way of understanding the azimuth coordinate, figure 2.15 is described. Altitude of the celestial object, in this example the sun, can also be seen, a coordinate that is described in the sun path diagrams.

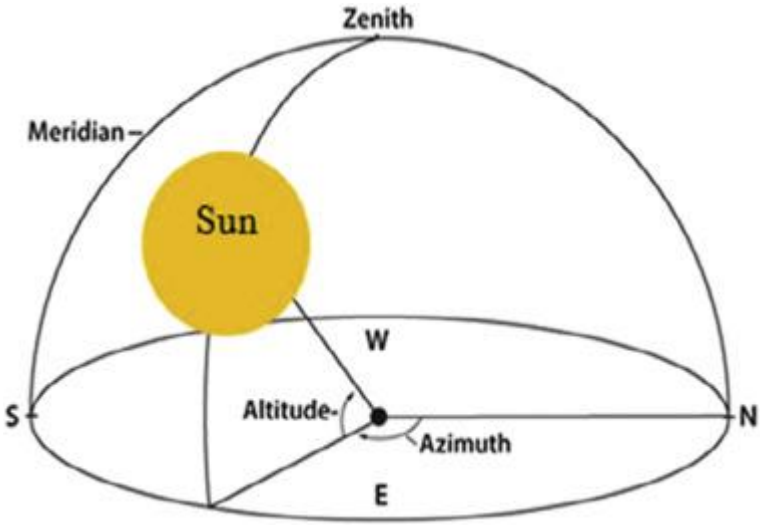


Figure 2.15 - Azimuth and altitude illustration in relation to the sun.

(Md. Shariful Alam Emon et al., 2022, Chapter 2 - Solar thermal energy conversion, Technologies for Solar Thermal Energy, Pages 25-54, https://doi.org/10.1016/B978-0-12-823959-9.00011-8)

These different parameters should be considered when choosing the best way to apply the radiation of the sun as solar passive solution, including orientation. This contributes for the decision of which types of façades should be used for the maximization of thermal comfort using radiation. Façades facing south, in case of the northern hemisphere, for example, and which type of material in those façades, as an example an opaque one or glazed one, can be decisions for the optimal design.

An important equation that relates to the heat absorbed indirectly or directly from the sun to the dwelling is described below (Del Rosario Heras Celemín & Marcos Montoro, 1990). The solar gains affect an important parameter in thermal comfort, the thermal transmittance value (U-value), which is the rate of transfer of heat through a structure (equation 2.1).

$$U = \frac{1}{R} \tag{2.1}$$

Where U is the thermal transmittance in W/m^2. ºC and R is the thermal resistance, expressed in m^2.ºC/W. Continuing the analysis, the U-value is function of the thermal conductivity (k), a property affected by the material in play and its thickness, as shown in equation 2.2.

$$U = \frac{k}{t} \tag{2.2}$$

Where *k* is the thermal conductivity expressed in W/m ºC, and *t* the thickness, in meters, of the surface. The thermal conductivity indicates how well a material conducts heat, it indicates the quantity of heat, in watts, that is conducted through 1 m² wall, in a thickness of 1 m, when the difference in temperature between the opposite surfaces of this wall equals 1 ºC (Del Rosario Heras Celemín & Marcos Montoro, 1990).

The importance of these relations in the context of the received energy from the sun are the effectiveness of the surfaces that receive that energy to sustain it without letting it dissipate easily, promoting thermal comfort in that way.

Solar radiation can be classified in different ways by how it is introduced and stored within a building. The most basic approach is direct gain, where sunlight enters the living space through large south-facing windows and directly strikes thermal mass elements such as floors or walls inside the room. These surfaces absorb and store heat throughout the day, slowly releasing it to maintain comfort during cooler periods. However, this system often faces challenges related to space usage, glare, and thermal comfort fluctuations, especially if thermal mass is obstructed by furniture or improperly insulated. Design strategies such as using diffusing glass or reflective surfaces can help distribute solar radiation more evenly, allowing thermal mass to be more effectively integrated throughout the space and reducing temperature swings (Ed. P. Achard & R. Gicquel, 1986).

A more controlled variation is the indirect gain system, such as the *Trombe wall*. This involves placing a thick, dark-coloured wall just behind a glazed south-facing opening. Solar radiation is first absorbed by the wall, which then transmits heat to the interior space through conduction, typically with a time lag that makes this method particularly effective for evening and night-time heating. Vents at the top and bottom of the wall can be used to circulate warm air during the day. While the Trombe wall can reduce reliance on active heating systems, it is less thermodynamically efficient than direct gain and can limit window views and design flexibility (Ed. P. Achard & R. Gicquel, 1986).

Isolated gain systems, such as *sunspaces* or *thermosyphon loops*, as it can be seen in figure 2.16, collect solar energy in a zone separated from the main living area and transfer the heat to interior spaces through convection, conduction, or radiation. A typical example is the sunspace, a glazed, south-facing enclosure that captures solar energy during the day. When designed with minimal thermal mass, the sunspace quickly heats up, allowing warm air to be circulated into adjacent rooms. Alternatively, if it includes thermal mass elements, it can store heat and gradually release it into the dwelling. This system also improves insulation performance by buffering the primary living area from direct heat loss, particularly at night. Thermosyphon systems, on the other hand, use a fluid or air-based collector that passively circulates heat from an exterior solar panel to a remote thermal store, which may be located beneath or adjacent to the building (Ed. P. Achard & R. Gicquel, 1986).

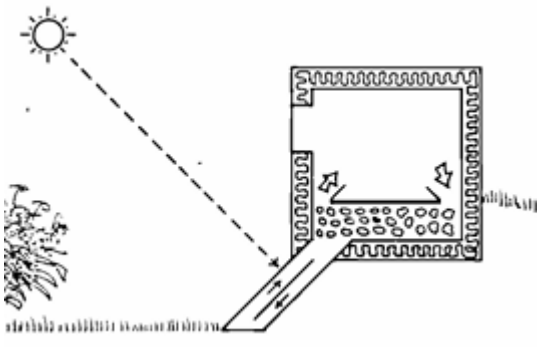


Figure 2.16 – *Thermosyphon loop* illustration as a solar passive technique for heating. (European passive solar handbook. Preliminary edition, Ed. P. Achard and R. Gicquel, 1986.)

- **Shading**

Associated with the building orientation there's the shading devices which play a crucial role in passive solar design by regulating solar radiation and controlling heat gain in buildings. Closely related to building orientation and the movement of the sun, shading helps enhance thermal comfort and reduce energy consumption by minimizing the need for mechanical cooling.

Studies have shown that shading devices can significantly reduce energy consumption. For instance, in commercial buildings with large, glazed facades, energy savings from shading strategies have reached up to 40% (Azimi Fereidani et al., 2021). In residential buildings, a study was done in Oman and, when used, these techniques have been observed to have savings of up to 9.4% (Al-Badi & Al-Saadi, 2020). The European Solar Shading Organization (ESSO) says that shading can indeed be used to reduce the energy needs for cooling by 2050 in about 60%, if buildings apply this type of techniques (European Solar Shading Organization, n.d.).

Shading solutions can have different physical aspects, it can be categorized into fixed and movable systems and further classified based on their configuration: vertical shading elements, positioned parallel to the glazing or perpendicular on the sides of windows, and horizontal systems, such as overhangs, which provide protection from direct sunlight (Azimi Fereidani et al., 2021). In figure 2.17, some of these types of shading devices can be seen.

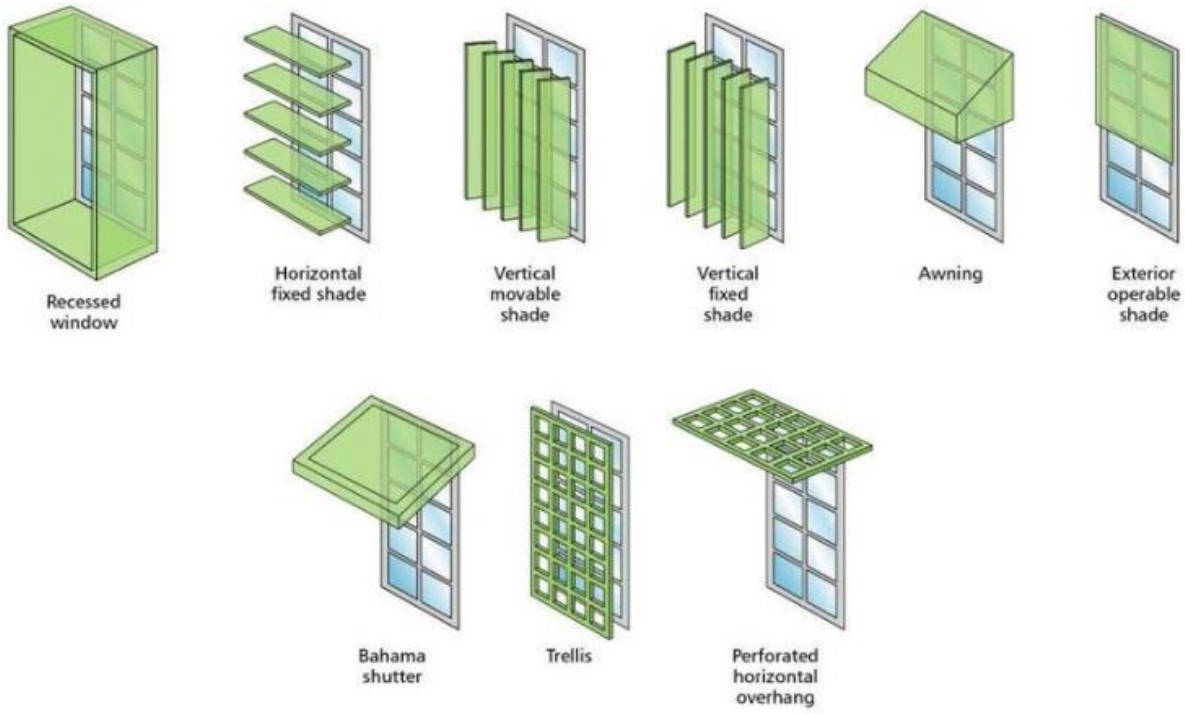


Figure 2.17 - Types of fixed shading devices used in buildings.

(Adapted from: Al-Yasiri, Qudama & Szabo, Marta. (2021). A short review on passive strategies applied to minimise the building cooling loads in hot locations. DOI: 10.14232/analecta.2021.2.20-30.)

Another way that shading can be used is with deciduous vegetation around the dwelling. In that way, in winter, without leaves, the tree doesn't block the sun, when it is most needed, and contrary, in the summer, leaves block the radiation from the sun, to help cooling the environment (Nogueira et al., 2024), see figure 2.18 for illustration.

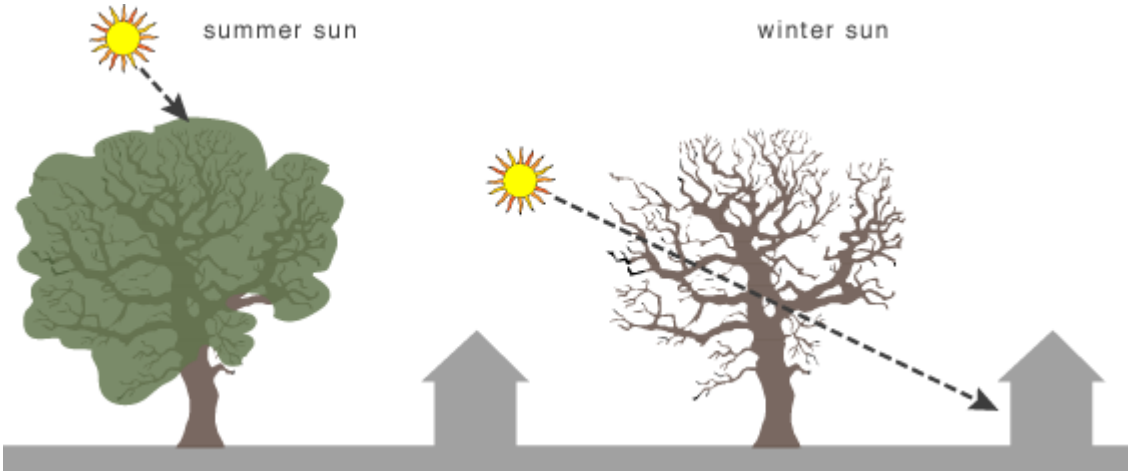


Figure 2.18 - Summer and winter shading with deciduous vegetation.

(Savvides, Andreas. (2015). Pedestrianization of a Vehicular Urban Corridor: Designing for User Comfort. Journal of Engineering and Architecture. DOI: 10.15640/jea.v3n2a1.)

- **WWR (window-to-wall ratio)**

The window-to-wall ratio (WWR) is defined as the relation between the window area within a wall and the wall area itself (U.S Energy Department, 2019), so mathematically:

$$WWR = \frac{Total\ window\ area}{Total\ wall\ area} \tag{2.3}$$

WWR is another important factor in building design, influencing both thermal performance and visual comfort. Compared to opaque elements, glazed surfaces generally exhibit higher thermal and solar transmittance, which can lead to increased heat gain or loss. However, they also provide significant benefits, such as improved indoor luminous quality, access to outdoor views, and enhanced daylight utilization. Given the growing trend of large glazing areas in modern architecture, balancing the advantages and drawbacks of WWR is essential for optimizing energy efficiency and occupant comfort (Pereira et al., 2022).

Since conventional glazing allows substantial heat exchange and can contribute to glare and overheating, solar control strategies must complement the window-to-wall ratio to achieve effective performance. While shading solutions—such as overhangs, blinds, and louvers—help mitigate excessive solar gains, they can sometimes obstruct outdoor views or alter the structure of the glazing. Therefore, WWR and shading should be working together as one affects the other, ensuring a design that maximizes daylight benefits while minimizing thermal discomfort and energy consumption (Pereira et al., 2022).

Some studies have shown how this solution has contributions for the energy needs in achieving thermal comfort. Nogueira et al., 2024, in her study shows how an optimal window-to-wall ratio can reduce the total annual energy needs by 23%, in Évora, Portugal. Troup et al., 2019, again shows, in different climate conditions, that an optimal fenestration design can reduce the need for mechanical systems energy from 10% to 40%.

The window-to-wall ratio is the relative quantity of windows in the dwelling compared to opaque walls or better defining, the proportion of exterior wall surface that is glazed (Troup et al., 2019). In the figure 2.19 can be seen an illustration of this solution within a normal wall.

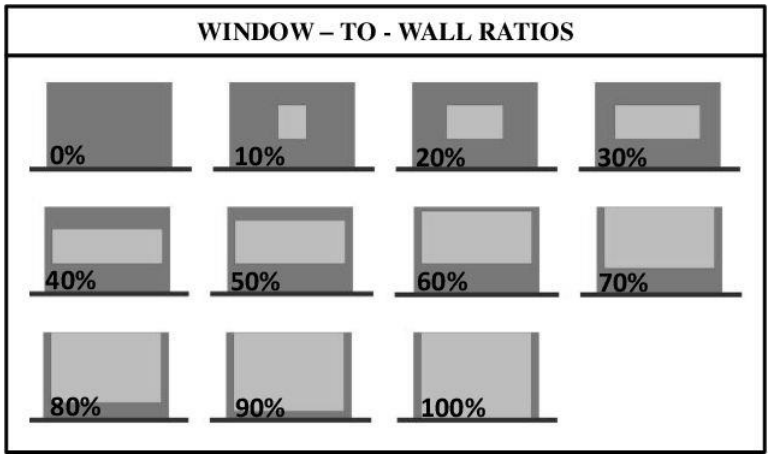


Figure 2.19 - Window-to-wall ratio illustration.

(El-Deeb, K. (2013). Combined Effect of Window-To-Wall Ratio and Wall Composition on Energy Consumption.)

- **Ventilation (Air changes per hour)**

Ventilation plays a crucial role in maintaining thermal comfort and indoor air quality while also impacting a building's overall energy consumption. Whether achieved through natural or mechanical means, proper ventilation helps regulate indoor temperatures by supplying fresh air, which can directly cool occupants through convective exchanges. This is particularly important during the hot season, as fresh air circulation not only enhances comfort

but also reduces the need for active cooling systems, thereby lowering energy consumption, as Mukhtar et al., 2019, pointed out, that a natural ventilation can reduce up to 25% of energy consumption.

As a result, understanding the so-called air changes per hour (ACH) becomes essential in optimizing ventilation strategies to balance cooling needs and energy efficiency. It refers to the number of times per hour that the total volume of air within a space is replaced with fresh or recirculated air. This is also known as the air change rate or air exchange rate (uslocationsca, 2021).

And not only this solution affects energy needs, but it is shown to increase health over all as natural air contributes for a cleaner and high-quality air (Aflaki et al., 2015).

Effective ventilation relies on airflow dynamics, which are influenced by factors such as temperature, humidity, air velocity, and pressure differences between indoor and outdoor environments (Q. Chen, 2009). Natural ventilation can generally be categorized into wind-driven ventilation and stack effect ventilation. Wind-driven ventilation occurs when wind interacts with a building's surfaces, creating high pressure on the windward side and low pressure on the leeward side, which encourages airflow through openings (Szokolay, 2013), see figure 2.20 for the illustration. Meanwhile, stack effect ventilation, or thermal force, is driven by temperature differences between indoor and outdoor air, causing warm air to rise and draw in cooler air, as it is used and most notably illustrated by the wind towers shown before. Both mechanisms, when properly utilized through passive design strategies and well-placed openings, can enhance indoor air circulation and thermal comfort while minimizing energy consumption.

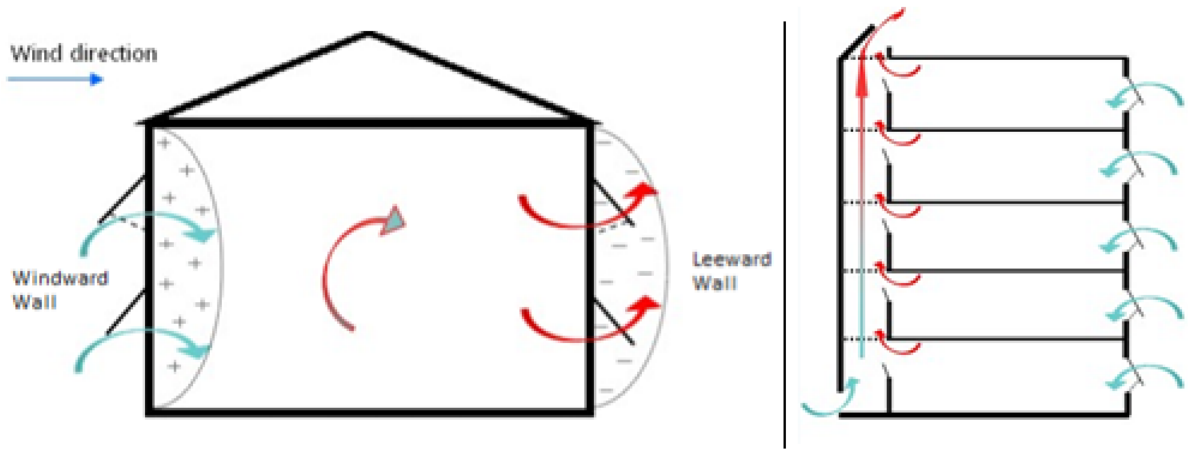


Figure 2.20 - Illustration of wind-driven ventilation (left) and stack effect ventilation (right).

(Adapted from: Building Technology Systems, 2023, "Natural Ventilation Types", https://www.buildingtechnologysystems.co.uk/our-services/natural-ventilation/index.html)

Aligned with these types of ventilation, there is the evaporative cooling, a technique used for a long time in history, as expressed before. Evaporative cooling is a process in which air is cooled by increasing its moisture content. As water evaporates into the air, the temperature decreases while humidity levels rise. This cooling method is particularly effective in hot and arid climates, where the ability to add moisture to dry air leads to significant temperature reductions, enhancing thermal comfort (Cuce & Riffat, 2016). This technique can be seen in the figure 2.21, as with the help of a spray device or simply a pool the water is evaporated, cooling the air adjacent to it.

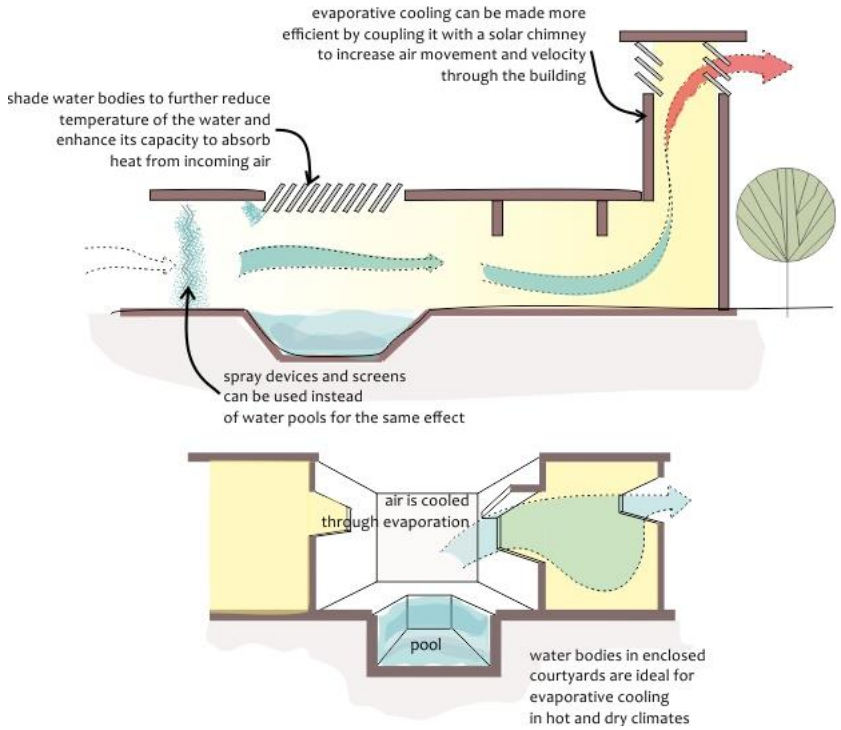


Figure 2.21 - Illustration of evaporative cooling align with ventilation.

(NZEB (2016a), 'Evaporative cooling', https://nzeb.in/knowledge-centre/passive-design/evaporative-cooling/.)

3 Methodology

3.1 Characterization of Portugal's Climate

Portugal's climate is primarily influenced by its latitude, topography, and proximity to the Atlantic Ocean. As the Portuguese Institute of the Sea and Atmosphere (IPMA, 2015) shows, these factors create significant variations in temperature and precipitation across different regions. In general, the northwestern areas, such as Minho, receive high levels of precipitation, exceeding 3000 mm annually, while the interior Alentejo experiences much lower rainfall, averaging less than 500 mm per year. Seasonal and interannual variations are also notable, making Portugal highly susceptible to droughts and extreme precipitation events.

Regarding temperature, annual averages range from 6–9°C in the mountainous interior regions (e.g., Serra da Estrela) to over 18°C along the southern coastline, as it can be seen in figure 3.1. A clear north-south temperature gradient is observed in winter, while in summer, coastal areas remain cooler due to the ocean's moderating effect (IPMA, 2025).

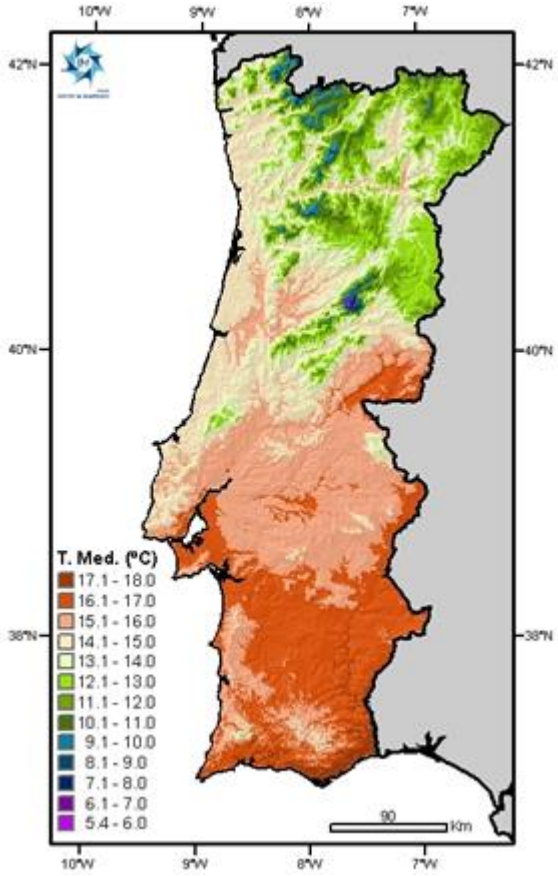


Figure 3.1 - Average annual temperature in Portugal.

(IPMA, 2025, "Clima de Portugal Continental", https://www.ipma.pt/pt/educativa/tempo.clima)

Climate Trends and Future Projections

Over the past few decades, as IPMA shows, Portugal has experienced a steady rise in temperature. Since the 1970s, the average temperature has increased by approximately 0.3°C per decade, with the ten hottest years on record occurring after 1990. Additionally, heatwaves have become more frequent and intense, while cold days have decreased. This data shows the tendency of cooling needs to increase (IPMA, 2015).

Future projections suggest that Portugal will continue to become hotter and drier. By 2040, the average annual temperature is expected to rise by 0.5 to 1.0°C, and by 2100, it could increase by 2 to 5°C, depending on greenhouse gas emissions. The warming trend will be more pronounced in the south and interior regions, which is in this case of Évora (IPMA, 2015).

All the data collected for each city in analysis comes for "Weatherspark" website (Weatherstat, 2025), a well-known database that gathers data from different sources.

- **Characterization of Lisbon climate**

Lisbon, the capital city of Portugal, is situated along the western coast of the Iberian Peninsula at approximately 38.7°N latitude and 9.1°W longitude, making it low on altitude with 4 m. This coastal location gives Lisbon a Mediterranean climate, characterized by hot, dry summers and mild, wet winters (Lisbon City Council, 2025).

Lisbon experiences moderate temperature fluctuations annually, with average temperatures ranging from 11.8°C in January to 23.6°C in August.

On the warm season (June – September), average daily high temperatures exceed 25.6°C, with August being the warmest month, reaching an average of 28.3°C.

On the cool season (November – March), average daily high temperatures remain below 17°C. January is the coldest month, with average lows of 8°C.

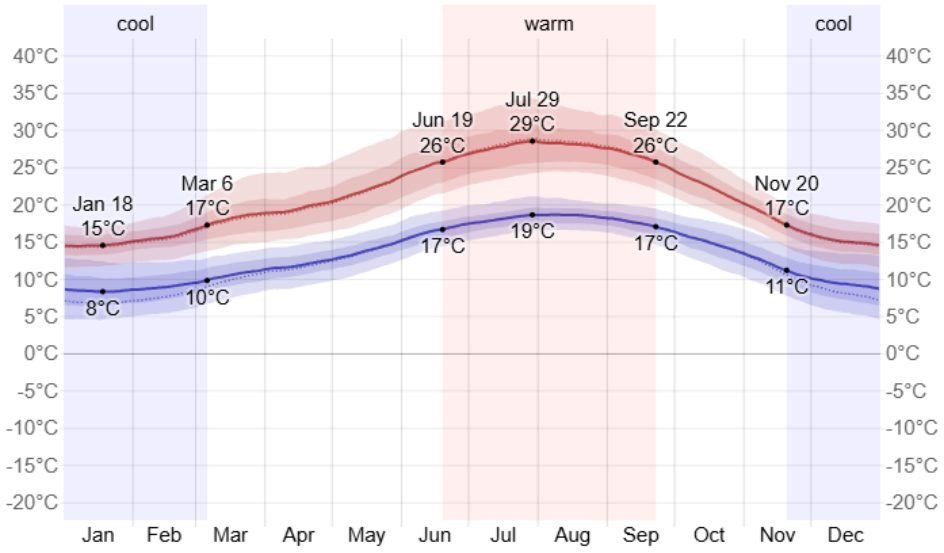


Figure 3.2 - Average high and low temperature in Lisbon.

(Weatherstats, 2025, "Climate and Average Weather Year Round In Lisbon", https://weatherspark.com/y/32022/Average-Weather-in-Lisbon-Portugal-Year-Round)

For solar parameters, Lisbon has abundant sunshine, particularly during summer, with July having the highest sunshine duration, reaching more than 14h in some days, while December having the least, with lowest as 9 hours per day.

Regarding the sun's elevation and azimuth, the solar altitude reaches its peak in June, with a maximum angle of approximately 75° at noon. In contrast, during December, the sun's altitude is much lower, around 28° at noon. The solar azimuth shifts significantly throughout the year, affecting shading strategies and passive solar design considerations.

- **Characterization of Bragança's climate**

Bragança is a city located in northeastern Portugal, near the Spanish border, at approximately 41.8°N latitude and 6.8°W longitude. It sits at a relatively high altitude, 690 m, contributing to its distinct climatic characteristics. The region falls within a humid temperate zone with Mediterranean influences, characterized by hot, dry summers and cold, wet winters. The surrounding vegetation reflects this transition, with a mix of Mediterranean forests and temperate deciduous landscapes (Bragança City Council, 2025).

Bragança experiences a wide range of temperatures throughout the year, with short, hot summers and long, cold winters. Temperatures typically vary between 1°C and 29°C, rarely dropping below -4°C or exceeding 35°C. In figure 3.2 is shown graphically the highest and lowest average temperatures observed all year around in Bragança.

On the warm season (June – September), daily high temperatures exceed 25°C, with July being the hottest month, averaging highs of 29°C and lows around 15°C.

On the cool season (November – March), daily high temperatures remain below 12°C, with January as the coldest month, experiencing average lows of 1°C and highs of 9°C.

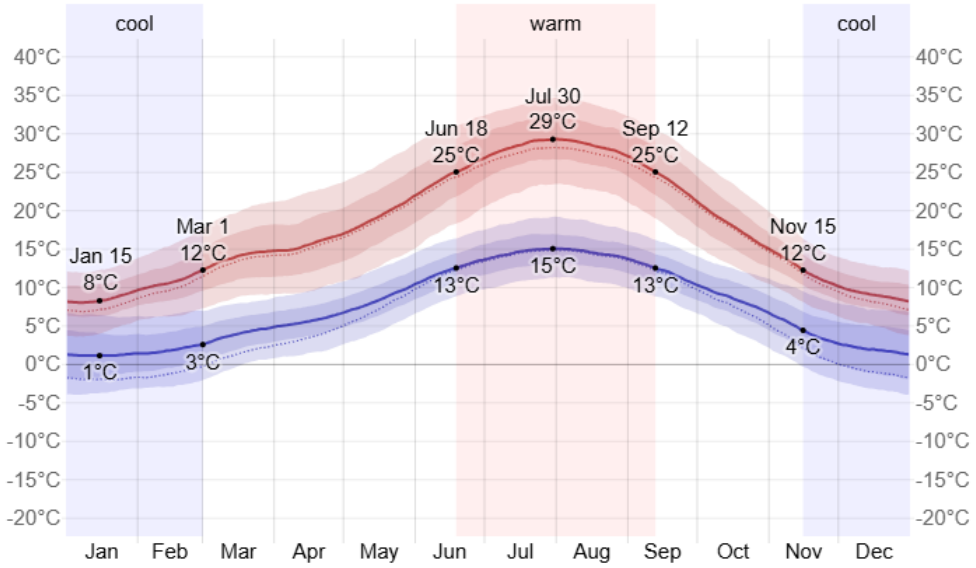


Figure 3.3 - Average high and low temperature in Brangança.

(Weatherstats, 2025, "Climate and Average Weather Year Round in Brangança", https://weatherspark.com/y/33562/Average-Weather-in-Bragan%C3%A7a-Portugal-Year-Round)

The number of sunshine hours and solar radiation varies significantly throughout the year, influencing both thermal comfort and building energy performance.

On summer months, Bragança receives approximately 12–14 hours of daylight per day, with high levels of solar radiation, which can increase cooling demands in buildings.

On winter Months, daylight hours are reduced to around 9 hours per day, and the sun remains at a lower angle, limiting solar gains makes solar passive solutions to be used efficiently to reduce mechanical energy needs.

- **Characterization of Évora's climate**

Évora, a historic city in southern Portugal, is located at approximately 38.6°N latitude and 7.9°W longitude in the Alentejo region and is located at an altitude of 304 m. Due to its inland location, Évora experiences a Mediterranean climate with hot, dry summers and mild, wet winters. The region is also known for its continental influences, which contribute to more significant temperature variations compared to coastal cities like Lisbon (Évora City Council, 2025).

Évora's temperatures vary significantly throughout the year, figure 3.4, with warm summers and relatively cool winters.

On the warm season (June – September), average daily high temperatures exceed 29°C, with August being the hottest month, reaching an average high of 32°C.

On the cool season (November – March), average daily highs remain below 17°C, and January is the coldest month, with an average low of 5°C.

Due to its inland position, Évora also experiences notable diurnal temperature variations, with significant differences between daytime and nighttime temperatures, especially in summer.

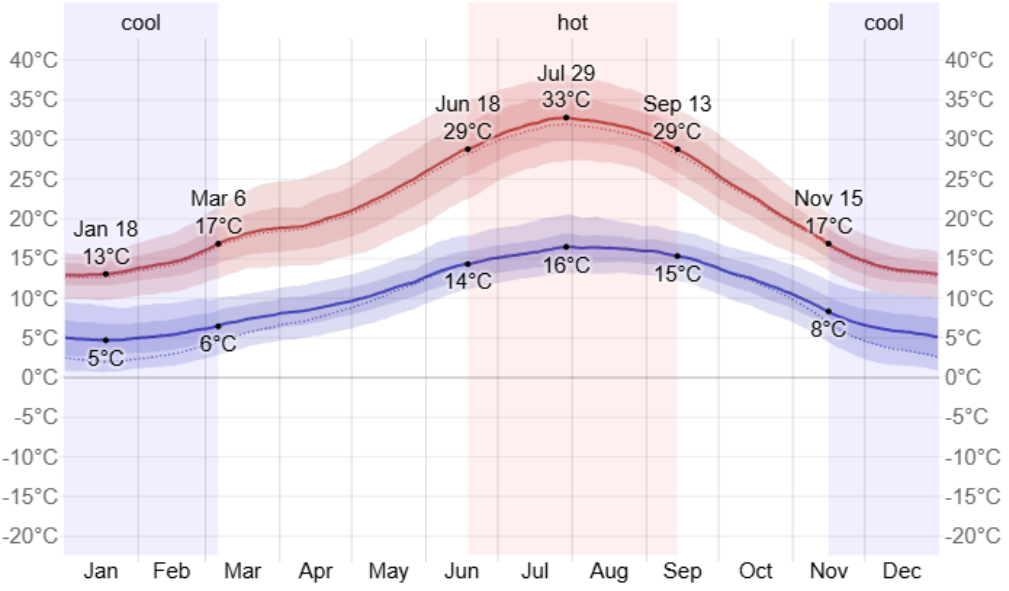


Figure 3.4 - Average high and low temperature in Évora.

(Weatherstats, 2025, "Climate and Average Weather Year Round In Évora", https://weatherspark.com/y/32806/Average-Weather-in-%C3%89vora-Portugal-Year-Round#Figures-Temperature)

For solar analysis, Évora has long hours of sunshine throughout the year, with June having the highest sunshine duration, reaching more than 14 hours of sunshine in some days, while December having the least, with as lowest as 9 hours per day.

Regarding solar angles, the sun's elevation reaches its peak in June, with a maximum altitude of approximately 74° at solar noon. In contrast, in December, the sun's altitude is lower, around 27° at noon. The solar azimuth varies throughout the year, impacting shading strategies and passive cooling techniques.

3.2 Simulation Software Overview

To carry out the thermal and energy performance simulations of the residential building models, the *OpenStudio* platform (version 1.8.0) was used, operating as a user-friendly interface for the *EnergyPlus* simulation engine. *EnergyPlus*, developed by the U.S. Department of Energy, is a dynamic building energy modelling software capable of simulating heating, cooling, ventilation, lighting, and internal loads. It is widely used in academic and professional settings due to its high accuracy and flexibility in modelling building physics (U.S Department of Energy, 2014).

OpenStudio simplifies the interaction with *EnergyPlus* by providing an interface that allows users to define building geometry, construction materials, internal loads, HVAC systems, and control strategies without the need for direct code manipulation. Within *OpenStudio*, *FloorSpaceJS* was used to design the building layout. *FloorSpaceJS* is a basic 2D geometry editor embedded in *OpenStudio*, allowing for the rapid creation of floor plans, as it can be seen in figure 3.5. It enables users to define zones, draw rooms, and position windows and doors, offering a simplified yet effective approach to modelling the physical structure of the building. This modelling tool was particularly useful for placing and adjusting fenestration elements such as windows and doors, as well as defining shading devices like overhangs directly within the graphical interface.

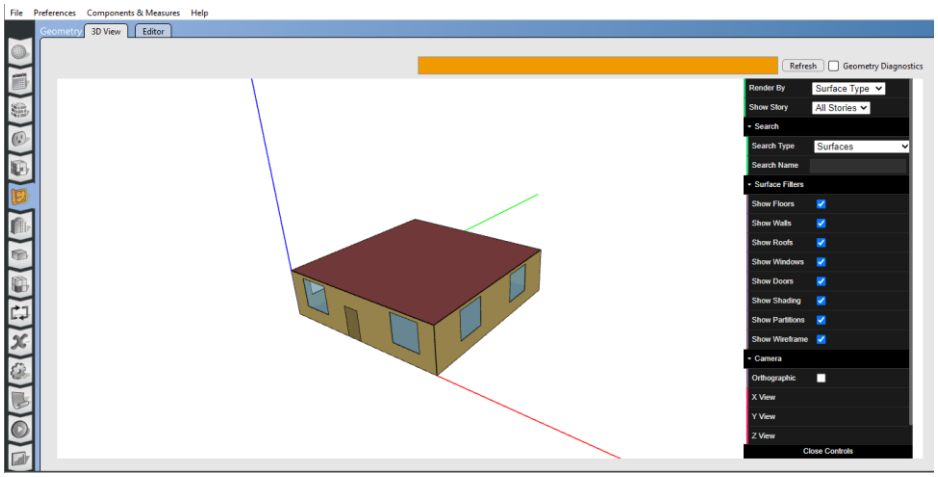


Figure 3.5 - *OpenStudio* interface with the 3D view of the building geometry (Lisbon) used for simulation setup, showing zone dimensions and fenestration placement. (OpenStudio)

Moreover, *OpenStudio* allows for the detailed input of internal loads, including lighting, occupancy, and electric equipment, as well as the specification of usage schedules that reflect realistic daily and seasonal behaviour. The software also supports simplified HVAC definition using the Ideal Loads Air System, which was enabled in this study to calculate heating and cooling demands without designing a specific mechanical system. This feature ensured a consistent and comparative evaluation of thermal loads across all models and simulation alternatives.

After setting up the models, simulations were run, and the results such as energy use intensity (kWh/m²), internal temperatures, heating and cooling loads, and thermal comfort metrics were analysed. These results formed the basis for evaluating the effectiveness of different passive solar strategies across the models.

3.3 Cases Studies

To ensure that the simulations are grounded in realistic and contextually appropriate designs, a representative single-family dwelling layout was used for each location. The base plan was adapted from Eskander et al., 2017, which incorporates architectural characteristics and construction typologies common to Portuguese regions. This ensures the thermal behaviour modelled in each case is reflective of actual residential buildings typically found in Lisbon, Bragança and Évora.

While the overall geometry of the floor plans remains largely identical, variations are noticed in window placement, glazing area, and total built area to reflect regional tendencies and adapt to the local climate conditions. Despite the similar architectural base, each location presents unique climatic challenges, meaning that even with a similar layout, the thermal performance differs significantly due to differences in solar exposure, temperature profiles, and seasonal dynamics. This approach ensures that comparisons across locations are methodologically consistent.

Table 3.1 summarizes the total and directional window-to-wall ratios for each location, along with the corresponding plan and façade areas. While the core layout remains consistent, these small variations in façade exposure and glazing distribution introduce meaningful differences in the thermal behaviour of each model, adapted to the distinct climate characteristics of Lisbon, Bragança and Évora.

Table 3.1 - Summary of geometric and glazing parameters for each dwelling

Location	Plan Area (m²)	Wall Area (m²)	WWR (%)				
			Total	Façade Orientation			
				North	East	South	West
Lisbon	121	132	24.10	21.42	21.42	21.42	32.13
Bragança	121	132	24.55	19.64	29.45	19.64	29.45
Évora	80	108	24.08	24.08	28.90	12.04	28.90

- **Lisbon**

For the Lisbon scenario, the residential layout from Eskander et al., 2017, was employed to maintain consistency across simulations. The dwelling reflects an urban housing typology typical of the Lisbon metropolitan area with its 3D view in figure 3.6, obtained with *Openstudio*. The total built area is 121 m², with a total glazed area of 31.8 m², yielding a window-to-wall ratio of 24.10%. These parameters were obtained when constructing the plan with the desired area and window size and then plugged into the energy simulation model to accurately assess performance under Lisbon's climatic conditions.

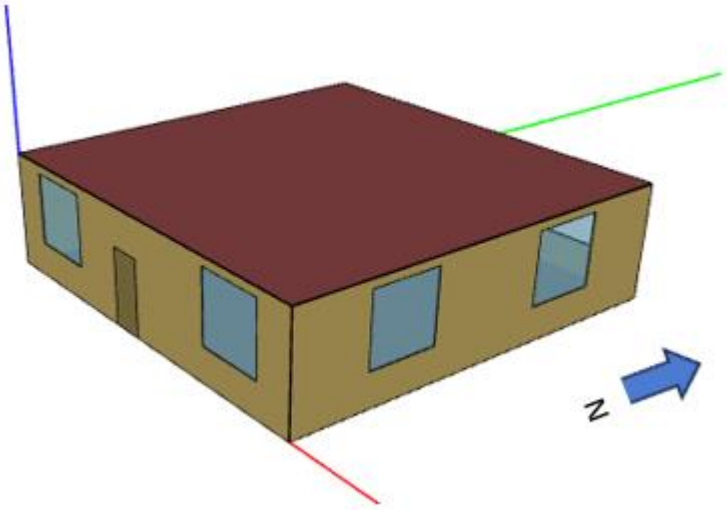


Figure 3.6 - 3D view of Lisbon's house base model. (*Openstudio*)

- **Bragança**

In the case of Bragança, as the other ones, the architectural base was also taken from Eskander et al., 2017. The house, with a floor area of 121 m² and a total glazed area of 32.4 m², can be seen in figure 3.7, designed with *Openstudio*. This results in a window-to-wall ratio of 24.55%. This configuration simulates a realistic northern Portuguese dwelling exposed to Bragança's colder and more continental climate.

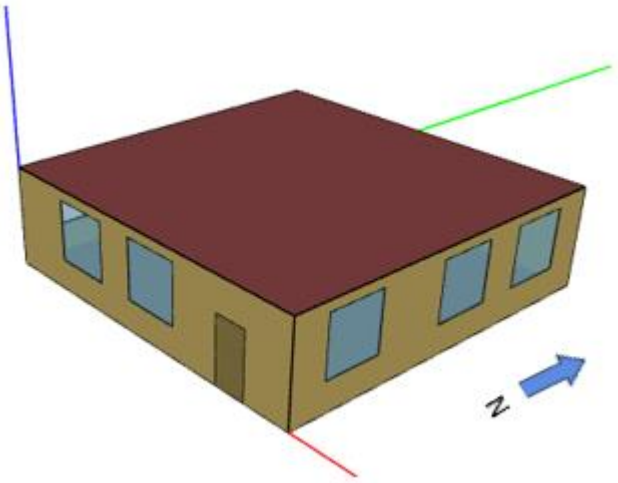


Figure 3.7 - 3D view of Bragança's house base model. (*Openstudio*)

- **Évora**

The selected floor plan for Évora was also taken from Eskander et al., 2017, generated using *OpenStudio*'s FloorSpaceJS interface, with its corresponding 3D visualization shown in figure 3.8. The layout results in a total floor area of 80 m², including a total glazed area of 26.01 m², corresponding to a window-to-wall ratio (WWR) of 24.08%.

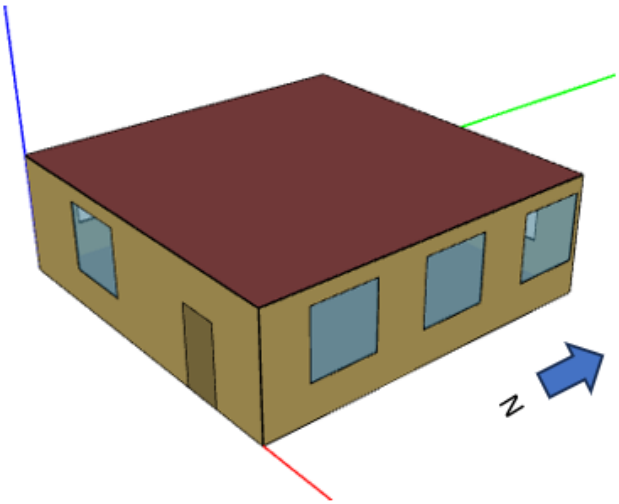


Figure 3.8 - 3D view of Évora's house base model. (*Openstudio*)

3.4 Simulation Parameters

To accurately simulate the building's thermal and energy performance, the software requires a weather file that contains detailed climatic information for the specific location under study. This file includes hourly data on air temperature, humidity, solar radiation, wind speed and direction, and other atmospheric conditions that directly impact the heat exchange between the building and its surroundings. In addition to weather files, the simulation also requires a Design Day (DDY) file, which provides the extreme weather conditions used for evaluating thermal loads under peak conditions. DDY files contain representative data for typical hottest and coldest days of the year, including parameters such as maximum and minimum temperatures, humidity, solar radiation, and wind conditions. These are essential for accurately calculating heating and cooling loads during design-day scenarios.

For this study, the weather files were obtained from https://energyplus.net/weather in EPW (*EnergyPlus* Weather) format, which is compatible with the simulation software. The DDY files were obtained from https://climate.onebuilding.org/, so the design days could be uploaded into the simulation and act in their role. These files are essential for ensuring that the model reflects real-world environmental conditions, allowing for a more precise evaluation of the building's energy behaviour across different climates.

Some initial parameters remained consistent across all simulations. The selected approach considers both thermal performances and overall energy consumption. The simulation period was set for 365 days for residential house setting with a ceiling elevation of 3 m and window base elevation of 0.9 m. The algorithm used for this study was the conduction transfer function, which focus on the heat transfers that happens within the building's envelope, as described in Vera et al., 2018 and in the *EnergyPlus* software reference (US Department of Energy, n.d.).

The thermal and physical properties of the materials used in the simulation are essential for accurately modelling heat transfer, energy efficiency, and indoor comfort conditions. The simulation software requires defining each material's thermodynamic and physical properties, which are then assigned in layers to construct different building elements, such as floors, walls, roofs, doors, and windows.

The software includes default material properties based on ASHRAE standards (ASHRAE, 2009), which establish minimum regulations for building envelope performance.

However, to achieve a more detailed and realistic representation, custom materials were introduced, ensuring that the construction elements accurately reflect real-world building practices in each location in the study.

The following sections detail the composition and properties of the materials used in the base model.

- **Walls**

The wall assembly consists of four layers, each contributing to the thermal and structural performance of the building envelope, where the properties and constitution are drawn from the Mr. Santos, Carlos A. Pina dos & Mr. Matias, Luís book "Coeficientes de Transmissão térmica de elementos da evolvente dos edifícios", 2010, associated with the Portugues Laboratory of Civil Engineering.

The outermost and innermost layers of the wall assembly serve primarily as protective finishes, providing weather resistance, mechanical durability, and aesthetic or fire protection, but they contribute negligibly to the overall thermal resistance of the wall. These layers can be a metal sheet, wood or ceramic for the outermost layer and for the innermost a stucco or plaster as expressed in Santos & Matias, 2010. For this reason, and in alignment with the reference used, only the brick layer and the insulation layer of expanded polystyrene (ESP) are considered in the U-value calculation, as they are the dominant elements influencing heat transfer. The thermal properties of these core materials are detailed in table 3.2. The U-value obtained was 0.76 $W/m^2.ºC$.

Table 3.2 - Walls material properties

Property	Brick Wall	Insulation (EPS)
Thickness (m)	0.240	0.030
Thermal Conductivity (W/m.K)	0.423	0.040
Density (kg/m^3)	1250	17.00
Specific Heat (J/kg.K)	950	1400
Thermal Absorptance	0.90	0.90
Solar Absorptance	0.70	0.70
Visible Absorptance	0.70	0.70

- **Roof**

The roof assembly consists of four layers and using the same reference of the walls model, the calculation for the U-value only the most influential layers are considered, being the insulation and the slab. The outermost roof membrane provides weather proofing and protection from external elements as the wall layer, while the roof insulation (EPS) enhances energy efficiency by reducing heat transfer. For the structural support, a slab is used and finally in the innermost layer, paint is used mainly for aesthetic finishing. The thermophysical properties of these materials are detailed in table 3.3. As referred in the book (Santos & Matias, 2010) the U-value obtained for this construction set is 0.66 $W/m^2.ºC$.

Table 3.3 – Roof materials properties

Property	Roof Slab (Ceramic Block)	Roof Insulation (EPS)
Thickness (m)	0.14	0.030
Thermal Conductivity (W/m.K)	0.20	0.037
Density (kg/m³)	1250	17.00
Specific Heat (J/kg.K)	950	1400
Thermal Absorptance	0.90	0.90
Solar Absorptance	0.70	0.70
Visible Absorptance	0.70	0.70

- **Windows**

The window assembly is composed of three layers, following a standard double-glazed configuration, and its properties were sourced from the same reference (Santos & Matias, 2010), ensuring consistency with the other construction elements. The assembly consists of two glass panes separated by an air gap, a common and widely used solution in residential buildings for improved thermal performance.

For the purposes of this analysis, only the thermal conductivity and thickness of the materials were considered, as these are the primary parameters influencing the U-value calculation. While additional optical properties such as solar transmittance and solar reflectance at normal incidence are included in the software's default glass material (from the *OpenStudio* library), they are not altered or used in this study, given the focus is on thermal behaviour rather than solar gain analysis. For the air gap layer, only the thickness and thermal conductivity were specified, as no other parameters were provided or deemed necessary.

The thermal resistance of each layer was calculated accordingly, and the resulting U-value of the window assembly is 3.29 W/m²·ºC, representing a typical performance level for standard double-glazed residential windows, matching the value presented in the literature. The detailed material parameters used for the calculation are presented in table 3.4.

Table 3.4 - Window material properties

Property	Glass	Air gap	Glass	Total R
Thickness (m)	0.004	0.0078	0.004	
Conductivity (W/m·K)	1	0.026	1	
R (m²·K/W)	0.004	0.3	0.004	0.308

- **Door**

For the simulation of the exterior door, a predefined construction available in the simulation software's material library was adopted. This choice was made considering that only one door is present in the model, and its contribution to the overall thermal transmittance of the building envelope is minimal. As such, a detailed custom definition was deemed unnecessary, and the default configuration was maintained for simplicity and consistency with common modelling practices.

The selected door assembly consists of two layers: a metal surface layer, representing the external protective skin, and an insulation board, serving as the primary thermal barrier (see table 3.5). Although the total thickness of the assembly may appear low compared to standard construction practices, the values are aligned with the internal database of the *EnergyPlus* engine and reflect typical inputs used in similar residential-scale simulations.

Table 3.5 - Thermal properties of the door assembly

Property	Metal Surface	Insulation Board	Total
Thickness (m)	0.0008	0.0254	
Conductivity (W/m·K)	45.28	0.03	
Resistance (m²·K/W)	0.000018	0.8467	0.847

- **Internal Loads**

Internal loads refer to the heat gains generated within a building from sources such as occupants, lighting, and electrical equipment. These internal sources contribute to the thermal environment and influence both heating and cooling demands. In the context of this study, internal loads are limited to people and lighting, as they are among the most consistent and significant contributors to internal heat generation in residential settings. Occupants produce heat through their natural metabolic activity, while lighting systems release heat as a byproduct of their operation. These elements are essential to account for in thermal simulations, as they directly affect indoor temperature and energy performance.

The lighting load was set to 11.63 W/m² of floor area, a standard value sourced from the simulation software's built-in libraries. The lighting schedule was designed to reflect typical residential usage patterns, with lights operating at 50% from 5:00 PM to 11:00 PM, and at 30% from 6:00 AM to 8:00 AM, corresponding to common active periods when occupants are present and daylight is limited, see table 3.6.

Table 3.6 - Values of the base parameters for the light's internal loads used

Parameter	**Value**
Light watts per space floor area	11.63 W/m² *
Schedule (Full Load)	5:00 pm – 11:00 pm (50%)
Schedule (Partial Load)	06:00 am – 08:00 am (30%)

* Source: simulation software library

The internal heat gain from occupants was modelled using a standard metabolic rate of 132 W/person, which represents light activity typical of an adult. A total of three occupants was assumed for the dwelling. The occupancy schedule was set to 100% presence from 5:00 PM to 8:00 AM, aligning with non-working hours when residents are expected to be at home, see table 3.7.

Table 3.7 - Values of the base parameters for the people internal loads used

Parameter	Value
Number of Occupants	3
Activity Level	132 W/person *
Occupancy Schedule	5:00 pm – 08:00 am (100%)

* Source: simulation software library

Electric equipment also contributes to internal heat gains in residential buildings, particularly through the operation of appliances and electronics commonly found in kitchens, living areas, and workspaces. Although the heat output from equipment varies based on usage patterns and device efficiency, for the purposes of this simulation, a standard value of 2.8 W/m² was applied across the total floor area. This value reflects typical usage in a residential setting as described in Moreira et al., 2024. For the schedule used in the equipment load an analysis was made based on Moreira et al., 2024, and with an analysis on what seems to be a reasonable approximation of the use in a common residential dwelling. In the table 3.8 is described the load used during the hours of the day as well as a brief description why each load was considered.

Table 3.8 - Hourly equipment load profile

Time Period	Load (%)	Description
23:00–06:00	10%	Minimal load: refrigerator, standby devices
06:00–08:00	40%	Morning activity: coffee maker, toaster
08:00–17:00	10%	Residents away: only essential equipment operating
17:00–19:00	60%	Return home: light cooking, general equipment uses
19:00–21:00	100%	Peak period: dinner prep, TV, appliances in use
21:00–23:00	30%	Evening relaxation: TV, phone charging

3.5 Simulation Variables and Design Alternatives

To ensure consistency across all scenarios and focus the analysis on passive strategies, several baseline simulation settings were standardized for all locations. First, instead of modelling a detailed HVAC system, the ideal air loads option in *EnergyPlus* was activated. This feature provides a simplified mechanical system automatically sized to meet the thermal loads of each zone, allowing accurate evaluation of heating and cooling demands without requiring the explicit design of complex HVAC components.

Thermal comfort setpoints were defined based on national regulations. According to DGEG (2023), the reference indoor temperature for residential buildings in Portugal is 18 °C for heating and 25 °C for cooling. These values were applied uniformly throughout all simulations.

Regarding ventilation, no mechanical systems were included, and only infiltration was considered. The default infiltration rate set - 0.5 air changes per hour (ACH) - was used, as it aligns with the worst-case values defined for buildings with two or more exposed facades and low-performance windows (DGEG, 2023). This value was used as a baseline for all locations, along with the corresponding default schedules.

To evaluate the impact of different passive solar solutions on the building's energy performance, a series of simulation alternatives were created, each modifying one or more key architectural or construction parameters. Starting from the base model, changes were applied incrementally to isolate the effect of each strategy, allowing a detailed comparison of thermal behaviour and energy demand across climates.

3.4.1 Building orientation

Building orientation significantly affects the exposure to solar radiation throughout the day and year. To assess its impact, the base model was rotated incrementally in *EnergyPlus* using the "Create Site" functionality. The reference orientation (Alternative 1) aligns plan north with true north (0° rotation), shown in figures 3.6, 3.7 and 3.8, respectively for each city. Seven additional rotations were tested, measured counterclockwise from true north to plan north, covering a full 360° in 45° steps.

This approach allows the identification of orientations that offer the best thermal performance in each climatic context, based solely on solar exposure. All other variables, including internal loads, construction elements, and climate files, remained unchanged.

The orientation alternatives are summarized in table 3.9.

Table 3.9 - Alternatives with the rotation angle described

Alternative	Rotation Angle
1 (Base)	0°
2	45°
3	90°
4	135°
5	180°
6	225°
7	270°
8	315°

3.4.2 Uniform Ventilation

Ventilation plays a crucial role in maintaining indoor air quality and influencing thermal comfort, particularly in naturally ventilated buildings. In this analysis, uniform ventilation refers to a consistent air exchange rate maintained throughout the simulation period, independent of seasonal variations or occupant behaviour.

To evaluate the impact of different constant ventilation rates on the building's thermal performance and energy needs, a series of simulations were carried out in *EnergyPlus* by

adjusting the air changes per hour (ACH) parameter. The ventilation was modelled as a continuous infiltration, uniformly applied during all hours of the year.

The base model (Alternative V.1) uses a minimal infiltration rate of 0.5 ACH, representing a tightly sealed building envelope, in line with national low-energy standards. Subsequent alternatives increase the ACH in fixed increments up to 5.0 ACH, simulating progressively higher ventilation scenarios. These values are selected based on the Portuguese Ministerial Ordinance No. 138-I/2021 of July 1st (Portugal, 2021), which defines ventilation rates for indoor spaces.

The ventilation scenarios in this study therefore explore the lower to mid-range ACH values typical of weakly ventilated residential buildings, ensuring relevance to local regulatory standards. This approach allows for a controlled analysis of how increased air exchange - without seasonal variation - affects indoor temperature stability, heating and cooling loads, and overall energy performance.

No other parameters such as internal gains, occupancy schedules, building geometry, or construction assemblies, were modified between these alternatives. The purpose of this approach is to isolate and evaluate the effect of uniform ventilation rates on energy demand and thermal comfort across different climatic zones. The uniform ventilation scenarios are summarized in table 3.10.

Table 3.10 - Alternatives for the uniform ventilation, in air changes per hour

Alternative	ACH
V.**1** (Base)	0.5
V.**2**	2
V.**3**	3.5
V.**4**	5

3.4.3 Seasonal Ventilation

While uniform ventilation provides useful insight into the influence of constant air exchange rates on energy performance, it does not reflect the dynamic nature of how ventilation is typically managed in residential buildings. In practice, ventilation strategies are adjusted seasonally to balance indoor air quality, thermal comfort, and energy efficiency, as pointed and demonstrated by Alhindawi et al., 2025.

To better represent realistic occupant behaviour and passive design strategies, a seasonal ventilation approach was implemented in this study. The ventilation rate was varied according to the time of year:

- During the cooler season (from September 21 to April 21), ventilation was minimized to reduce heat loss, maintaining a constant rate of 0.5 ACH across all alternatives;
- In the warmer season (from April 21 to September 21), ventilation rates were increased to enhance natural cooling and reduce the need for mechanical air conditioning. In this period, the same ACH levels used in the uniform ventilation scenarios were tested: 0.5, 2.0, 3.5, and 5.0 ACH.

By applying seasonal variation in ventilation, this approach aims to optimize passive climate control by leveraging higher natural airflows during summer while minimizing energy loss in winter. This seasonal strategy reflects more realistic occupant behaviour and aligns with principles of adaptive comfort and energy-conscious design.

All other simulation variables, including internal loads, construction characteristics, orientation, and occupancy schedules were held constant, ensuring that only the ventilation strategy varied between alternatives. The seasonal ventilation alternatives are summarized in table 3.11.

Table 3.11 - Alternatives for the seasonal ventilation, in air changes per hour

Alternative	**ACH**	
	Warmer Season	**Cooler Season**
SV.**1** (Base)	0.5	0.5
SV.**2**	2	0.5
SV.**3**	3.5	0.5
SV.**4**	5	0.5

3.4.4 Window-to-Wall Ratio

For this parameter, the WWR was systematically varied to assess its impact on thermal performance across the different climates and base model geometries. Since the reference buildings differ in their facade configurations and number of windows, the initial WWR's and window dimensions also vary by model and location.

Each base model was developed using fixed window dimensions based on the original architectural configuration for that location. The windows were modelled with square proportions (equal width and height), maintaining consistent dimensions across all façades for each specific base model:

- Lisbon: 1.88 m x 1.88 m
- Bragança: 1.80 m x 1.80 m
- Évora: 1.70 m x 1.70 m

These dimensions resulted in an approximate WWR of 24% for each base model as shown before.

To study the effect of varying WWR, two additional alternatives were created for each model by adjusting the window dimensions. The target WWR values were defined as ±10% from the base model's WWR, resulting in one alternative with increased glazing area and another with reduced glazing area. The exact WWR values and corresponding window dimensions for each case are presented in table 3.12. Important to note that the window height, meaning the dimension from the bottom of the wall up to the window's base was the same for all the models and alternatives, being 0.9 m, the initial value described before.

To achieve the desired WWR values, a geometric analysis was conducted to calculate the required window sizes for each alternative. This involved maintaining window placement and number, while adjusting individual window dimensions proportionally in all facades to meet the target WWR for each case.

No other parameters such as window type, frame material, glazing performance, or internal loads were altered. This ensures that any variation in thermal performance can be attributed solely to changes in WWR.

This approach allows for an isolated evaluation of how varying the glazed area impacts energy performance across different climates and base building designs. The exact window dimensions used for each model and alternative are summarized in table 3.12.

Table 3.12 - WWR and dimensions of the windows for each location and each alternative

Alternative	**Location**					
	Lisbon		**Bragança**		**Évora**	
	WWR (%)	**Dimensions (meters)**	WWR (%)	**Dimensions (meters)**	WWR (%)	**Dimensions (meters)**
W.**1** (Base)	24.08	1.88 x 1.88	24.55	1.80 x 1.80	24.08	1.70 x 1.70
W.**2**	34.00	2.10 x 2.30	33.41	2.10 x 2.10	33.33	2.00 x 2.00
W.**3**	14.00	1.45 x 1.45	14.85	1.40 x 1.40	14.08	1.30 x 1.30

3.4.5 Wall and Roof Modifications

To assess the impact of improved thermal insulation on the energy performance of residential buildings, this parameter focuses on modifying the thickness of the expanded polystyrene (EPS) insulation layer applied to the external walls and roof. All other components of the building envelope—including layer composition, materials, and construction geometry, were kept constant to ensure that only the insulation thickness influences the resulting thermal behaviour.

In the base model (Alternative WR.1), the EPS insulation has a thickness of 0.03 meters, commonly used in standard residential construction (Santos & Matias, 2010). Two additional alternatives were developed by increasing this thickness to 0.04 m and 0.06 m, for alternatives WR.2 and WR.3, respectively. These alternatives were uniformly applied to all base models across the different locations.

To quantify the thermal performance of each configuration, the resulting U-values of the external walls and roof were calculated automatically for each insulation level from the simulation software. These are shown in table 3.13. Lower U-values indicate better insulation performance and reduced heat transfer through the building envelope.

Table 3.13 - Wall and Roof modification on EPS thickness with the corresponding total U-Values

Alternative	**Wall and Roof EPS thickness (mm)**	**Total U-Value (W/m^2.ºC)**	
		Wall	**Roof**
WR.**1** (Base)	30	0.75	0.66
WR.**2**	40	0.65	0.56
WR.**3**	60	0.49	0.43

3.4.6 Horizontal Shading

To assess the impact of passive solar control on cooling loads during warmer periods, this parameter introduces horizontal shading devices (overhangs) above the windows of the reference models. The purpose of the overhangs is to reduce direct solar radiation entering the windows during the summer months, while still allowing solar gains in winter as it was described in the theory.

The design of the overhangs was based on solar geometry calculations, considering the solar altitude angle specific to each location. The methodology follows standard passive design principles, where the solar altitude is used to determine the projection length of the overhang that blocks direct sunlight during specific periods of the year.

A uniform solar altitude of 50° was chosen based on the solar chart for latitude 38° (representative of Lisbon), as this latitude closely matches the other locations studied (Bragança and Évora), making the variation negligible for the purpose of shading design.

The solar chart analysed for this purpose is described below, it was obtained with the solar chart's software *Benapoz*. In it, a line on the 50º solar altitude is discriminated to visually help understand at what time and period of the year is the shading taking over.

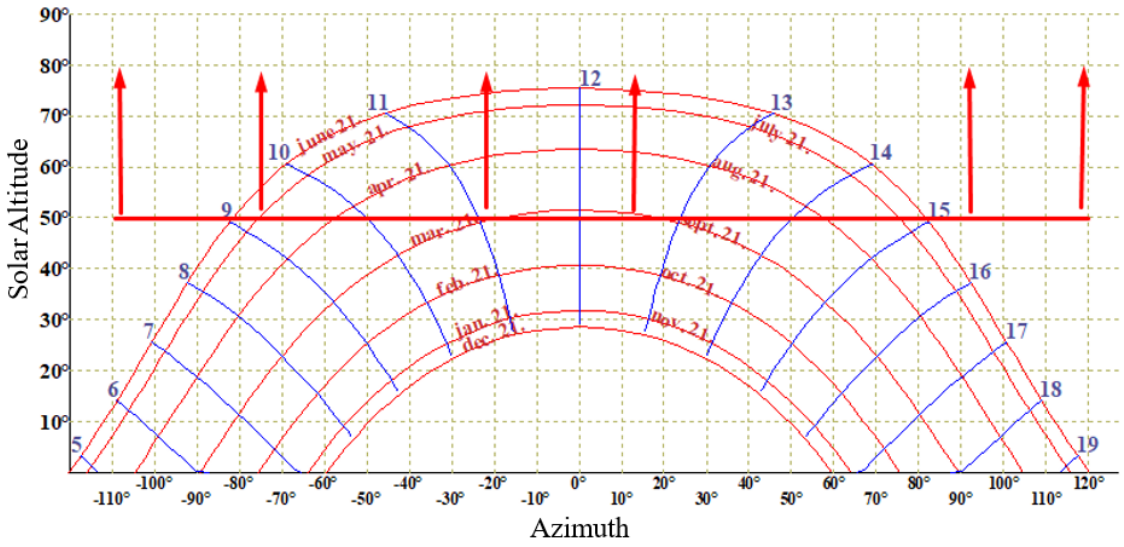


Figure 3.9 - Solar chart for Lisbon at the latitude of 38º N, as well as the 50º solar altitude discriminated. (*Benapoz* software)

This solar altitude was selected because it corresponds to the period between 21 April at 10:00 AM and 21 August at 2:00 PM, during which shading is most desirable due to elevated temperatures and higher solar gains. The goal was to ensure that direct sunlight is blocked during these peak periods, thereby reducing cooling demand.

Using the known geometric relationship between the solar altitude and shading projection, the overhang lengths were calculated using the following trigonometric equation, adapted from Duffie & Beckman, 2013, the base book for solar engineering:

$$\tan(solar\ altitude) = \frac{Window\ height}{Overhang\ projection} \tag{3.1}$$

For a visualization of the equation used to the real-world scenario, the figure below is presented.

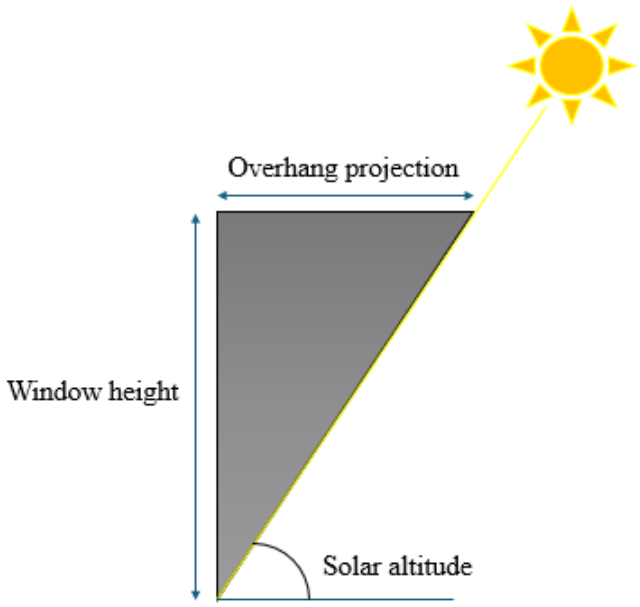


Figure 3.10 - Visualization of the relationship between solar altitude with the overhang projection and window height. (Author's figure)

Using these dimensions, the overhang lengths were individually calculated for each base model to ensure consistent performance relative to the specific window geometry. The final dimensions are presented in table 3.14.

Table 3.14 - Values obtained for the overhang projection for each location as well as the window height and solar altitude

Location	Alternative	Window height (m)	Solar altitude (º)	Overhang projection (m)
Lisbon	O.**1**	1.88	(base)	(base)
	O.**2**		50	1.57
Bragança	O.**1**	1.80	(base)	(base)
	O.**2**		50	1.51
Évora	O.**1**	1.70	(base)	(base)
	O.**2**		50	1.43

Only one alternative was modelled for this parameter: the inclusion of horizontal overhangs, sized to block direct solar radiation at a 50° solar altitude, and applied exclusively to the south-facing windows of the building. The south façade was selected because it receives the most consistent and intense solar gains in the Northern Hemisphere, making it the most effective orientation for horizontal shading devices. Overhangs were not applied to the east, west, or north façades, since these orientations are less suitable for fixed horizontal shading due to the low solar angles at sunrise and sunset.

All other variables - such as glazing type, window-to-wall ratio, wall and roof U-values, and internal, etc - remained the same, ensuring that any performance changes are attributable only to the shading intervention.

3.4.7 Optimized Model

After the individual evaluation of each passive design parameter - building orientation, ventilation strategy, window-to-wall ratio, envelope insulation, and horizontal shading - a final simulation model was created, combining the most effective alternative from each category. This "combined solution" represents an optimized version of the dwelling, tailored to each climatic context.

The objective of this approach is to analyse the cumulative effect of the selected passive strategies on thermal comfort and energy demand, compared to the base case. The combined model was simulated under the same conditions using *EnergyPlus*, and its performance is later evaluated in the Results section.

4 Results and Discussion

In this chapter the outputs generated in *EnergyPlus* are presented and interpreted. Graphs and key numerical indicators are used to expose how the three reference dwellings perform and how each passive-design measure alters that performance. By examining both the visual trends and the underlying values, the chapter exposes practical insights that feed back into the broader goal of identifying low-energy building strategies for Portuguese climates.

4.1 Exterior Climate Profile

A clear understanding of the surrounding climate is essential before any envelope or system parameter can be judged. Therefore, the first step was to map the hourly outdoor temperatures for Lisbon, Bragança and Évora over a full typical meteorological year. This baseline reveals the range of conditions the building must buffer against and provides the reference against which later design interventions are evaluated.

Daily outdoor dry-bulb temperatures for Lisbon (figure 4.1), Bragança (figure 4.2) and Évora (figure 4.3) are plotted side-by-side to frame the temperature conditions of the study. This climate gradient defines how hard the envelope must work before any active conditioning intervenes.

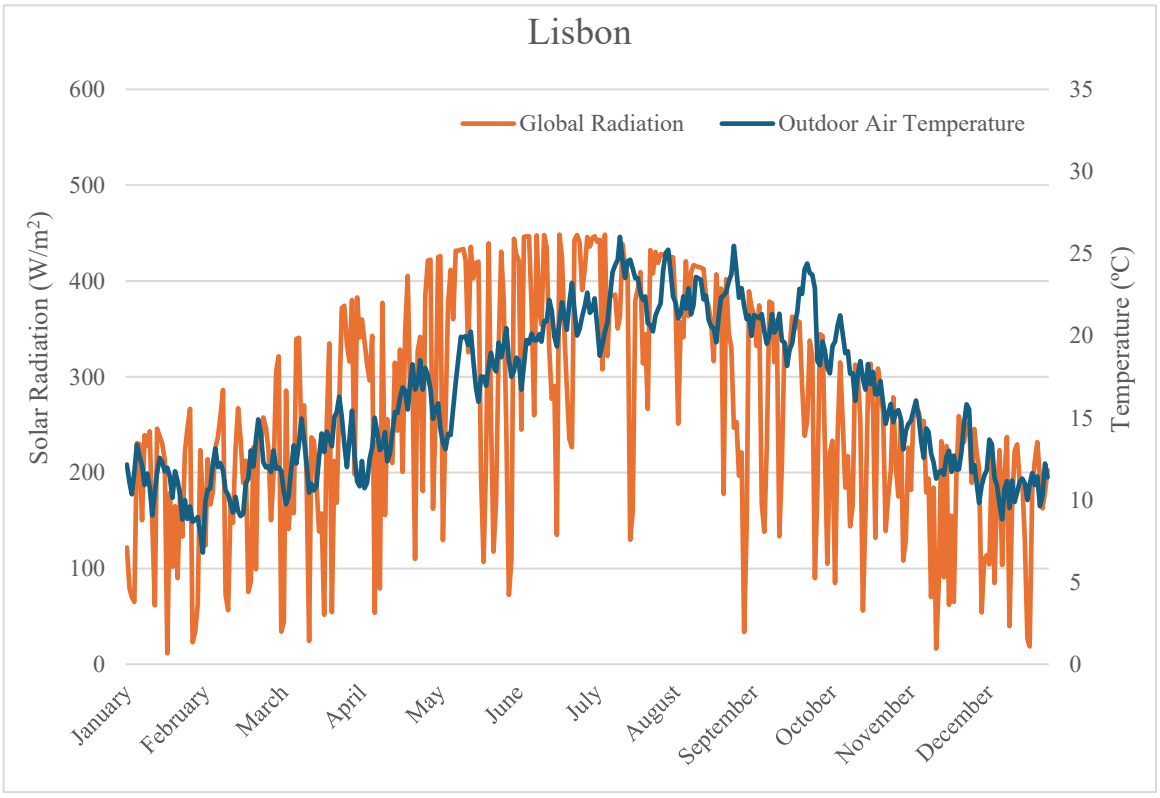


Figure 4.1 - Daily average outdoor dry-bulb temperature and global solar radiation for Lisbon during the run period.

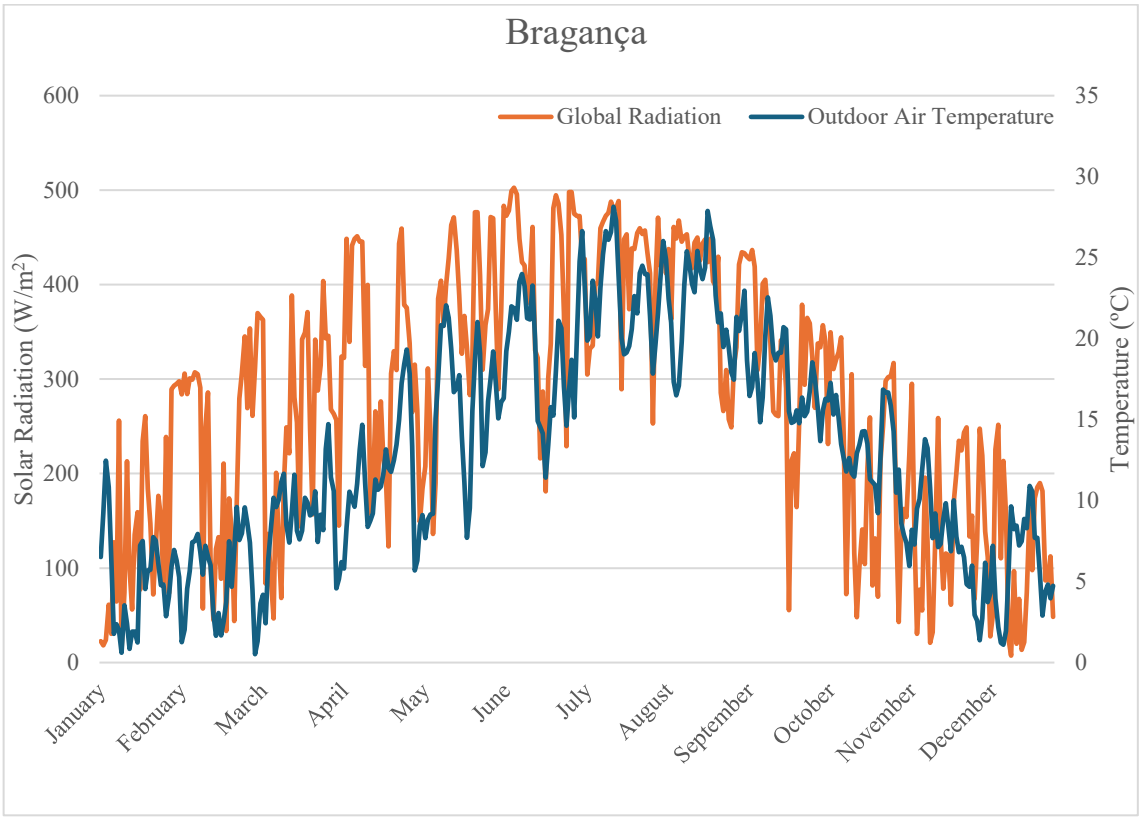


Figure 4.2 - Daily average outdoor dry-bulb temperature and solar radiation for Bragança during the run period.

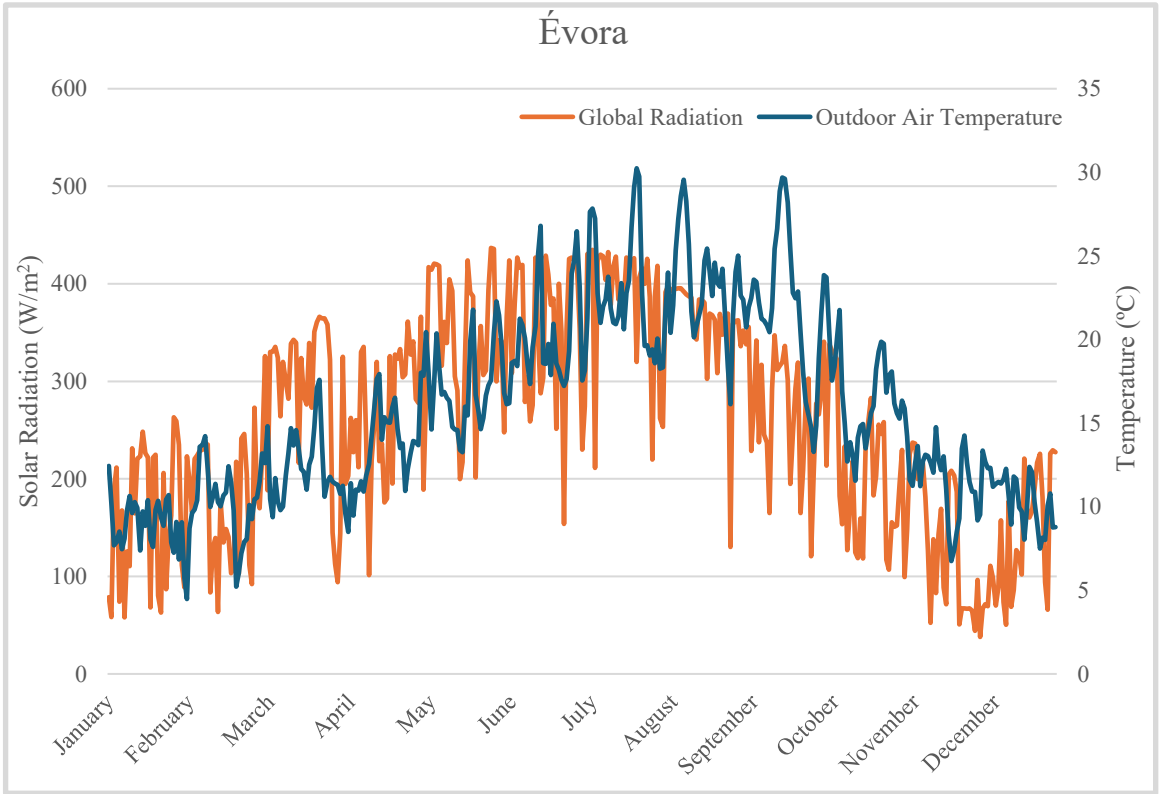


Figure 4.3 - Daily average outdoor dry-bulb temperature and global solar radiation for Évora during the run period.

4.2 Zone temperature profile – Base Models

To reveal the building's interior thermal behaviour, zone air temperatures are compared under two modes: set-point-controlled HVAC (18 °C heating / 25 °C cooling) and free-floating with the system disabled. Active control keeps conditions tightly inside the comfort band, while free-float lets temperatures sag below 18 °C in winter and above 25 °C in summer. The contrast highlights the scale of conditioning energy that later chapters will quantify.

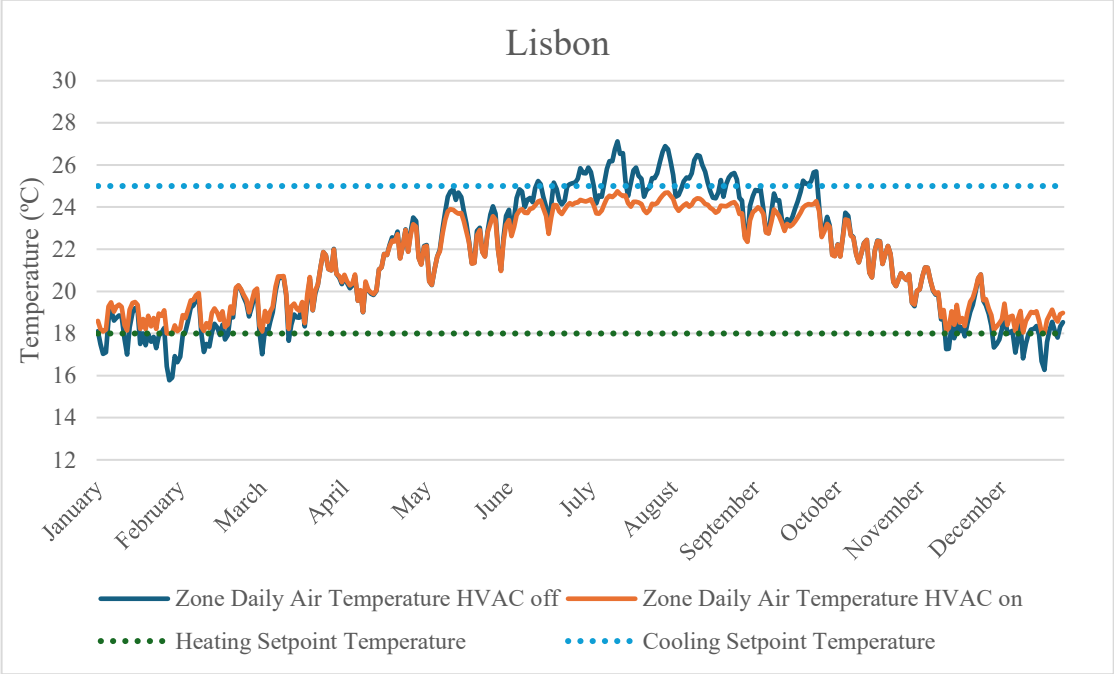


Figure 4.4 - Daily indoor zone mean temperature for Lisbon during the run period with HVAC off and on as well as the cooling and heating setpoints.

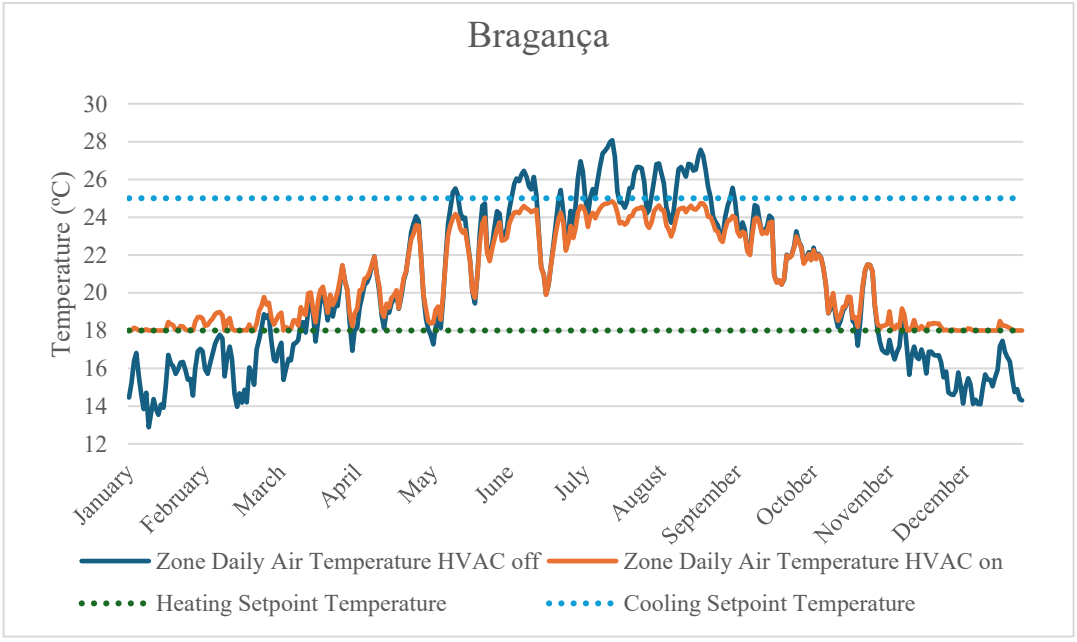


Figure 4.5 - Daily indoor zone mean temperature for Bragança during the run period with HVAC off and on as well as the cooling and heating setpoints.

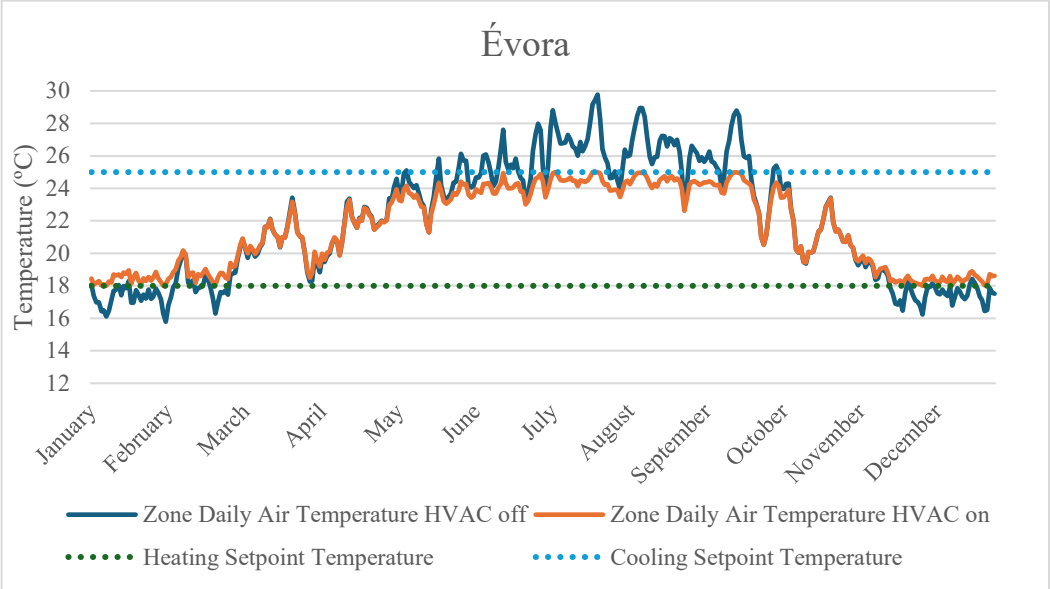


Figure 4.6 - Daily indoor zone mean temperature for Évora during the run period with HVAC off and on as well as the cooling and heating setpoints.

These results present the indoor air temperature profiles for the base-case dwellings in each location, comparing scenarios with and without HVAC operation. As expected, when the HVAC system is turned on, temperatures are consistently maintained within the defined comfort boundaries, confirming that the system responds effectively to both heating and cooling demands. This validates the base model's ability to meet thermal comfort requirements under controlled mechanical conditions and establishes a reference benchmark for evaluating passive design alternatives.

In contrast, the temperature profiles without HVAC reveal the natural thermal behaviour of the buildings and their sensitivity to local climate conditions. Bragança, with its northern latitude and cooler climate, shows the lowest mean indoor temperature at 20.3 °C. Lisbon follows with a slightly higher average of 21.5 °C, while Évora reaches 22.0 °C despite its more extreme climate, largely due to stronger solar gains. It is also important to consider that the dwelling models differ slightly in design and geometry across the three locations, which can independently influence indoor temperatures, regardless of external climate conditions.

To complement this analysis, the next figure illustrates the percentage of occupied hours spent within defined temperature intervals throughout the simulation period, with the HVAC turned off. This breakdown provides two key insights: first, it reveals the passive thermal performance of each building—how well the envelope alone maintains indoor comfort without mechanical intervention; second, it highlights the extent of unmet comfort hours, where indoor temperatures fall outside typical comfort thresholds. These exceedance hours indicate where and when mechanical systems (heating or cooling) would be required to maintain comfort, setting the stage for the performance evaluation of HVAC-supported scenarios and passive design improvements in the following sections.

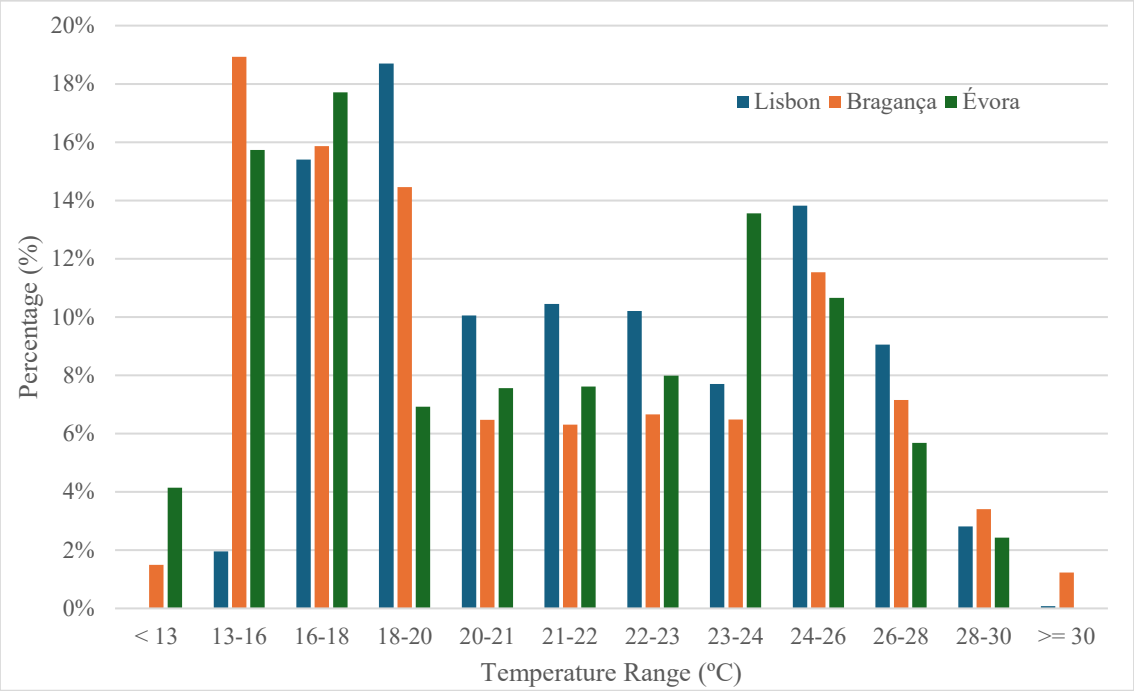


Figure 4.7 - Percentage of hours in the run period spent in each range of indoor temperatures inside the base models with HVAC turned off.

When no HVAC system is operating, indoor temperatures tend to follow the external climate patterns. This is clearly reflected in the percentage of unmet hours, particularly those falling outside the defined comfort band (18 °C for heating and 25 °C for cooling). In Bragança, 36% of the total hours fall below the heating setpoint, indicating a significant heating demand. Despite potential solar gains, the colder northern climate strongly influences the building's thermal conditions.

A similar trend is observed in Évora, where 38% of the hours fall below the heating setpoint—slightly more than in Bragança. Although Évora's climate is generally warmer, this outcome may be explained by the base model's specific characteristics. In particular, the Évora dwelling has a smaller internal area and potentially less thermal mass, which can lead to faster heat loss and greater temperature fluctuations. This suggests that, beyond the outdoor climate, building design and geometry play an important role in passive thermal regulation.

Lisbon performs better in this respect, with only 17% of the hours falling below the heating setpoint. However, when it comes to cooling, Lisbon shows a higher vulnerability: 26% of the total hours exceed the cooling setpoint, resulting in a total of 43% unmet comfort hours. Bragança, despite its cooler climate, experiences 23% of the hours above the cooling setpoint, leading to 59% of total hours outside the thermal comfort range. Évora records the lowest unmet hours above the cooling setpoint with 19% of the time exceeding, marking a total of 57% of total unmet hours.

This analysis highlights how passive performance varies not only with location and climate, but also with building form and internal characteristics. Another important insight is the distribution of unmet hours between heating and cooling: while Bragança's discomfort is mostly winter-driven, Lisbon and Évora exhibit more balanced challenges between heating and cooling seasons. This difference will be critical when selecting appropriate passive strategies and estimating mechanical energy needs in the next phases of the study.

The following table summarizes the percentage of unmet hours by location, distinguishing between those below the heating setpoint and those above the cooling setpoint.

Table 4.1 - Percentage of yearly hours that fall outside the thermal comfort boundaries during the run period, in each location.

Location	% Hours Below Heating Setpoint (<18 °C)	% Hours Above Cooling Setpoint (>25 °C)	Total Unmet Hours (% of the Year)
Lisbon	17%	26%	43%
Bragança	36%	23%	59%
Évora	38%	19%	57%

4.3 Energy Load - base models

In this section, the annual energy demands of the base models in Lisbon, Évora, and Bragança are presented, with HVAC systems active and operating within the defined comfort setpoints (18 °C for heating and 25 °C for cooling). These results serve as a benchmark against which the performance of passive design strategies will later be evaluated. Figure 4.3 presents these values in kWh/m^2.

Table 4.2 - Energy loads (cooling, heating and total) for the base models with HVAC on

Location	Cooling Load (kWh/m^2)	Heating Load (kWh/m^2)	Total (kWh/m^2)
Lisbon	11.7	5.9	17.6
Bragança	11.7	25.7	37.4
Évora	22.2	8.2	30.3

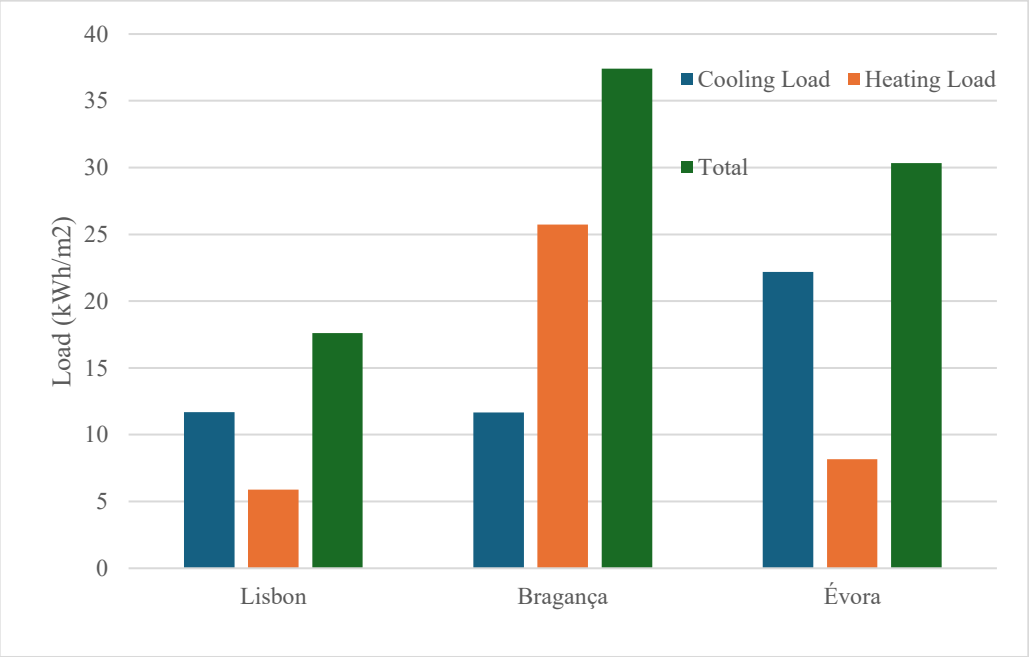


Figure 4.8 - Base model's cooling and heating loads for each location for the total simulation period.

To further illustrate the role of mechanical systems in ensuring thermal comfort, the following graph (figure 4.9) presents the percentage of occupied hours within specific temperature ranges for each location, this time with the HVAC system active. Unlike the previous free-floating scenario (figure 4.7), the results show a clear concentration of hours within the defined comfort zone (between 18 °C and 25 °C), confirming the system's ability to maintain indoor conditions within the comfort range throughout the year. A very small percentage of hours fall just outside these bounds, likely due to transient periods or control tolerances in system operation, which are typical in dynamic building simulations and do not significantly affect the overall thermal performance.

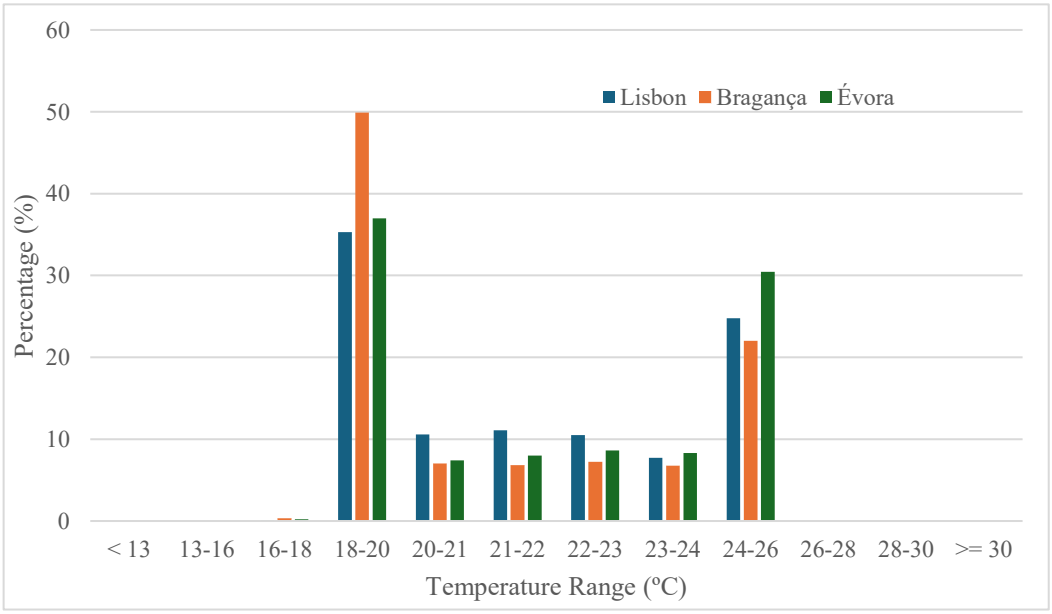


Figure 4.9 - Percentage of hours in the run period spent in each range of temperatures inside the base models with HVAC turned on.

4.4 Building Orientation

This section explores the impact of building orientation on the annual energy performance of the base model in each location. The analysis is performed independently for each city, maintaining all other variables constant, to isolate the influence of orientation alone. The results are presented in terms of specific energy loads (kWh/m²) for heating, cooling, and the combined total demand, allowing for a comparative understanding of how optimal orientation strategies vary depending on climatic context.

Table 4.3 - Energy loads (heating, cooling and total) for each location and each rotation angle of the building for the whole run period with the best rotation highlighted

Location	Rotation (º)	Cooling Load (kWh/m^2)	Heating Load (kWh/m^2)	Total (kWh/m^2)
Lisbon	0	11.7	5.9	17.6
	45	13.0	5.9	18.9
	90	11.4	5.4	16.7
	135	13.2	5.7	18.9
	180	12.0	5.7	17.7
	225	12.3	6.3	18.6
	270	10.1	6.0	16.1
	315	11.8	6.3	18.2
Bragança	0	11.7	25.7	37.4
	45	12.2	26.1	38.2
	90	9.5	25.1	34.6
	135	11.9	26.0	37.9
	180	11.6	25.7	37.3
	225	12.2	26.1	38.3
	270	9.6	25.2	34.7
	315	12.0	26.0	38.0
Évora	0	22.2	8.2	30.3
	45	22.1	8.2	30.3
	90	18.8	7.2	26.0
	135	23.3	7.4	30.7
	180	24.3	7.3	31.6
	225	23.1	7.5	30.6
	270	18.0	7.2	25.1
	315	21.3	8.0	29.3

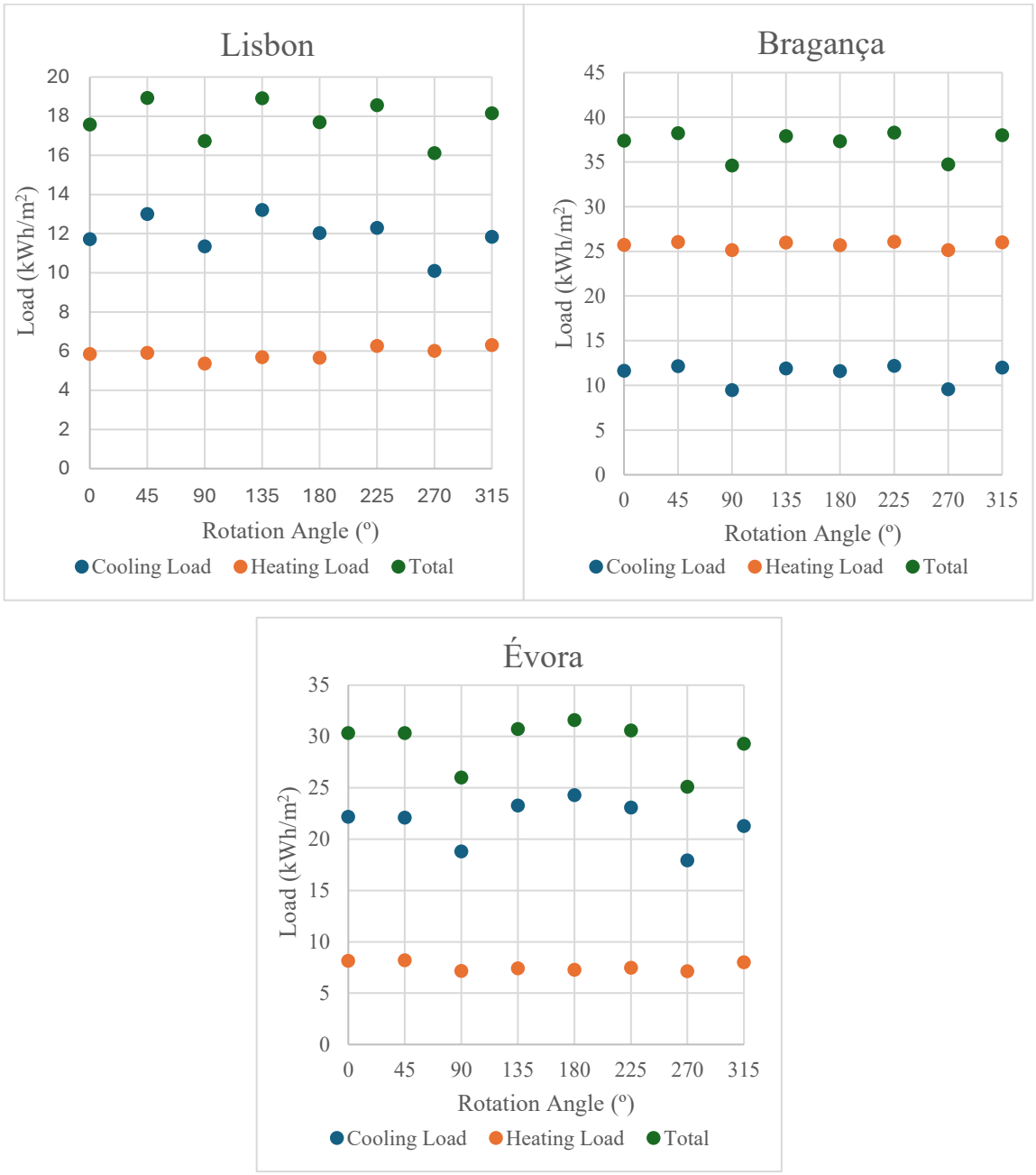


Figure 4.10 - Energy loads (heating, cooling and total) for each location and each rotation angle of the building for the whole run period.

- **Lisbon**

Analysing the Lisbon model, it is evident that building orientation significantly influences the energy demand required to maintain thermal comfort, in line with theoretical expectations. In Lisbon, the most energy-efficient orientation is the 270° rotation, where the façade with the highest window-to-wall ratio (32.13%) is facing north. This orientation minimizes solar gains through glazing, particularly during the warmer months, contributing to a reduction in cooling demand.

Overall, the cooling load in Lisbon consistently exceeds the heating load, reflecting the city's predominantly warm climate and the greater need for mechanical cooling throughout the year. The highest total energy demand occurs at a 45° orientation, where the west façade—and therefore the one with the largest glazing area—faces southwest. This position likely maximizes

solar heat gains through the windows, especially during the warmer periods of the year, thus increasing the cooling energy requirement to maintain comfort. This result raises the question of whether the façades with the highest glazed area contribute to a better energy performance when oriented toward the south. However, the data indicates that this is not necessarily the case. Configurations where the largest glazed façades face southeast and southwest tend to have better energy result for heating load but worst for cooling load, making the overall energy load higher. This can be attributed to the angle of solar incidence: southeast and southwest facing windows receive more direct sunlight during the morning and late afternoon hours, respectively — periods when solar radiation enters at low angles and penetrates deeper into the interior spaces while maintaining a part of the high solar altitude incident radiation, heating the building to a higher extent.

When isolating the heating load, the lowest value is observed when the largest glazed façade (originally west-facing) is rotated toward the south. This suggests that increased solar exposure during the colder months is beneficial for passive heating. Although this result may initially appear to contradict the previous observation, it becomes clearer when both heating and cooling loads are considered separately. Orienting the largest glazed area toward the south tends to reduce the heating load effectively, as it maximizes solar gains during the winter months. However, this same orientation can lead to increased cooling loads during warmer periods because of the layout of the other façades. In comparison, other orientations may perform better in terms of limiting cooling demand, even if they are less efficient for heating.

Comparing the best and worst alternatives (270° and 45°, respectively), the optimal orientation results in a 14.9% reduction in total annual energy consumption. This underscores the relevance of considering solar exposure and glazing distribution when orienting a building for energy efficiency in Lisbon’s climate.

- **Bragança**

Bragança, characterized by a colder and more severe climate, exhibits a clear dominance of heating demand over cooling, which is reflected in the higher heating loads across all orientations. In such climates, optimizing solar gains becomes essential for reducing energy consumption, particularly for space heating.

The building's façade design features a higher window-to-wall ratio (29.45%) on the east and west sides, which significantly influences performance when the building is rotated. The most efficient orientation occurs at 90°, where the façades with greater glazing face north and south. This setup minimizes exposure to low-angle morning and afternoon sun from the east and west, which tends to result in undesirable heat gains during warmer periods and less useful solar input in colder months.

The least efficient orientation is at 225°, where the façades with the highest glazing now face northeast and southwest. This orientation may lead to increased solar gains during the summer afternoons, with the low-angle sun exposure, through the southwest-facing façade, contributing to higher cooling loads. At the same time, during winter, the northeast-facing façade receives limited solar exposure, reducing the opportunity for passive heating when it's most needed. Additionally, this orientation might be suboptimal for capturing winter sun due to less direct exposure throughout the day.

Overall, the worst-performing orientation (225°) consumes 10.1% more energy than the best-performing one (90°), underlining the importance of aligning high-glazed façades with orientations that balance solar gains throughout the seasons.

- **Évora**

In Évora's climate, the cooling load is more than twice as high as the heating load, clearly reflecting the region's hot and dry summers. The best-performing orientations are at 90° and 270°, where total energy demand is minimized. This performance can be attributed to the interaction between solar exposure and the window-to-wall ratios of each façade.

In the 270° orientation, the best scenario, the façade with the lowest window-to-wall ratio (12.04%) faces west, while now, the south and north, façades have the higher glazing ratio (28.09%). This combination allows the building to benefit from early, lower-intensity solar gains while minimizing afternoon overheating, which is particularly intense from southwest and west exposures in Évora's summer climate. As such, this orientation offers a more balanced distribution of solar gains and promotes better thermal regulation, reducing the need for mechanical cooling.

Conversely, the worst-performing orientation is 180°, where the façade with the lowest window-to-wall ratio faces due north, minimizing solar gain throughout the year. As a result, the more glazed façades are directed toward south, east, and west, increasing solar exposure during both morning and afternoon periods. This leads to higher internal heat gains and significantly elevates the cooling load.

Overall, the worst orientation consumes 20.5% more energy than the best-performing one, reinforcing the importance of orientation in passive design.

4.5 Ventilation

To evaluate the impact of natural ventilation and infiltration on the building's energy performance, a parametric analysis was conducted by varying the air changes per hour (ACH) across four alternatives. The base model assumes 0.5 ACH, representing a relatively airtight dwelling, as is expressed as the minimum for the Portuguese legislation (Portugal, 2021). This value was gradually increased in three additional alternatives: 2 ACH, 3.5 ACH, and 5 ACH. These values simulate progressively more naturally ventilated buildings, and their impact on the heating, cooling, and total energy loads was analysed across the three studied locations. The results are presented in the column charts below.

Table 4.4 - Energy load (heating, cooling, and total) for different ACH uniformly increased values throughout the simulation period

Location	Alternative	Cooling Load (kWh/m^2)	Heating Load (kWh/m^2)	Total (kWh/m^2)
Lisbon	V.1	11.7	5.9	17.6
	V.2	14.3	35.6	50.0
	V.3	18.7	74.2	92.9
	V.4	23.6	115.7	139.3
Bragança	V.1	11.7	25.7	37.4
	V.2	13.9	95.8	109.7
	V.3	17.6	181.6	199.1
	V.4	21.6	256.4	277.9
Évora	V.1	22.2	8.2	30.3
	V.2	23.8	44.2	68.0
	V.3	28.2	89.4	117.6
	V.4	33.4	138.0	171.4

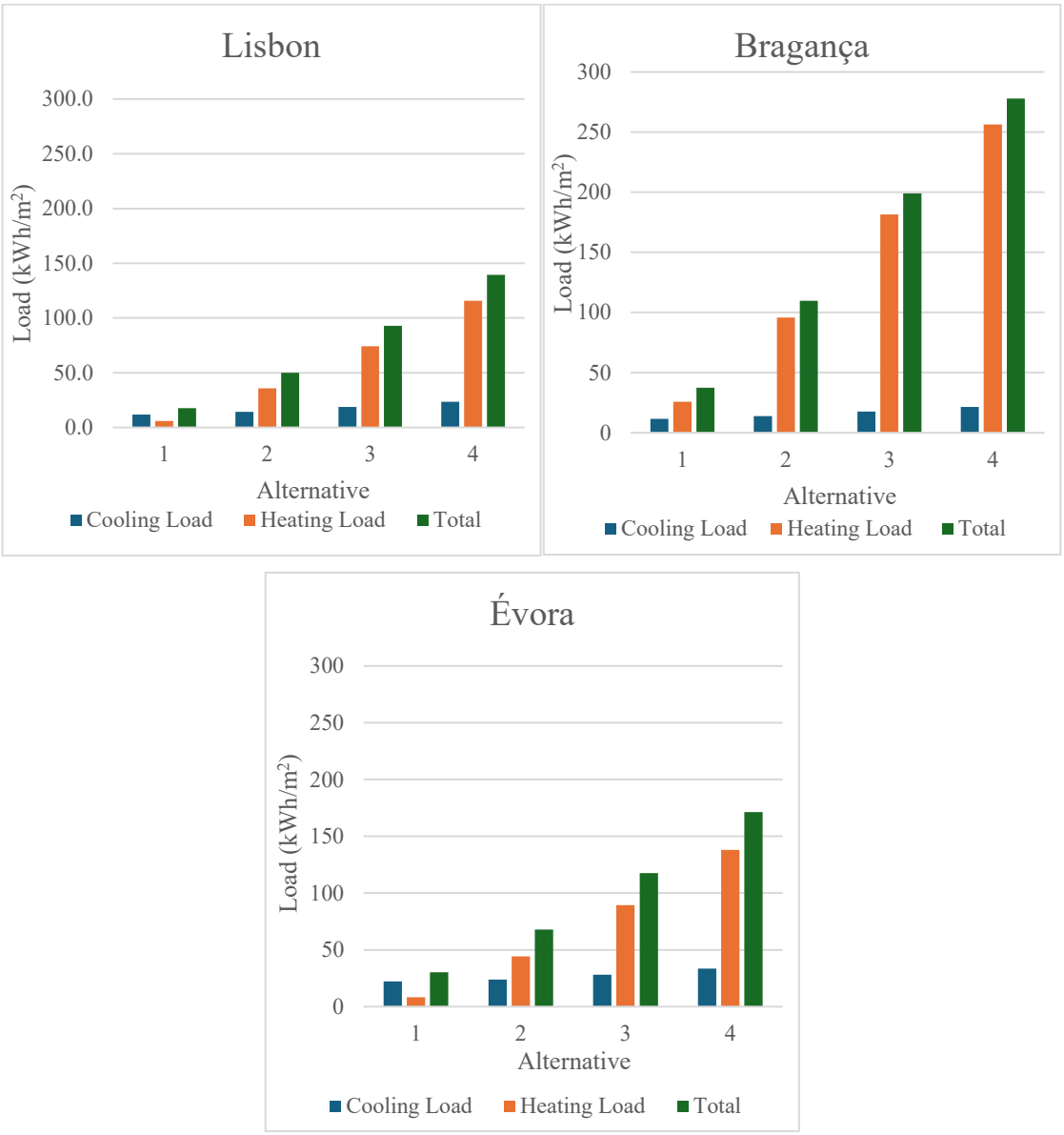


Figure 4.11 - Energy load (heating, cooling, and total) for different ACH uniformly increased values throughout the simulation period.

A clear trend emerges across all locations: increasing the ACH has a significantly larger impact on the heating load than on the cooling load. While cooling demand rises modestly with higher ACH values, heating demand escalates sharply. This is expected, as increased air exchange during colder periods leads to greater heat losses. As outdoor cold air replaces indoor conditioned air more frequently, the mechanical system must work harder to maintain thermal comfort, thereby increasing heating energy consumption. In contrast, during hotter periods, the effect of ventilation is somewhat mitigated by the smaller temperature gradient between indoor and outdoor conditions, which limits the impact on cooling loads.

It is evident that increasing air changes per hour (ACH) has a significantly greater impact on the heating load in colder climates. In Bragança, for instance, the heating demand more than doubles compared to Lisbon under the same ventilation conditions. This reflects how sensitive cold climates are to infiltration: when more cold outdoor air enters the building, the mechanical system must work harder to maintain indoor comfort, leading to a sharp increase in energy consumption.

In contrast, Lisbon and Évora, with their milder winters, experience a comparatively smaller rise in heating load as ACH increases. As for cooling loads, these also rise slightly across all locations with increased ACH, but not to the same extent as heating. This moderate increase may be due to the potential for ventilation to aid in dissipating heat during cooler nighttime periods, helping to regulate indoor temperatures and reducing the burden on active cooling systems.

These results underline the importance of airtightness, especially in colder environments, where uncontrolled infiltration can drastically raise energy needs. However, this introduces a key trade-off: while tighter envelopes reduce energy consumption, they may compromise indoor air quality. Adequate ventilation is essential for maintaining healthy indoor environments, and higher ACH values can improve air quality but at the cost of increased thermal load.

According to current regulations, the minimum ventilation rate is set at 0.5 ACH, which must be met. Yet, these findings suggest that a dynamic approach — where ventilation rates are seasonally adjusted — could be more effective. Lower ACH values in winter could preserve heating energy, while higher rates in summer would improve air quality and potentially aid cooling. This balance between energy efficiency and indoor air quality will be further explored in the next chapter.

4.6 Seasonal Ventilation

Following the previous analysis on the impact of air changes per hour (ACH) on energy loads, this chapter explores an alternative ventilation strategy: applying different ACH values for the summer and winter seasons. The goal is to investigate whether seasonal adjustment of natural ventilation can optimize indoor thermal comfort while minimizing energy consumption aligned with air quality inside the dwelling also. Specifically, the approach considers increasing ACH during summer months to enhance heat dissipation and improve indoor air quality, while maintaining ACH during winter to limit heat loss and maintain a lower heating demand.

The following figures present the results of this strategy applied to each of the three case study locations, detailing the respective heating, cooling, and total loads under the seasonal ventilation scenario.

Table 4.5 - Energy load (heating, cooling, and total) for ACH seasonally changed values throughout the simulation period

Location	Alternative	Cooling Load (kWh/m^2)	Heating Load (kWh/m^2)	Total (kWh/m^2)
Lisbon	SV.**1**	11.7	5.9	17.6
	SV.**2**	13.8	6.6	20.4
	SV.**3**	17.6	8.8	26.4
	SV.**4**	21.8	12.6	34.4
Bragança	SV.**1**	11.7	25.7	37.4
	SV.**2**	13.9	30.5	44.4
	SV.**3**	17.6	38.7	56.3
	SV.**4**	21.6	48.5	70.1
Évora	SV.**1**	22.2	8.2	30.3
	SV.**2**	23.9	8.8	32.6
	SV.**3**	28.2	11.1	39.3
	SV.**4**	33.3	14.9	48.2

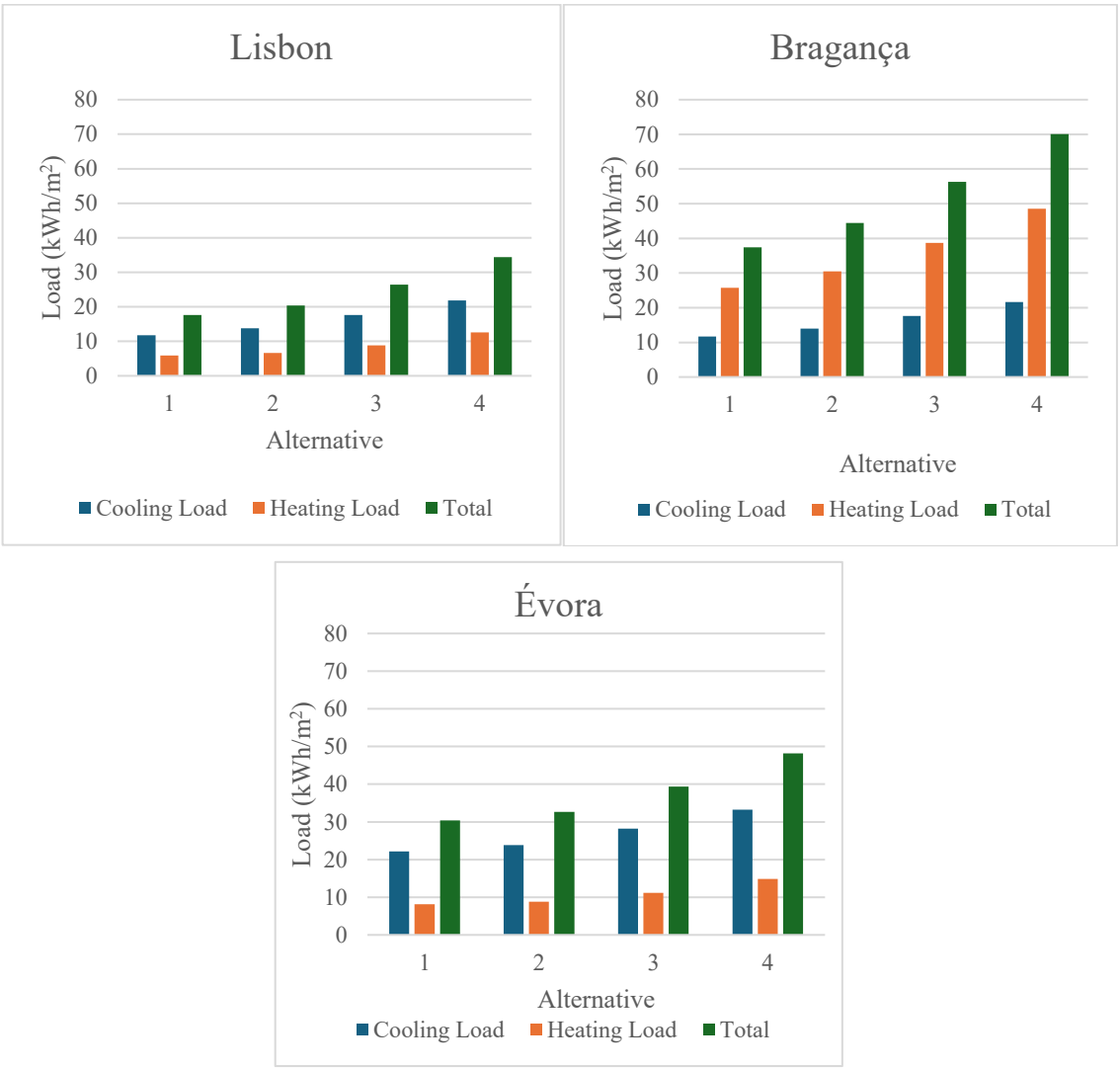


Figure 4.12 - Energy load (heating, cooling, and total) for ACH seasonally changed values throughout the simulation period.

When applying differentiated ventilation rates between summer and winter seasons, several key trends emerge across the three locations. Most notably, energy consumption increases more gradually and steadily compared to the uniform ventilation scenarios. This is primarily due to the consistent winter ACH being maintained at 0.5 across all alternatives, which avoids the sharp increases in heating loads observed when winter ventilation was also intensified. This supports the conclusion that increased air changes during the winter are the primary driver of elevated heating demand, especially in colder climates.

In Lisbon and Évora, the results also show a reversal compared to the uniform ACH scenario: cooling loads now surpass heating loads. This is expected given the warmer climates and the increased summer ventilation, which allows more hot outdoor air to enter the indoor space, raising the internal temperatures and prompting the mechanical system to work harder to maintain thermal comfort. However, the rate of increase in cooling demand remains lower than that observed for heating in the previous uniform scenarios, demonstrating that summer ventilation has a less aggressive impact on energy consumption than winter ventilation.

This suggests that while increasing summer ACH raises energy use, the magnitude of this impact is moderate enough that it could potentially be justified by improvements in indoor

air quality — an essential consideration in ventilation design. Therefore, a regulated increase in summer ventilation may be a promising compromise between thermal comfort and air quality, particularly in climates where overheating is a concern.

In the case of Bragança, the regional climate remains the dominant factor. Even when only summer ACH is increased, heating loads continue to be significantly higher than cooling loads, underlining the persistent need for heating in colder northern regions.

4.7 Window-to-wall Ratio

The window-to-wall ratio (WWR) plays a key role in a building's thermal performance, directly influencing solar heat gains, internal daylight levels, and overall energy demand. To assess its impact, this study compares three alternatives for each location: the base model with a WWR around 24%, an increased WWR (33%), and a reduced WWR (14%). These variations were applied uniformly across all façades of the building, allowing for a consistent evaluation of their effect on heating, cooling, and total energy loads.

The following figures present the simulation results for Lisbon, Bragança, and Évora, illustrating the influence of WWR on seasonal and annual energy requirements. After the table, three graphs were made, providing a more visually clearer picture of the performance of each alternative. The subsequent discussion will analyse these trends in detail and explore their implications for energy efficiency and design decision-making.

Table 4.6 - Loads for the WWR parameter change for each location

Location	Alternative	Cooling Load (kWh/m^2)	Heating Load (kWh/m$^{2)}$	Total (kWh/m^2)
Lisbon	W.**1**	11.7	5.9	17.6
	W.**2**	22.1	5.6	27.7
	W.**3**	4.3	6.8	11.0
Bragança	W.**1**	11.7	25.7	37.4
	W.**2**	21.2	24.9	46.0
	W.**3**	5.2	28.2	33.4
Évora	W.**1**	22.2	8.2	30.3
	W.**2**	38.0	8.0	46.0
	W.**3**	10.0	9.5	19.5

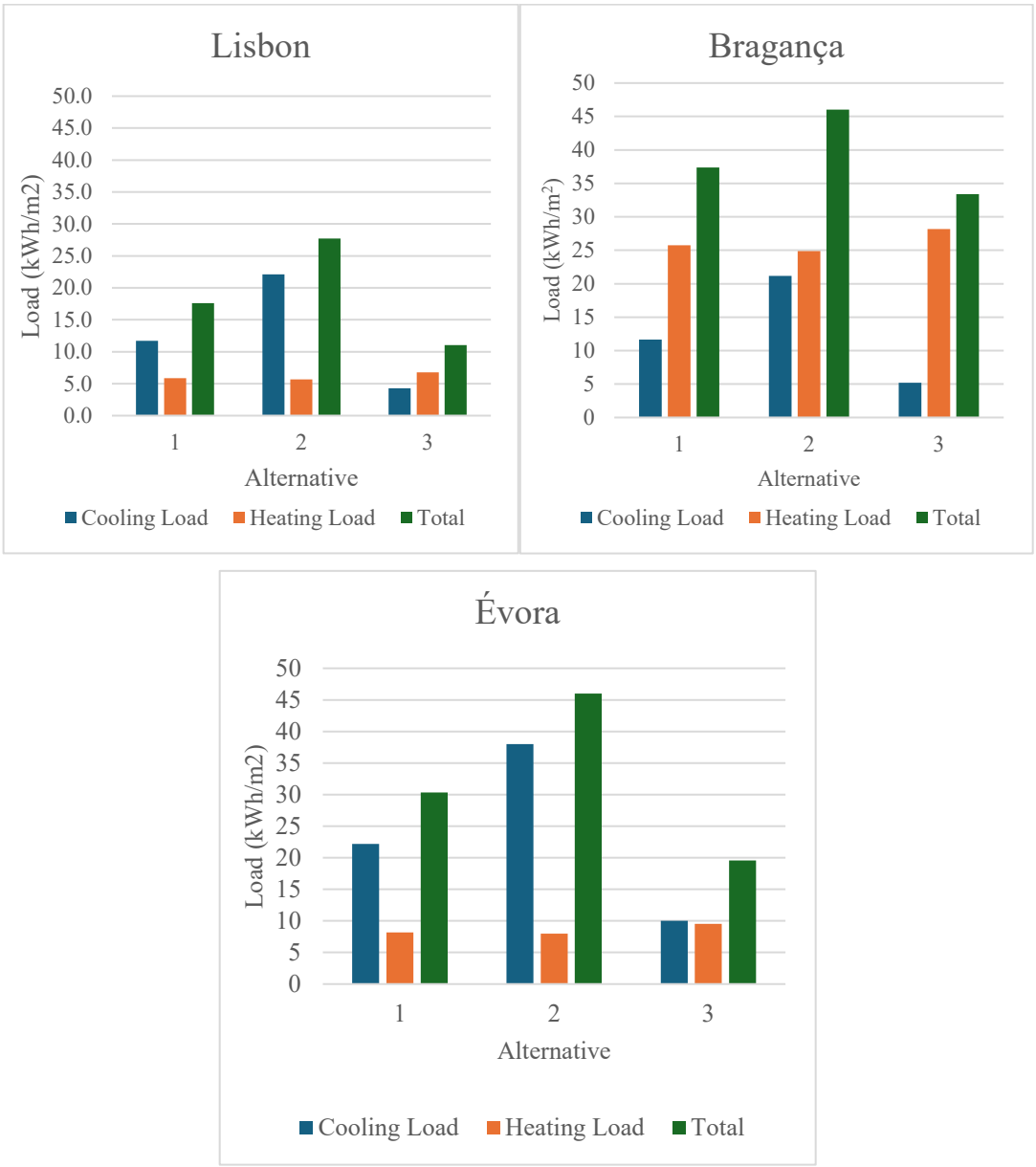


Figure 4.13 - Energy load (heating, cooling, and total) for different WWR values for the simulation period.

A clear and consistent trend emerges from the analysis of the window-to-wall ratio (WWR) variations across all locations: an increase in WWR leads to higher total energy loads, while a reduction results in lower energy demands. This behaviour aligns with theoretical expectations. Larger window areas allow more solar radiation to enter the building, intensifying indoor temperatures during warmer months and driving up cooling requirements. Conversely, smaller window areas reduce solar heat gains, helping stabilize indoor temperatures and reducing energy loads.

Among all load types, cooling demand is most affected by changes in WWR, with heating loads remaining relatively stable across variations. This is particularly evident in Lisbon. In the base case, the cooling demand exceeds the heating demand, but with a reduced WWR (Alternative 3), the cooling load drops significantly — becoming nearly half of the heating load. This shift underscores how windows act as major conduits for unwanted heat gain in summer yet contribute comparatively less to passive heating in winter.

That said, it's important to note that an increase in WWR does result in a slight reduction in heating load, suggesting that passive solar gains during colder periods still occur. However, this effect is relatively minor compared to the sharp rise in cooling demand, particularly in warm climates. This reinforces the idea that heating benefits from solar gains via windows are limited, especially when compared to the overheating risks during summer.

Given this dynamic, shading devices could emerge as a valuable strategy. If larger window areas are desired — for daylighting, views, or aesthetic reasons — then incorporating external or integrated shading solutions can help mitigate excessive solar gains during summer, without significantly impeding winter solar heat contributions. Shading becomes especially impactful in climates where cooling dominates the energy profile. By reducing overheating while preserving access to daylight, it offers a balanced approach to comfort and performance.

Ultimately, these findings suggest that optimal design should not aim solely to minimize window area to reduce energy demand. Instead, a thoughtful combination of moderate WWR, strategic orientation, and effective shading provides a more sustainable and responsive solution enhancing both thermal and visual comfort and reducing energy use across seasons.

4.8 Wall and Roof Modifications

This section explores the influence of increased thermal insulation in the opaque elements of the envelope, specifically the walls and roof, on the overall energy performance of the dwelling. Three levels of insulation were tested: the base case (Alternative 1), followed by Alternatives 2 and 3, which increase insulation thickness by 10 mm and 30 mm, respectively. The following results are presented through comparative graphs for each location, supported by a summary table with the corresponding numerical values.

Table 4.7 - Loads for the wall and roof parameter change for each location

Location	Alternatives	Cooling Load (kWh/m^2)	Heating Load (kWh/m^2)	Total (kWh/m^2)
Lisbon	WR.**1**	11.7	5.9	17.6
	WR.**2**	11.2	5.1	16.2
	WR.**3**	10.4	4.0	14.4
Bragança	WR.**1**	11.7	25.7	37.4
	WR.**2**	11.1	23.0	34.0
	WR.**3**	10.3	19.4	29.7
Évora	WR.**1**	22.2	8.2	30.3
	WR.**2**	21.3	7.0	28.3
	WR.**3**	20.0	5.6	25.7

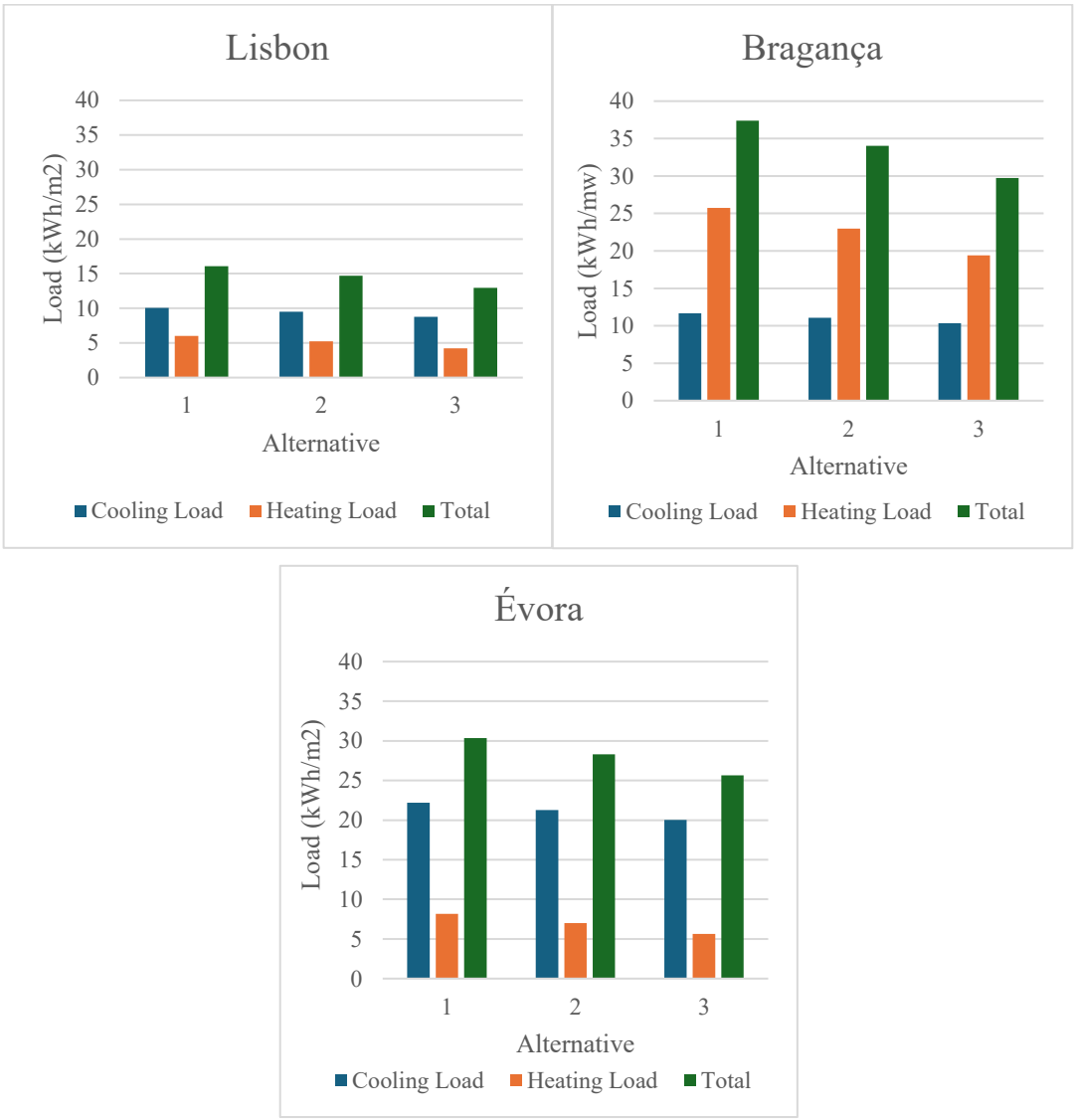


Figure 4.14 - Energy load (heating, cooling, and total) for different insulation thickness values for the simulation period.

As expected, increasing the insulation thickness of the roof and walls results in a reduction of both heating and cooling loads across all locations. This parameter behaves consistently regardless of the climate, indicating that enhanced insulation effectively improves thermal performance in both warm and cold environments.

The reduction in energy demand is more significant for heating loads, a trend observed uniformly across the three cities. This aligns with the theoretical principle that insulation reduces heat loss from the interior, thereby decreasing the energy required to maintain comfortable indoor temperatures during colder periods. A similar effect is observed for cooling loads, though to a lesser extent. In this case, insulation helps retain the cooler air provided by the mechanical system and slows down heat gain from outside.

However, the relationship between insulation thickness and energy savings is not linear. In Alternative 2, an increase of 10 mm in insulation leads to an approximate 10% reduction in energy consumption. In contrast, Alternative 3 increases insulation by 30 mm—three times more—but the energy savings do not triple in response. This diminishing return highlights the importance of identifying an optimal insulation thickness. Excessively thick insulation may not

be cost-effective, as the energy savings gained may not justify the additional material and construction costs.

4.9 Horizontal Shading

The final parameter evaluated in this study is the implementation of fixed overhangs for shading. Overhangs were applied to the south windows in all locations. Their projection depth was based on an optimized solar altitude of 50°, resulting in an overhang-to-window height ratio of 0.84. This configuration aimed to balance shading during the hotter months with solar access during the winter season, as described in the methodology. The next table expresses the result obtained from the base model and the model with the overhangs.

Table 4.8 - Loads for the shading parameter change for each location

Location	Alternative	Cooling Load (kWh/m²)	Heating Load (kWh/m²)	Total (kWh/m²)
Lisbon	O.**1**	11.73	5.85	17.58
	O.**2**	11.55	5.92	17.47
Bragança	O.**1**	11.66	25.73	37.40
	O.**2**	11.48	25.87	37.35
Évora	O.**1**	22.19	8.16	30.35
	O.**2**	22.12	8.23	30.35

The results from the overhang simulations, applied exclusively to the windows on the south-facing façade, were aligned with theoretical expectations, albeit with minimal overall impact. As anticipated, the overhangs reduced the cooling load slightly due to shading during warm months, while heating loads increased marginally as in some days the overhang can block positive solar gains. This balance, although, made the net effect on total annual energy load negligible.

For example, in Lisbon, the base model's energy demand was 17.58 kWh/m², and with the addition of south-facing overhangs, this dropped only to 17.47 kWh/m² — a difference of just 0.11 kWh/m². In Évora, the balance was even more neutral: although the cooling load decreased, the increase in heating demand offset any potential gain, resulting in virtually no change in the total load. This outcome can be explained by the low glazed area on the south façade in Évora, where only one window is shaded by the overhang, thus minimizing its effectiveness. Looking at Bragança, the difference between the base model and the overhang use is just 0.05 kWh/m², even lower than in Lisbon. As Bragança has a harsh climate in terms of heating needs, as analysed before, the impact on the heating load is higher, with 0.14 kWh/m² surplus when compared with the base model.

These results reaffirm the theoretical principle that overhangs are most effective in reducing solar heat gain during warmer seasons, particularly in climates where cooling demand dominates. However, their effectiveness depends heavily on both window size and orientation, and their application should be prioritized in designs where larger glazed areas face high sun angles. Is then predicted that a building with high glazed area on the south façade would have a non-despised energy load reduction.

While the simulation did not reveal substantial energy savings, it confirms the directional logic of the strategy: overhangs are intended to cut solar radiation during periods of high sun (summer) while allowing beneficial gains in winter when the sun is lower.

However, fixed overhangs should not be dismissed entirely. Their value extends beyond thermal performance, contributing to improved occupant comfort by reducing glare and regulating daylight penetration. It's important to note that while they decrease solar incidence, this can result in either improved indoor light quality—by filtering direct sunlight and favouring diffuse light—or in reduced daylight availability, potentially increasing the need for artificial lighting. This balance must be carefully assessed to avoid undermining visual comfort and lighting efficiency.

Additionally, the fixed nature of these overhangs is a limitation. Operable or dynamic shading systems could better adapt to seasonal and daily solar variations, optimizing both cooling and heating loads depending on the conditions. Further exploration of such adjustable shading strategies may yield more substantial energy savings and greater overall performance.

4.10 Combined Solutions

After analysing the performance of individual passive design strategies, a final simulation was carried out to evaluate the impact of integrating the best-performing parameters into a single, optimized building model. The objective of this combined scenario is to minimize the building's overall energy demand, particularly the mechanical energy required for heating and cooling, and thereby reduce reliance on active systems.

It is important to note that this combined analysis focuses solely on the thermal performance and resulting energy loads. Parameters such as indoor air quality and natural lighting levels were not explicitly evaluated and are assumed to meet the minimum regulatory requirements. As such, the primary goal of this model is to explore the potential energy savings achievable through passive design measures alone, based on thermal behaviour over the annual simulation period.

The table below summarizes the configuration of the optimized model for each location, including adjustments to orientation, glazing, shading, ventilation, and wall and roof modifications. These tailored combinations reflect the best-performing strategies identified for each climate zone in the earlier simulations and form the basis for the final energy performance comparison.

In the table and graph that follow, the results of the base and optimized models are presented for each location, allowing for a clear visual comparison of the energy savings achieved through this integrated passive design approach.

Table 4.9 - Parameters used in the optimized passive design models for each location

Location	Model	Rotation (º)	Ventilation (ACH)	Total WWR (%)	Wall and Roof (EPS thickness, m)	Shading
Lisbon	Base	0	0.5	24.1	0.03	No
	Optimized Model	270	0.5	14.0	0.06	South windows
Bragança	Base	0	0.5	24.6	0.03	No
	Optimized Model	90	0.5	14.9	0.06	No
Évora	Base	0	0.5	24.1	0.03	No
	Optimized Model	270	0.5	14.1	0.06	South windows

Table 4.10 - Energy load (heating, cooling and total) for the base and combined model in each location for the simulation period

Location	Alternative	Cooling Load (kWh/m^2)	Heating Load (kWh/m^2)	Total Load (kWh/m^2)
Lisbon	Base Model	11.7	5.9	17.6
	Optimized Model	2.2	4.8	7.1
Bragança	Base Model	11.7	25.7	37.4
	Optimized Model	3.1	20.4	23.5
Évora	Base Model	22.2	8.2	30.3
	Optimized Model	5.9	5.5	11.4

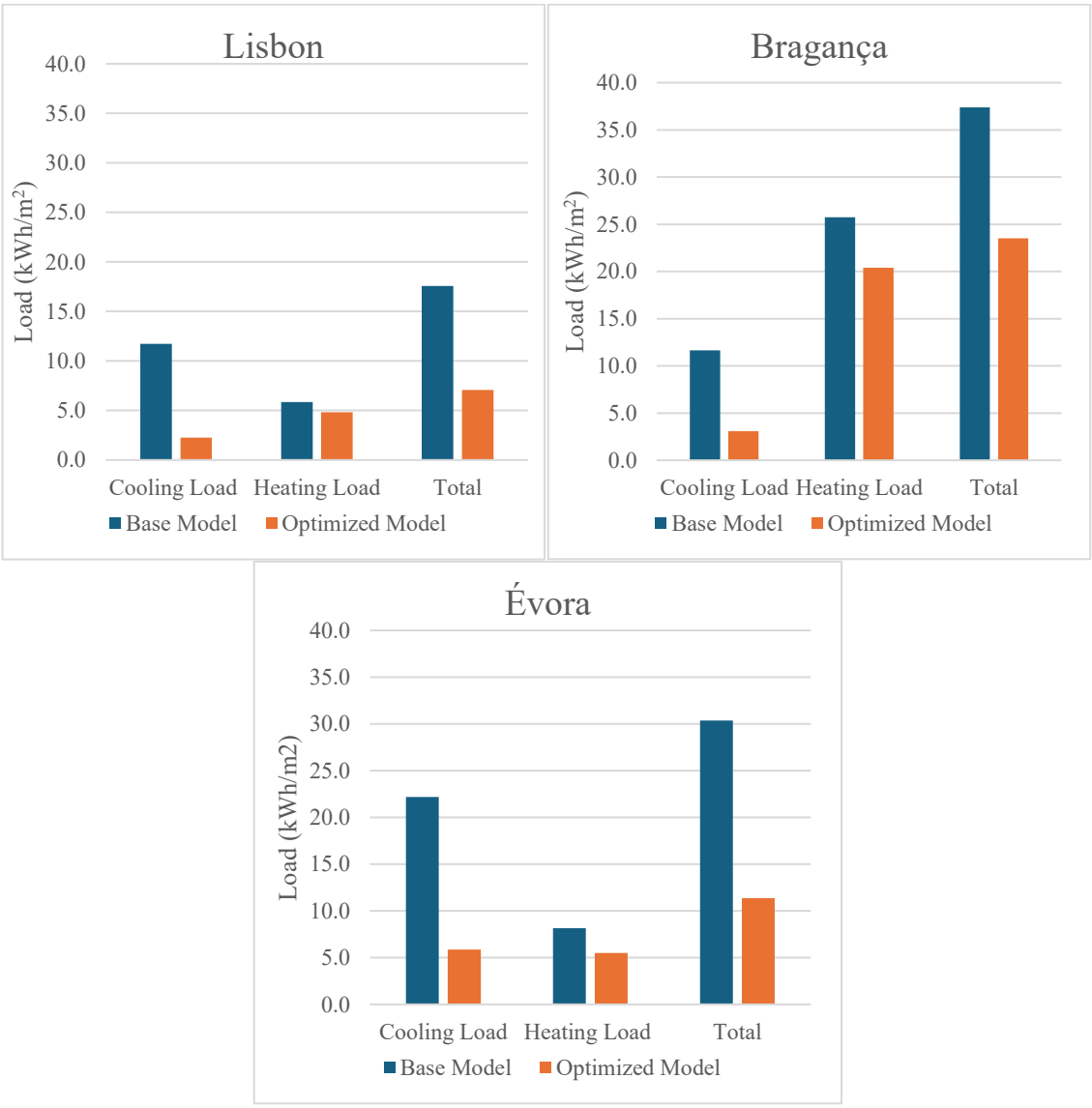


Figure 4.15 - Energy load (heating, cooling and total) for the base and optimized model for each location during the simulation period.

As expected, this comprehensive strategy led to a significant reduction in total annual energy use for thermal comfort. In Lisbon, the energy demand dropped from 17.6 kWh/m² in the base case to 7.1 kWh/m² in the optimized model, representing a reduction of over 60%. In Bragança, the load decreased from 37.4 kWh/m² to 23.4 kWh/m² — nearly 40% less energy. And in Évora, where the climate combines both hot summers and relatively mild winters, the results were particularly striking: a reduction from 30.3 kWh/m² to just 11.4 kWh/m², amounting to an energy savings of approximately two-thirds.

This dramatic drop can be attributed to the cumulative effect of multiple passive strategies acting in synergy. Optimizing the building's orientation allowed solar gains to be limited appropriately depending on the season. For Évora's optimized model, the new south façade has 28.90% of glazed area, the same as the new north façade. The same happens to Bragança's optimized model, the new south and north façades have the same and highest glazed with a WWR of 29.45. For Lisbon's case, the highest glazed area façade is facing north with a 32.13% of WWR. At the same time, the application of thermal insulation layers, especially in roofs and external walls, improved the envelope's resistance to external temperature fluctuations. The choice of materials with lower thermal transmittance (U-values) and proper

layering configurations significantly reduced heat losses in winter and minimized heat gains in summer.

Shading devices were selectively included on façades with higher solar exposure depending on the final orientation. While in Lisbon and Évora the addition of horizontal shading led to low but consistent improvements in performance, in Bragança — a cooler climate — shading was excluded from the final configuration as it slightly increased heating demand and so the total load increased when compared to the model without it.

Adjusting the window-to-wall ratio further enhanced performance. In general, south-facing façades benefited from larger openings when solar gains were advantageous, in the case of Bragança's and Évora's model while Lisbon's one, the highest glazed area façade were facing north to limit overheating. These changes were reinforced by the inclusion of natural ventilation, calibrated to stay at 0.5 air changes per hour during the whole year, which maintained the minimum requirements and the lowest energy demand.

Interestingly, the most substantial improvements were observed in cooling loads, even in Bragança, where the annual heating demand remains dominant. This underscores the fact that passive solar solutions have their greatest impact in mitigating cooling energy. Even when the heating load remains relatively high, the relative ease of reducing cooling energy makes it the more responsive variable in climate zones like those studied here.

In summary, the results of the combined model simulations clearly demonstrate the effectiveness of passive strategies when applied in a coordinated and climate-specific manner. The significant reductions in total energy demand — particularly the remarkable decrease observed in Évora — highlight the potential of passive solar design to meet thermal comfort needs while minimizing reliance on active mechanical systems. While the primary focus of this study is on energy performance rather than economic cost, it is important to note that these reductions in energy demand would naturally lead to lower operational costs, reinforcing the practical value of such optimizations beyond their environmental benefit.

4.11 Final Discussion

The results obtained in this study reinforce the significant potential of passive design strategies in reducing residential building energy demand and improving thermal comfort across diverse Portuguese climate zones. When implemented individually, measures such as building orientation optimization, reduced window-to-wall ratios and material insulation upgrades each contributed to measurable improvements in energy performance. However, it was the integration of these strategies into a combined model that produced the most remarkable reductions in total energy use — with Évora, for instance, showing a decrease of nearly two-thirds in annual energy demand.

A key takeaway from the results is that passive design interventions are most effective when considered holistically and in response to specific climate conditions. For instance, while overhangs are theoretically well-suited for solar protection, their effectiveness was limited in cases with small south-facing glazing areas. Conversely, the adjustment of glazing distribution and material layers had more consistent and substantial impact on both heating and cooling loads. Across all locations, it was the cooling demand that proved most sensitive to passive measures, reaffirming that such strategies are particularly valuable in mitigating overheating and reducing summer energy consumption.

It is important to emphasize that this study focused exclusively on thermal comfort and energy loads. Other crucial aspects of building performance such as daylight availability, indoor

air quality, and user behaviour, were assumed to meet regulatory thresholds but were not directly evaluated. Nevertheless, the results provide a solid foundation for further exploration of passive design strategies, particularly in support of long-term sustainability goals and the decarbonization of the built environment.

While this study demonstrates clear energy savings from individual and combined passive strategies, it also reveals the difficulty of directly comparing their effectiveness. Each strategy operates under different physical principles and has context-specific applicability. Some, like natural ventilation, rely on environmental conditions and scheduling, while others such as window-to-wall ratio (WWR) adjustments or overhangs involve fixed architectural features. Comparing these on equal terms is not always meaningful. For instance, WWR is a continuous design variable that directly influences both energy demand and daylight availability, while overhangs are discrete elements, typically implemented or not, with additional considerations for visual impact and façade design.

Even so, some trends were evident. Natural ventilation stood out as one of the most impactful strategies in the final energy loads. It proved to be a valuable but sensible passive solution for mitigating indoor overheating without mechanical intervention — particularly in regions with hot summers like Évora or Lisbon. However, its effectiveness depends heavily on how it is applied and controlled. If not carefully scheduled or adjusted to match external conditions, natural ventilation can inadvertently lead to spikes in energy demand, as observed in some cases during the simulations.

WWR reduction also proved to be a critical factor. Lower glazed areas generally translated into reduced heat transfer, especially solar gains during summer, contributing to overall lower energy loads. Nevertheless, this strategy must be balanced carefully. Reducing WWR too much can compromise daylight access and visual comfort, which are also essential for occupant well-being and must be considered in parallel to energy performance.

Although the passive measures evaluated differ in nature and scope, their combination in the final model achieved consistent reductions in energy demand across all studied climates. Importantly, the final values obtained in this study are in line with those reported in other relevant works, such as Eskander et al., 2017 and Nogueira et al., 2024, where the energy values in kWh/m² are of the same order of magnitude over a one-year simulation period. This alignment not only strengthens the credibility of the modelling assumptions and validates the effectiveness of the strategies applied, but also ensures compliance with standard reporting units defined in national regulations—specifically, decree-law n.º 101-D/2020, 7th December, article 4 (Portugal, 2020), which establishes kilowatt-hours per square meter (kWh/m²) as the reference unit for expressing energy performance in buildings.

Ultimately, while there is no single passive measure that universally outperforms the rest, this study demonstrates the value of climate-specific, integrative design. Rather than relying on one solution, energy performance improves most when multiple strategies work together — each tuned to its environment and role in the building system.

5 Conclusions and Future Work

This thesis successfully met its initial objectives by evaluating the application of passive solar design strategies in residential buildings through detailed simulations using *EnergyPlus* via *OpenStudio*. The study focused on three distinct climatic regions in Portugal - Évora, Lisbon, and Bragança - and examined how various passive strategies could improve thermal comfort and reduce energy demand, focused on heating and cooling.

A base model was developed for each location using a representative residential layout, incorporating realistic construction assemblies, internal loads, and climate-specific weather files. Through step-by-step simulations, the impact of individual passive strategies was analysed — including building orientation, window-to-wall ratio (WWR), external shading devices, natural ventilation rates, and improvements in envelope insulation for walls and roofs.

The results demonstrated that all passive measures contributed to reducing the building's mechanical energy needs, with natural ventilation and glazing strategies showing the most significant effects on energy loads. Although natural ventilation was applied conservatively (0.5 ACH) across all models and with seasonal changes, it showed to be the most sensible solution, the one that must have more attention when designing as it can drastically affect the energy load.

In terms of building orientation, variations in annual energy demand ranged from 7% in Bragança to 17% in Évora, depending on which façade was most exposed to solar gains when compared to the base model. The effectiveness of this parameter is closely tied to the Window-to-Wall Ratio (WWR) of each façade, highlighting the interdependence between orientation and glazing area. This reinforces the importance of integrating orientation into multi-parameter analyses for energy efficiency. The simulations revealed a consistent trend: in warmer climates, minimizing WWR on the south façade led to improved performance, underscoring the role of windows as a primary source of solar heat gain.

Changes to the WWR produced important effects as well, reductions in glazed area helped minimize energy use. The reduction of 10% of general WWR resulted in a reduction of energy use from 10% in Bragança to up to 37% in Lisbon, showing once again the heat gain from the sun that enters trough glazed areas. Although, this parameter can't solely be analysed as an energy reducing strategy as a balance as to be made with natural lighting and visual comfort.

Modifications to the thermal insulation of walls and roof also demonstrated a notable impact on energy performance. Increasing the insulation (expanded polystyrene) thickness contributed to reducing heat transfer through the building envelope, especially during the winter season, where the heating load is more pronounced. The simulation results showed that upgrading insulation from 0.030 m to 0.060 m led to energy savings ranging from 8% in Lisbon to 20% in Bragança, where heating needs are more significant. This strategy presented itself as one of the most suitable for colder climate, as it is beneficial to reduce heating load. However, while insulation reduces energy demand, particularly for heating, the benefit must be weighed against potential increases in embodied energy and cost associated with thicker materials.

Horizontal shading devices (overhangs) applied on the south façade showed a little effect on reducing load. The energy savings observed were less pronounced compared to other parameters as they reduce cooling loads but always, even if in a small scale, increase heating loads. Overhangs are most effective when solar gains are substantial, making them a climate-

dependent solution with higher impact in buildings with larger glazed areas (which was verified by the unchangeable value for Braganca's cold climate), being the conclusion that the values are low because of the low glazed area where the solution was applied. Though their individual effect was limited in this study's context, overhangs contribute meaningfully to peak load reduction and indoor comfort during the hottest months, justifying their inclusion in integrated passive design strategies.

At the end of evaluating the single parameters, the combined optimized models were simulated — integrating the best-performing parameters per region — achieved energy demand reductions of 60% (from 17.6 kWh/m^2 to 7.1 kWh/m^2) for Lisbon, 37% (from 37.4 kWh/m^2 to 23.5 kWh/m^2) for Bragança and 62% (from 30.3 kWh/m^2 to 11.4 kWh/m^2) for Évora, compared to the base case. From the results obtained, it is seen that the techniques evaluated in this work have a bigger impact on the warmer climates, where the cooling load dominates.

Having these analysed results, a lot more could be considered that could bring more to bioclimatic architecture discussion. Building on the results and methodology established in this study, several directions for future research are proposed to expand the depth and applicability of the findings.

First, economic analysis could be integrated to assess the financial impact of each passive strategy. By translating energy savings into monetary values such as estimating the reduction in annual energy bills a clearer picture of the cost-benefit of each intervention can be drawn. This would support more informed decision-making by homeowners, developers, and policy makers.

Additionally, the same simulation framework could be extended to multi-storey dwellings. This would allow investigation into how vertical expansion, internal zoning, and inter-floor heat transfer affect thermal performance and the efficiency of passive solutions. The introduction of multiple thermal zones within the same building—such as different temperature setpoints for bedrooms versus common areas—would also bring the model closer to real-world living conditions and allow analysis of zonal control strategies.

Future studies should also focus on ventilation with more detailed and climate-responsive schedules. In this thesis, ventilation was applied uniformly or seasonally throughout the year; however, refining this approach by limiting or maximizing airflow during specific hours and months could enhance performance.

Another area of interest lies in the optimization of shading devices. Although overhangs were applied only to facades that in these cases have limited glazed areas, future work could test the impact of such devices when applied to non-despised glazed south-facing facades. This could reveal whether a higher glazed area combined with efficient shading could have visible benefits on the energy load.

Furthermore, a more technical exploration of building envelope upgrades could be conducted by selecting materials with lower U-values based on updated standards. This would help determine the practical limits of envelope performance and how close one can get to passive thermal comfort thresholds without mechanical systems.

In summary, the proposed future work aims to make the analysis more detailed, realistic, and economically grounded, offering practical pathways for designing low-energy residential buildings that are adaptive, efficient, and suited to a variety of contexts.

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