Edelweiss Applied Science and Technology
ISSN: 2576-8484
Vol. 10, No. 4, 756-778
2026
Publisher: Learning Gate
DOI: 10.55214/2576-8484.v10i4.12790

Parametric optimization of passive envelope design under 2020 and 2050 climate conditions: A case study of Marrakech

Houcine KASMI[1]*, Ouadia MOUHAT[2]
[1,2]Civil Engineering and Environment Laboratory, Mohammadia School of Engineers, Mohammed V University in Rabat, Morocco; houcine_kasmi@um5.ac.ma (H.K.) ouadie.mouhat@est.um5.ac.ma (O.O.).

Abstract: This study evaluates the thermal performance of passive building envelope strategies under current (2020) and future (2050 under Representative Concentration Pathway 8.5) climate conditions in Marrakech, a hot semi-arid city facing increasing cooling demand. Glazing types, including tinted glazing (AL-Tinted) and low-emissivity glazing (Low-E), are used in building envelopes, along with phase change materials (PCM). A dynamic simulation approach was employed to assess 27 configurations combining different levels of expanded polystyrene (EPS) insulation, glazing types including tinted glazing (AL-Tinted) and low-emissivity glazing (Low-E) used in building envelopes, and phase change materials (PCM). Results indicate that in 2020, the most insulated configuration (EPS 10 cm + Low-E glazing + 4 cm PCM) reduced cooling demand by 62.7% but increased heating demand by 76.9%. Under future climate conditions, a configuration with moderate insulation (EPS 4 cm), Low-E glazing, and 4 cm PCM achieved the highest cooling reduction (−65.8%) while avoiding overheating. Configurations without insulation led to significant heating penalties exceeding +100%. The influence of envelope parameters shifts under climate change, with insulation dominating current performance and PCM becoming more significant in future scenarios. The findings highlight the need for climate-responsive design strategies, supporting a transition from insulation-driven approaches to adaptive combinations of glazing and thermal storage for hot climates.

Keywords: *Climate change, Glazing, Insulation, Passive building envelope, Phase change materials (PCM), Thermal performance.*

1. Introduction

Climate change stands as one of the most pressing challenges of the 21st century, with profound implications for energy systems, socio-economic stability, and the built environment [1]. Rising global temperatures, more frequent heatwaves, and shifting seasonal patterns are altering energy demand profiles in buildings worldwide, particularly in climate-sensitive regions such as the Mediterranean basin [2]. Globally, the building sector accounts for approximately 36% of final energy consumption and nearly 40% of energy-related CO_2 emissions [3], making it a critical target for both mitigation and adaptation strategies.

At the international level, the Paris Agreement [4] has set the ambitious goal of limiting global warming to well below 2°C, ideally within 1.5°C, thereby prompting nations to adopt decarbonization pathways and strengthen their climate commitments. In line with this global momentum, Morocco reaffirmed its national climate engagement through the updated Nationally Determined Contributions (NDCs) submitted in 2021 [5], targeting a 45.5% reduction in greenhouse gas (GHG) emissions by 2030 and 53% by 2035. Within the framework of Morocco's climate strategy, the building sector plays a central role, directly contributing around 23% of CO_2 emissions from final energy consumption, 21% from the residential, and 2% from the tertiary subsectors. When considering indirect emissions from electricity used in buildings, the sector's share rises to approximately 38% [6].

History: Received: 20 February 2026; Revised: 9 April 2026; Accepted: 15 April 2026; Published: 28 April 2026
* Correspondence: houcine_kasmi@um5.ac.ma

The Moroccan Long-Term Low-Emission Development Strategy (LT-LEDS 2050) identifies the building sector as a pillar of the national decarbonization trajectory, highlighting its considerable potential for energy savings through efficiency enhancements, reduced thermal losses, and improved end-user behaviors. It also emphasizes the role of buildings in supporting the shift toward low-carbon energy vectors, including decarbonized electricity, biogas, and sustainable heating systems.

At the global level, the Global Alliance for Buildings and Construction (GlobalABC) [7] proposes eight strategic action areas to transform the sector. These include promoting net-zero energy buildings, deep retrofits, improved envelope performance, passive design integration, and life-cycle optimization of materials. Among these, enhancing the thermal performance of building envelopes is a priority for reducing operational energy, increasing resilience, and achieving climate neutrality.

In Morocco, technical and regulatory instruments such as the Thermal Building Regulation in Morocco (RTCM) [8] provide the framework for improving envelope performance through minimum standards for insulation, glazing, and airtightness. However, a large share of the national building stock remains outdated, poorly insulated, and inefficient. As climate conditions evolve under high-emission scenarios, notably RCP 8.5, projected by the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) [9] to induce significant warming by mid-century, there is a pressing need for adaptation strategies that address both current inefficiencies and future climate realities. Although this study is based on Representative Concentration Pathways (RCPs) from IPCC AR5, these scenarios remain comparable to the Shared Socioeconomic Pathways (SSPs) introduced in AR6 [1], as they correspond to similar radiative forcing levels. Therefore, the findings remain consistent with recent climate projections.

The intensification of global warming is expected to shift the energy balance in buildings [3, 10]. These findings are consistent with previous studies showing that climate change leads to a general decrease in heating energy demand and an increase in cooling consumption, with significant variations depending on climate zones. Such trends are strongly associated with changes in heating and cooling degree days (HDDs and CDDs), which are key indicators for evaluating building energy performance under future climate scenarios [11], particularly in hot climate zones, where the cooling demand is projected to grow substantially.

While heating needs are likely to decline, especially in high-performance buildings, the growing frequency of heatwaves and the rising number of cooling degree days suggest a sharp increase in energy use for air conditioning. In fact, projections indicate that global demand for space cooling will sharply rise by mid-century, especially in developing countries [3, 9, 10]. This dynamic reinforces the urgency of promoting passive design approaches and climate-responsive construction in regions like Marrakech, where future adaptation strategies must account for both environmental and socio-economic vulnerabilities.

While numerous studies have explored the effects of climate change on building energy performance across diverse global contexts [2, 12, 13], relatively few have focused on North African or semi-arid Mediterranean regions, despite their high vulnerability to climate change. Even fewer studies have conducted comprehensive parametric approaches to analyze multiple passive envelope strategies, particularly assessing the performance of selected parameters under both current climatic conditions and future climate scenarios.

Existing literature tends to focus on individual parameters. For instance, several studies have investigated the role of thermal insulation [14, 15], others have examined window glazing properties [16], while some have evaluated the effectiveness of phase change materials (PCM) as thermal storage components [17, 18]. However, these parameters are often studied separately, without accounting for their potential interactive effects, which are essential to fully understanding energy performance in real-world applications.

Some notable exceptions exist, including studies that adopt a more integrative methodology, for example, Lin et al. [19] explored the optimization of building design by varying thermal mass, insulation, solar absorptance, and glazing ratio, using a prediction model combined with artificial intelligence and genetic algorithms to minimize thermal loads and improve indoor comfort. Albatayneh [20], in turn, investigated the optimization of envelope parameters in a semi-arid Mediterranean context, focusing on insulation, glazing, and thermal mass in residential buildings to enhance energy efficiency while ensuring thermal comfort. Boumlik et al. [21] introduced an optimization-based approach tailored to the Moroccan context, analyzing the interactive effects of multiple energy efficiency measures across six climate zones.

This is particularly relevant as recent research emphasizes that achieving ultra-low or net-zero energy performance is significantly more challenging in hot, arid climates compared to temperate or cold ones, even when advanced passive design strategies are implemented. This climate-based performance asymmetry is especially evident in cities like Marrakech, where future scenarios such as RCP 8.5 for 2050 project increased thermal stress and longer cooling seasons [22].

To address this research gap, the present study conducts a comprehensive parametric analysis of passive envelope strategies tailored to hot semi-arid climates. It specifically examines the influence of climate change on the annual heating and cooling energy demand of a typical residential building located in Marrakech. The analysis contrasts the building's energy performance under current climatic conditions (baseline year: 2020) with future projections for the year 2050, based on the high-emission RCP 8.5 scenario. A full-factorial simulation approach is employed, encompassing 27 envelope configurations derived from the combination of three key parameters: thermal insulation levels, glazing types, and the integration of phase change materials (PCM) in the external walls and roof. All simulations are performed using the EnergyPlus engine through the DesignBuilder software.

The central hypothesis is that the interaction between insulation, glazing, and PCM produces nonlinear, climate-dependent effects on energy performance that cannot be captured by single-variable analyses. It is also expected that some combinations may perform well under current conditions but degrade significantly under future climate scenarios, indicating the need for climate-resilient design strategies.

This study contributes to advancing knowledge in climate-adaptive architecture by providing new insights into the synergistic role of passive envelope elements and their resilience under high-emission future projections.

2. Materials and Methods

This study follows a structured simulation-based methodology to assess how passive envelope design strategies influence residential buildings' annual heating and cooling energy demand under current and future climatic conditions in Marrakech. The methodological framework is structured into five sequential stages, ensuring a systematic and reproducible process. These stages are summarized in Figure 1 and detailed in the following subsections:

- Climate Data Acquisition: Selection and preparation of weather data for 2020 and 2050 (RCP 8.5).
- Building Model Development: Creation of a representative residential model within DesignBuilder software.
- Envelope Design Scenarios: Definition of 27 configurations combining insulation, glazing, and PCM levels.
- Dynamic Thermal Simulations: EnergyPlus simulations are used to estimate annual heating and cooling loads for each configuration under both climate scenarios.
- Result Analysis: Interpretation of dynamic simulation outputs to evaluate the energetic performance of each envelope configuration. Heating and cooling energy demands are compared across all scenarios to identify trends, seasonal trade-offs, and the influence of design parameters under both current and future climate conditions.

DOI: 10.55214/2576-8484.v10i4.12790

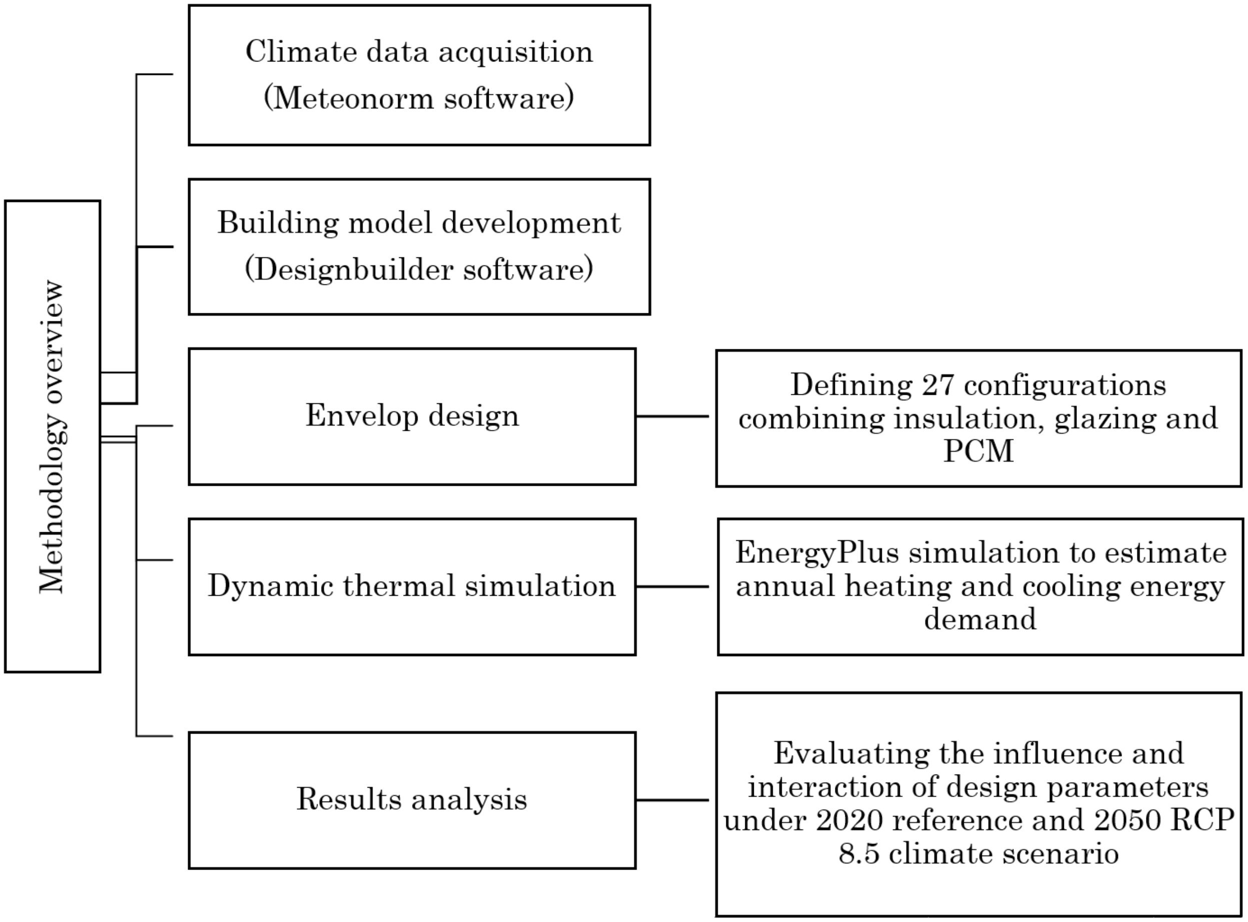

Figure 1.
Methodology framework for Parametric Analysis of Envelope Strategies for Residential Buildings in Marrakech under RCP 8.5 Climate Scenario.

2.1. Climate Data and Scenario Definition

The climate data utilized in this research correspond to Marrakech, Morocco, situated at approximately 31.63° N latitude and 8.00° W longitude, with an elevation of nearly 466 meters above sea level. According to the Köppen-Geiger climate classification, Marrakech is categorized within the hot-summer Mediterranean climate zone (Csa) [23], which features prolonged, dry, and hot summers along with mild and wet winters. Furthermore, according to Morocco's RTCM classification, the city falls under climatic zone 5, which stipulates specific requirements for building envelope design based on seasonal thermal variations and solar exposure.

The climatic datasets employed, including hourly values for temperature, solar radiation, wind speed and direction, and atmospheric pressure, were generated using Meteonorm software (version 8.0), a globally recognized and validated climate data platform extensively used for building energy modeling. Baseline data for 2020 were obtained from interpolated weather records, while future projections for 2050 were derived under the RCP 8.5 scenario.

The generated datasets were directly exported from Meteonorm in EnergyPlus Weather (EPW) format and used in building energy simulations. Figure 2 presents the daily average temperature profiles for 2020 and 2050 obtained through this process.

In 2020, Marrakech exhibited a typical semi-arid climate, with the hottest days averaging around 36.7 °C and the coldest days averaging 6.8 °C. In terms of extreme hourly conditions, the maximum temperature reached 45.2 °C, while the minimum dropped to 2.3 °C. These extremes define the thermal context in which residential buildings currently operate.

By 2050, under continued high-emission pathways, a general increase in temperature is observed throughout the year. The hottest days may average around 37.8 °C, while the coldest still fall to about 8.0 °C. Hourly extremes are projected to intensify, with temperatures peaking up to 47 °C and dropping no lower than 3.5 °C. This overall shift confirms the intensification of heat stress conditions, particularly during the summer season.

This study uses 2020 as the baseline to reflect current climatic conditions, while projections for 2050 are based on the RCP 8.5 scenario, a high-emission pathway that presumes continuous increases in greenhouse gas concentrations throughout the 21st century. RCP 8.5 is commonly adopted in impact studies to assess extreme warming outcomes [24-26].

The selection of 2050 as the projection horizon is consistent with global climate policy timelines, such as the Net Zero objectives articulated under the Paris Agreement [4]. It also aligns with Morocco's national climate strategies aimed at curbing emissions and reinforcing climate adaptability.

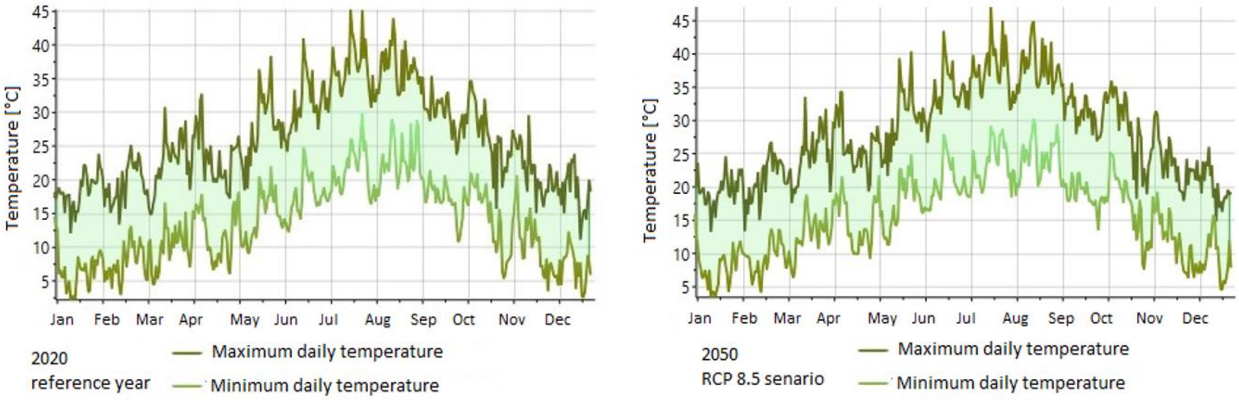

Figure 2.
Daily outdoor temperature profiles in Marrakech for the years 2020 and 2050 under the RCP 8.5 climate scenario (Meteonorm 8.3).

2.2. Architectural and Envelope Characterization of the Studied Building

2.2.1. Architectural Description of the Building

The case study building analyzed in this research (Figure 3) is a three-story residential dwelling featuring two main façades oriented to the east and south. Each level has a floor area of approximately 100 m², giving a total gross floor space of 300 m². The height from floor to ceiling on each story measures 3.5 meters. Internally, each floor includes two bedrooms, a living room, a kitchen, a bathroom, and a toilet. Fenestration is uniformly distributed across all rooms, with window openings covering approximately 30% of the external wall surface area on each façade.

The case study building analyzed in this research is a virtual prototype that reflects the most common typology of residential dwellings in Marrakech. This type of two-story urban dwelling, with a floor area of approximately 100 m², brick walls, a flat roof, and a standard glazing ratio, is representative of a large share of the city's housing stock. Therefore, the chosen prototype provides a reproducible and scientifically valid baseline for assessing the impact of envelope strategies under current and projected climatic conditions.

The reference building was modeled as a fully exposed prototype, without considering the influence of surrounding buildings, vegetation, or other shading elements. In this study, the climatic conditions applied correspond exclusively to those representing Marrakech, with no corrections for local microclimatic variations. This assumption was adopted to isolate and assess the effect of building envelope parameters under direct climatic exposure.

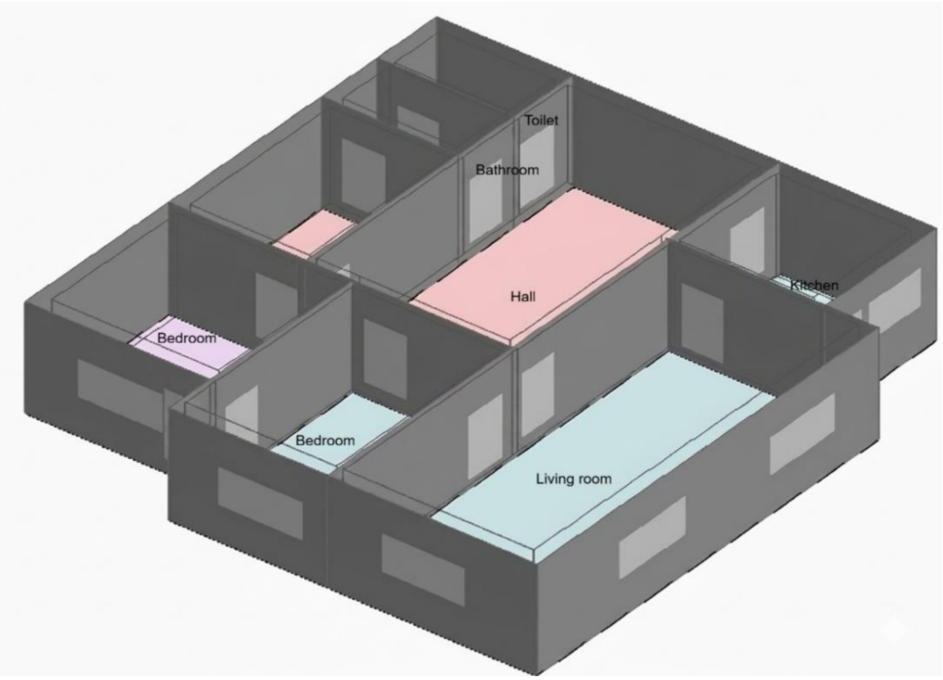

Figure 3.
Architectural floor plan.

2.2.2. Building Envelope Description

The building envelope consists of structural and non-structural components that collectively contribute to thermal regulation and indoor comfort, serving as a barrier between the indoor environment and external conditions. To evaluate the impact of passive envelope strategies on energy performance in Marrakech's Moroccan climate, focus will be on three main parameters: glazing, thermal insulation of exterior walls and roof, and the use of PCM materials in exterior walls and roofs.

This involves analyzing different configurations representing the application of a solution for only one parameter, the analysis of a combination of two parameters, and the analysis of the application of all three parameters.

2.2.3. Comprehensive Overview of Study Parameters

To assess the impact of passive design parameters on building energy performance under both current (2020) and future climate scenarios (RCP 8.5, 2050), a full factorial parametric analysis was conducted involving 27 unique building envelope configurations (V1 to V27). These configurations result from the combination of three passive design parameters, each evaluated at three levels of application:

- Thermal insulation using expanded polystyrene (EPS) applied to walls and roofs;
- Window glazing, ranging from standard single glazing to high-performance low-emissivity (Low-E) double glazing;
- Phase change materials (PCM) integrated into walls and roofs.

Each parameter was assessed at three levels: 0 = no application, 0.5 = partial application, 1 = full application)

This full-factorial combination ($3^3 = 27$) allows for a comprehensive evaluation of the individual and combined effects of the selected parameters.

The thermal properties of building components for each configuration are presented in Table 1.

The selection of thermal insulation (EPS), glazing type, and phase change materials (PCM) as the primary passive design parameters in this study is based on their proven influence on building energy performance, especially in hot and semi-arid climates [14, 27, 28].

Expanded polystyrene (EPS) is a widely used thermal insulation material due to its low thermal conductivity, cost-effectiveness, and ease of implementation. Its ability to reduce conductive heat transfer through opaque building envelope elements makes it especially effective in minimizing cooling loads in warm regions.

Glazing performance plays a critical role in controlling solar gains and heat exchange through fenestrations. The use of double glazing with low-emissivity (Low-E) coatings enhances the building's thermal resistance while allowing adequate daylight, thereby reducing both cooling and heating demands depending on seasonal variations.

Phase Change Materials (PCM) have gained increasing attention in passive thermal regulation strategies due to their capacity to store and release latent heat near indoor comfort temperatures. Their integration into walls and roofs helps attenuate indoor temperature fluctuations and shift peak cooling loads, especially when combined with other passive elements.

This simulation framework is designed to quantify both the individual effects of key passive envelope parameters on annual heating and cooling energy demand and their interactive influences when combined.

By exploring these interactions, the study provides a more comprehensive understanding of synergistic or antagonistic relationships between thermal insulation, glazing, and PCM strategies. It also supports the development of a predictive model capable of estimating energy performance based on envelope characteristics.

Table 1.
Thermal properties of the building components. (a): glazing type; (b) external walls and roof.

(a) Glazing type

Element	Configuration	Glazing type	Solar Heat Gain Coefficient (SHGC)	Direct Solar Transmittance	U-Value [W/m^2·K]
windows	0	Single Clear Glazing (6 mm)	0.819	0.775	5.778
	0.5	Double Glazing A-L Tint 6/13/6	0.144	0.032	2.228
	1	Double Glazing Low-E e=1 Tint 6/13/6	0.380	0.284	1.761

(b) External walls and roof

Element	Configuration	Layer type	Thickness (m)	Density (kg/m^3)	Thermal conductivity (w/m.k)	U-Value [W/m^2·K]
External wall configurations using EPS	0: Uninsulated wall and roof	Cement mortar	0.015	2000	1.4	0.829
		Brick	0.2	743	0.197	
		Cement mortar	0.015	2000	1.4	
	0.5: Insulated wall with eps 4cm	Cement mortar	0.015	2000	1.4	0.414
		Brick	0.07	743	0.197	
		EPS insulation	0.04	100	0.039	
		Air gap	0.02	1	0.117	
		Brick	0.12	743	0.197	
		Cement	0.015	2000	1.4	

		mortar				
	1: Insulated wall with eps 10 cm	Cement mortar	0.015	2000	1.4	0.252
		Brick	0.07	743	0.197	
		EPS insulation	0.10	100	0.039	
		Air gap	0.02	1	0.117	
		Brick	0.12	743	0.197	
		Cement mortar	0.015	2000	1.4	
Roof configurations using EPS	0: Uninsulated roof	Tiling	0.01	2100	1.5	1.598
		Slab	0.04	2400	1.7	
		Slope form	0.05	600	0.42	
		Compression slab	0.05	2400	1.7	
		Slab	0.2	0.8	1300	
		Plaster	0.02	0.35	950	
	0.5: Insulated roof with eps 4 cm	Tiling	0.01	2100	1.5	0.565
		Slab	0.04	2400	1.7	
		EPS insulation Heavyweight	0.04	25	0.035	
		Slope form	0.05	600	0.42	
		Compression slab	0.05	2400	1.7	
		Slab	0.2	0.8	1300	
		Plaster	0.02	0.35	950	
	1: Insulated roof with eps 10 cm	Tiling	0.01	2100	1.5	0.287
		Slab	0.04	2400	1.7	
		EPS insulation Heavyweight	0.10	25	0.035	
		Slope form	0.05	600	0.42	
		Compression slab	0.05	2400	1.7	
		Slab	0.2	0.8	1300	
		Plaster	0.02	0.35	950	
External wall configurations using PCM	0.5: Integration of BioPCM M27/Q29 (1 cm)	Cement mortar	0.015	2000	1.4	2.184
		Brick	0.2	1920	0.72	
		BioPCM	0.01	235	0.2	
		Cement mortar	0.015	2000	1.4	
	1: Integration of BioPCM M27/Q29 (4 cm)	Cement mortar	0.015	2000	1.4	1.645
		Brick	0.2	1920	0.72	
		BioPCM	0.04	235	0.2	
		Cement mortar	0.015	2000	1.4	
Roof configurations using PCM	0.5: Integration of BioPCM M27/Q29 (1 cm)	Tiling	0.01	2100	1.5	1.480
		Slab	0.04	2400	1.7	
		Slope form	0.05	600	0.42	
		Compression slab	0.05	2400	1.7	
		Slab	0.2	0.8	1300	
		BioPCM	0.01	235	0.2	
		Plaster	0.02	0.35	950	

	1: Integration of BioPCM M27/Q29 (4 cm)	Tiling	0.01	2100	1.5	1.211
		Slab	0.04	2400	1.7	
		Slope form	0.05	600	0.42	
		Compression slab	0.05	2400	1.7	
		Slab	0.2	0.8	1300	
		BioPCM	0.04	235	0.2	
		Plaster	0.02	0.35	950	

2.3. Numerical Model

In this research, building energy simulations were performed using DesignBuilder software (version 7), which utilized the EnergyPlus simulation engine. Recognized for its robustness, EnergyPlus has undergone extensive validation in prior studies, where its outputs were benchmarked against experimental results and real-world measurements, confirming its suitability for evaluating energy performance in buildings [28].

The simulation workflow followed a structured approach consisting of three main phases:

- Building Geometry and Envelope Definition: The reference building was modeled in DesignBuilder using predefined architectural, physical, and thermal characteristics, consistent with typical Moroccan residential constructions. Envelope elements were defined in terms of material layers, thicknesses, and thermal conductivities.
- Climatic Input Data: Hourly weather data for the base year 2020 and future year 2050 under the RCP 8.5 scenario were generated using Meteonorm software. The selected location for simulation was Marrakech, representing a hot semi-arid climate, highly sensitive to thermal loads and cooling needs.
- Simulation Scenarios: A total of 27 envelope configurations (V1 to V27) were simulated. These result from a full factorial combination of three passive design variables (EPS insulation, glazing type, and PCM integration), each applied at three levels (0 = none, 0.5 = partial, 1 = full application).

Each configuration was simulated twice, once under 2020 climate conditions and once under projected 2050 conditions (RCP 8.5), enabling a comparative temporal assessment.

For the simulations, the indoor setpoint temperatures were fixed at 20°C for heating and 26°C for cooling, following national thermal comfort guidelines, Moroccan standard NM ISO 7730 [29]. A ventilation rate of 0.6 air changes per hour (ACH) was assumed, alongside an occupancy density of 20 m^2 per person. The outdoor air renewal rate was specified as 12.5 l/s per occupant, in compliance with Moroccan standard NM 10.5.022 [30].

The modeling approach adopted in this study applied the Conduction Finite Difference (CondFD) method, which enables detailed tracking of the enthalpy and temperature relationship within building materials at each simulation step. This ensures an accurate representation of the thermal inertia of construction components, including the dynamic behavior associated with phase change materials (PCM).

The software models the building's thermal performance by solving time-dependent energy balance equations for each thermal zone, accounting for conductive, convective, and radiative heat transfer, as well as internal gains and HVAC interactions [31, 32]

The general energy balance equation per zone is:

$$C\,\frac{dT}{dt} = Qcond + Qconv + Qrad + Qint + QHVAC \ 1 \quad (1)$$

Where:
C: Heat capacity of the zone air [J/K]
T: Indoor air temperature [°C or K]
Qcond: Heat flux by conduction through envelope elements [W]

Qconv: Heat flux by convection between surfaces and indoor air [W]
Qrad: Net radiative heat exchange (long-wave and short-wave) [W]
Qint: Internal gains from occupants, equipment, lighting [W]
Q_{HVAC}: Heat supplied or removed by the HVAC system [W]
Conductive heat flux through building elements is modeled by Fourier's law:

$$Qcond = -kA\frac{\Delta T}{\Delta x}$$

K: Thermal conductivity of the material [W/m·K]
A: Surface area of the building element [m^2]
ΔT: Temperature difference across the element [K]
Δx: Thickness of the element [m]
Convective heat transfer is expressed by Newton's law of cooling:

$$Qconv = hA(Ts - Ta)$$

h: Convective heat transfer coefficient [$W/m^2 \cdot K$]
Ts: Surface temperature [°C or K]
Ta: Air temperature [°C or K]
A: Surface area in contact [m^2]

3. Results and Discussion

3.1. Energy Demand for the 2020 Reference Period and 2050 RCP 8.5 Scenario

The results presented in this section are derived from dynamic thermal simulations conducted using DesignBuilder software, which integrates the EnergyPlus simulation engine. As described in the methodology, climatic datasets for Marrakech (2020 baseline and 2050 RCP 8.5 scenario) were used to evaluate annual heating and cooling energy demand. The outcomes reported below correspond to the parametric configurations applied to the reference residential building model.

3.1.1. Implementation of Single-Parameter Configuration

The simulation results presented in Table 2 provide insights into the energy performance of various single-parameter envelope strategies under two climate scenarios: the 2020 reference year and the 2050 projection based on RCP 8.5. Each configuration (V1 to V7) integrates a single type of improvement, either EPS insulation, glazing enhancement, or PCM, allowing us to evaluate the isolated impact of each parameter.

3.1.1.1. Energy Demand Under 2020 Climate Conditions

Under 2020 climate conditions, the baseline scenario, represented by Configuration V1, characterized by the absence of insulation and PCM, and the use of single glazing, registered the highest cooling demand, reaching 14.18 kWh/m^2, and a moderate heating demand of 3.68 kWh/m^2. Gradual incorporation of EPS insulation, improved glazing, and PCM implementation resulted in varying degrees of impact on energy performance.

Implementing EPS insulation alone, as illustrated in configurations V2 and V3, resulted in a steady decline in both heating and cooling energy demands. For instance, the transition from no insulation (V1) to a 4 cm expanded polystyrene (EPS) layer (V2) led to a measurable decrease in energy demand, with heating requirements reduced by 12% and cooling needs by 23.9%. Further increasing the EPS thickness to 10 cm (V3) resulted in more significant energy savings, reducing heating demand by 24.4% and cooling demand by 30.7%. These findings underscore the effectiveness of EPS insulation in enhancing the thermal performance of buildings across both heating and cooling seasons. These results align with findings reported in studies demonstrating that while increasing insulation thickness significantly reduces heat loss initially, the marginal improvement gradually decreases as thickness grows, and [15, 25], which similarly observe a general reduction in cooling demand as the key parameters are optimized, without further analyzing the individual contributions or the relative significance of each factor.

The improvements are particularly notable in semi-arid regions such as Marrakech, where mitigating summer heat gains is essential for energy efficiency and indoor comfort. EPS thus emerges as a cost-effective and balanced solution for climate-responsive building design in hot, dry zones. These results align with the literature emphasizing the high thermal resistance of EPS, especially in warm climates where reducing solar heat gains is crucial [33, 34].

Replacing single glazing with double-glazed windows (AL Tint-V4) led to a 17.6% reduction in cooling energy demand. However, this intervention also resulted in a 28.5% increase in heating demand. Further transitioning to low-emissivity glazing (Low-E-V5) improved summer performance with a 22.7% reduction in cooling needs, but caused a 52% rise in heating demand.

These results illustrate a distinct seasonal trade-off: while advanced glazing systems effectively reduce solar heat gains and internal loads during the cooling season, they also limit passive solar gains during winter. In climates like Marrakech, characterized by hot summers and mild yet cool winters, this duality is particularly relevant. Therefore, the selection of glazing should balance both seasonal objectives and may necessitate complementary passive or active strategies to mitigate winter heating penalties.

The incorporation of 1 cm thickness of PCM (V6) led to a 12% reduction in cooling energy demand. However, this was accompanied by a significant 69% increase in heating requirements. When the PCM layer was increased to 4 cm (V7), the cooling benefit improved substantially, with a 23.8% reduction in demand, yet heating still exhibited a 56% increase.

These findings highlight the dual nature of PCM integration in building envelopes. While the latent heat storage capacity of PCM proves effective in mitigating daytime cooling loads, particularly in hot climates, its contribution during winter is limited. These results confirm the seasonal sensitivity of PCM-based systems, which are especially effective for cooling-dominant climates but require careful integration in mixed-mode contexts. Reduced solar radiation and insufficient thermal charging during colder periods diminish PCM effectiveness and may even induce heating energy penalties. This seasonal discrepancy underscores the importance of climate-adapted PCM design, suggesting the need for hybrid strategies or dynamic control systems to fully leverage their potential.

In summary, the simulation findings emphasize the necessity of a seasonally balanced and context-adapted envelope design. While glazing and PCM strategies offer valuable reductions in cooling energy use, their impact on heating performance can be adverse under cold-season conditions. Conversely, EPS insulation demonstrated robust benefits across both seasons, positioning it as a core component of thermal envelope optimization in semi-arid climates such as Marrakech.

3.1.1.2. Energy Demand Under 2050 Climate Projections (RCP 8.5)

Under projected climatic conditions for 2050, cooling energy demand shows a substantial increase across all configurations, primarily due to elevated temperatures associated with the RCP 8.5 scenario. In contrast, heating demand declined by more than 50% in most cases, reflecting the effects of milder winter conditions.

The baseline configuration, V1, showed a 44% increase in cooling requirements, reaching 20.40 kWh/m², and a 52.7% decrease in heating energy demand, down to 1.74 kWh/m². EPS insulation continues to demonstrate significant energy-saving potential. At 4 cm thickness (V2), heating demand is reduced by 16.2%, while cooling demand drops by 22.1%. Increasing insulation to 10 cm (V3) further improves performance, with heating demand decreasing by 30.1% and cooling by 28.9% (Figure 4).

These results indicate that EPS insulation remains an effective strategy for future climate conditions, even as space heating needs decline due to rising ambient temperatures. The amplified reductions in cooling demand emphasize the increasing importance of thermal resistance in buildings as a key adaptation measure. In warmer future scenarios, insulation's role shifts from dual-season optimization to predominantly cooling-focused performance, especially in hot semi-arid regions like

Marrakech. This reinforces the long-term relevance of passive design strategies for resilience under climate change.

Transitioning from single glazing (V1) to advanced glazing systems results in significant reductions in cooling energy demand, 15.9% for double-glazed tinted windows (V4) and 20.5% for Low-E glazing (V5). However, these improvements increase heating energy demand, with rises of 38.3% for V4 and 72.9% for V5.

These results underscore a shift in thermal performance dynamics under future climates, where cooling demand becomes the dominant concern. In this context, high-performance glazing proves increasingly advantageous for limiting solar gains and internal overheating. Nonetheless, the marked increase in heating demand, particularly for Low-E glazing, reveals the sensitivity of building envelopes to solar access during winter months. This highlights the necessity of integrating seasonal or dynamic solar control strategies, such as adjustable shading or smart façades, to reconcile summer protection with winter heat gains, especially in regions with variable interseasonal needs like Marrakech.

PCM demonstrates superior performance in reducing cooling energy demand, with savings of 20.7% at 1 cm thickness (V6) and up to 32% at 4 cm (V7), the highest cooling efficiency recorded across all single-parameter configurations tested. However, the heating energy demand increases remain significant, with a 57% rise for V6 and a 28.5% increase for V7 compared to the uninsulated baseline (V1).

These results reveal a dual behavior of PCM under future climate scenarios. The anticipated intensification of daily temperature amplitudes enhances the activation of latent thermal storage cycles, thereby improving cooling load mitigation. Nonetheless, the seasonal inversion effect, where PCM fails to retain or deliver useful heat during colder periods, introduces a substantial heating penalty.

The interpretation of percentage variations in energy demand requires caution, as relative changes may not adequately represent the absolute magnitude of energy consumption. While heating demand exhibits substantial relative reductions when passive measures are applied, its absolute values remain marginal compared to cooling demand. Under projected climatic conditions, cooling constitutes the dominant share of total energy requirements; therefore, even moderate percentage reductions in cooling demand translate into a significantly greater absolute impact.

Table 2.
Annual Heating and Cooling Energy Demand (kWh/m²) for Configurations V1–V7, using Single Envelope Parameters, under 2020 and 2050 RCP 8.5 Climate Scenarios.

				2020		**2050**	
Configuration	**Insulation EPS**	**Glazing**	**PCM**	**Heating (kWh/m²)**	**Cooling (kWh/m²)**	**Heating (kWh/m²)**	**Cooling (kWh/m²)**
V1	0	0	0	3.68	14.175	1.743	20.40
V2	0.5	0	0	3.24	10.80	1.460	15.88
V3	1	0	0	2.78	9.83	1.218	14.50
V4	0	0.5	0	4.73	11.68	2.410	17.15
V5	0	1	0	5.60	10.96	3.014	16.22
V6	0	0	0.5	6.23	12.479	2.730	16.17
V7	0	0	1	5.74	10.81	2.24	13.88

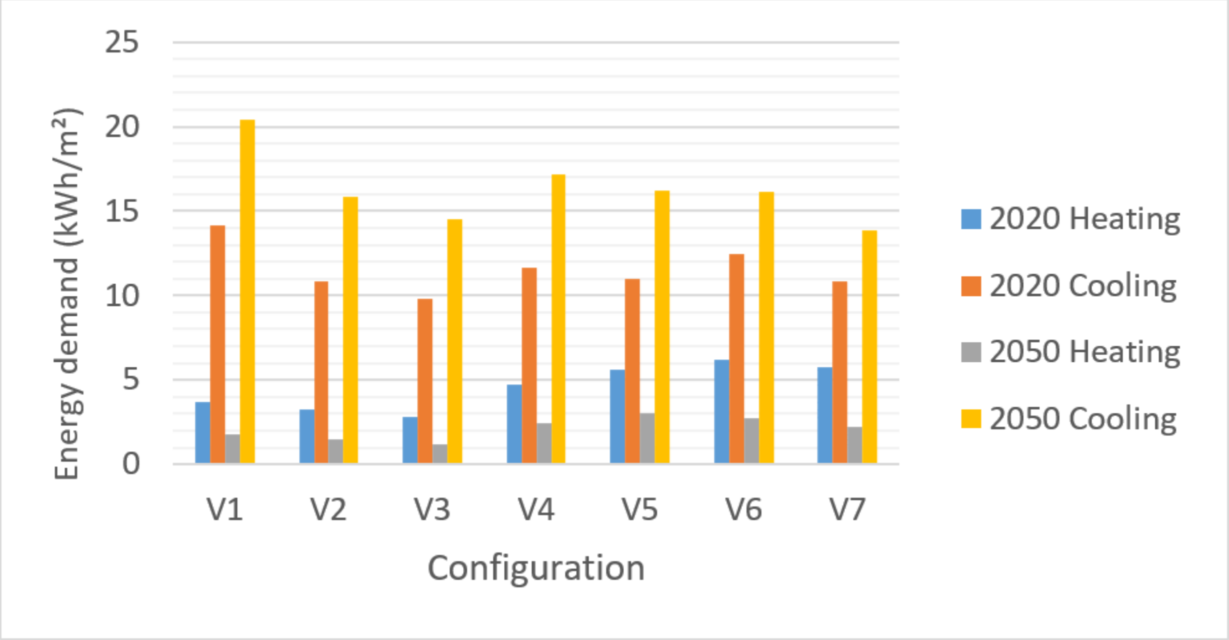

Figure 4.
Cooling and heating demand across a single parameter configuration.

3.1.2. Combined Parameter Effects: Insulation and Glazing

The performance of configurations combining thermal insulation (EPS) and glazing types offers an essential perspective on the synergistic or conflicting effects of passive envelope strategies under changing climatic conditions. Table 3 presents four configurations (V8–V11) that allow us to isolate and evaluate these interactions.

3.1.2.1. Energy Demand Under 2020 Climate Conditions

Under the 2020 baseline climatic context, the building is subject to dual thermal demands, with significant heating needs in winter and moderate to high cooling loads during summer peaks. In this framework, combined envelope configurations demonstrate varying levels of energy performance.

Among the evaluated solutions illustrated in Figure 5, Configuration V11 achieves the lowest cooling energy demand, measured at 6.77 kWh/m², corresponding to a 46% reduction compared to the baseline case (V1 = 14.18 kWh/m²). However, it records the highest heating demand, reaching 4.95 kWh/m², representing a 34.5% increase over V1.

Conversely, Configuration V9 offers a more balanced performance, yielding a slightly higher cooling demand of 6.91 kWh/m² but significantly lower heating demand at 3.85 kWh/m², representing a 4% improvement over the V1 heating baseline.

The marginal difference in cooling demand between V9 and V11 (less than 2%) indicates that glazing type has a limited influence on cooling performance when high thermal insulation is present. However, the heating energy gap is more significant, with V11 requiring 28.6% more heating energy than V9. This reflects the penalizing effect of Low-E glazing on passive solar gains during winter months, which is especially relevant in climates with seasonal variability.

These findings are consistent with recent literature emphasizing that thermal insulation and high-performance glazing are among the most effective passive strategies for improving building energy performance under climate change conditions. However, their combined effects may lead to trade-offs between heating and cooling demands, depending on climatic context and solar gain availability [35].

3.1.2.2. Energy Demand Under 2050 Climate Projections (RCP 8.5)

Climate projections under the RCP 8.5 scenario for 2050 indicate a marked shift toward higher summer temperatures and milder winters, especially in semi-arid regions like Marrakech. This evolving climate significantly impacts the effectiveness of envelope configurations, particularly regarding cooling dominance and reduced heating relevance.

Although the absolute difference in cooling demand between V11 and V9 is relatively small (0.32 kWh/m^2), this difference gains strategic importance under future climate conditions, where cooling becomes the dominant thermal load. Small percentage gains in cooling efficiency can translate into substantial cumulative energy savings at the operational scale, particularly during prolonged heat waves and extended cooling seasons.

In contrast, the heating demand becomes increasingly negligible: V11 records 2.61 kWh/m^2, while V9 performs better with only 1.87 kWh/m^2. However, this improvement in heating performance carries less weight in the overall energy balance as winter severity decreases.

Table 3.
Annual Heating and Cooling Energy Demand (kWh/m^2) for Configurations V8–V11, Combining EPS Insulation and Glazing Types, under 2020 and 2050 RCP 8.5 Climate Scenarios.

				2020		**2050**	
Configuration	**Insulation EPS**	**glazing**	**PCM**	**Heating (kWh/m^2)**	**Cooling (kWh/m^2)**	**Heating (kWh/m^2)**	**Cooling (kWh/m^2)**
V8	0.5	0.5	0	4.310	8.361	2.135	12.683
V9	1	0.5	0	3.848	6.910	1.868	10.622
V10	0.5	1	0	5.314	7.770	2.825	11.767
V11	1	1	0	4.949	6.770	2.613	10.300

The findings confirm that envelope optimization strategies must evolve with climate projections. While in 2020 a balanced performance (e.g., V9) may have been more desirable, the 2050 scenario favors configurations that minimize cooling demand, even at the cost of higher, but marginal, heating loads. Thus, V11 becomes the most context-appropriate envelope strategy for future-proofing buildings in hot semi-arid climates.

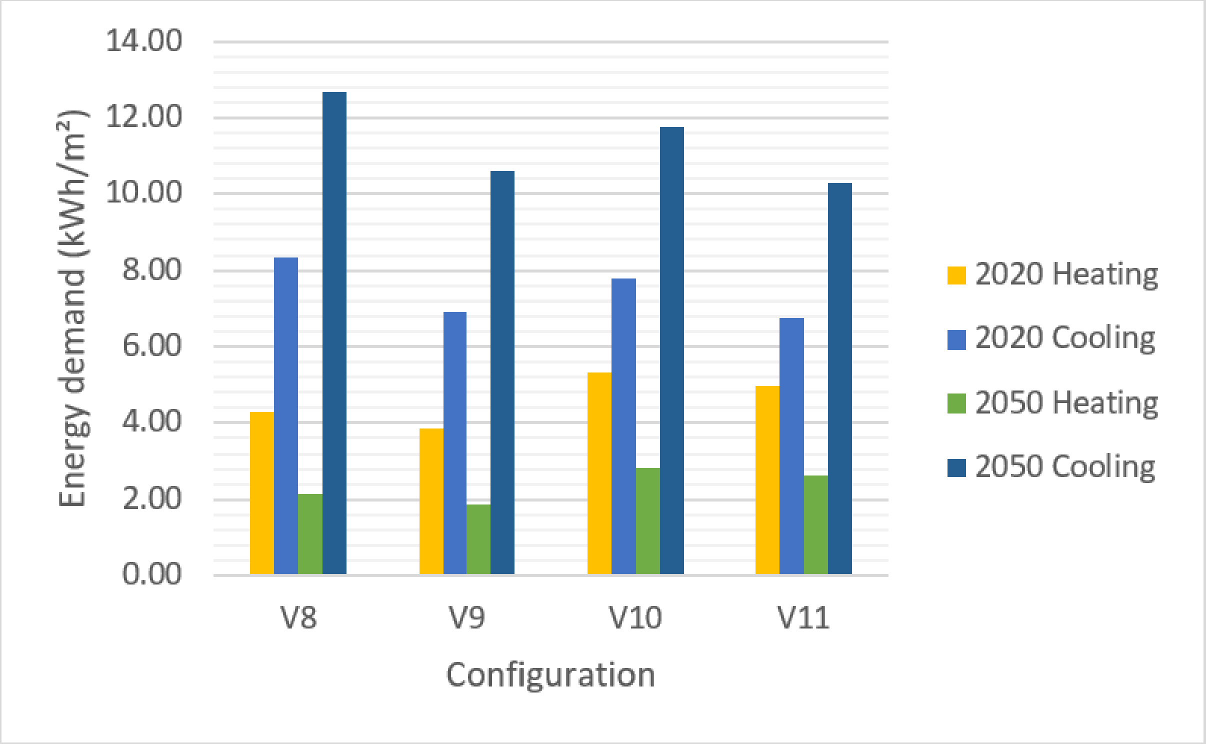

Figure 5.
Cooling and heating energy demand across two combined parameters (EPS Insulation-Glazing type).

3.1.3. Combined Effects: Insulation and PCM Integration

The configurations combining EPS insulation and PCM (Phase Change Materials), as presented in table 4, provide valuable insights into hybrid passive design strategies, aiming to reduce both heating and cooling energy needs through thermal resistance and latent heat storage (Figure 6).

3.1.3.1. Energy Demand Under 2020 Climate Conditions

Under 2020 climate conditions, the combination of 10 cm EPS with 4 cm PCM (Configuration V15) exhibits the most favorable thermal performance. It achieves a cooling energy demand of 7.95 kWh/m², representing a 43.96% reduction compared to the uninsulated baseline (V1 = 14.18 kWh/m²). Additionally, heating demand is marginally reduced to 3.55 kWh/m², reflecting a 3.47% improvement. This performance confirms the synergistic interaction between the two materials: EPS effectively limits conductive heat transfer, while the PCM increases the thermal inertia of the envelope, absorbing heat during peak daytime temperatures and releasing it during cooler night periods. The comparison between V15 and V13 (same insulation, with only 1 cm PCM) further demonstrates the role of PCM thickness, as V15 achieves an additional 2.3% cooling reduction, highlighting the enhanced effectiveness of increased latent storage capacity up to a certain threshold.

3.1.3.2. Energy Demand Under 2050 Climate Projections (RCP 8.5)

Projections for 2050 under RCP 8.5 indicate a shift toward a predominantly cooling-driven thermal profile, with heating loads becoming increasingly marginal. Within this future context, the performance hierarchy among configurations changes. Configuration V14, which combines 4 cm EPS with 4 cm PCM, outperforms all other setups in cooling efficiency, achieving a cooling demand of 11.28 kWh/m². Surprisingly, V15, despite offering higher insulation, shows a slightly elevated cooling demand of 11.79

DOI: 10.55214/2576-8484.v10i4.12790

kWh/m². This inversion of ranking between 2020 and 2050 highlights a crucial insight: over-insulation in hot climates can become counterproductive. When outdoor temperatures remain high over extended periods, excessive insulation may trap internal heat, impeding night-time heat dissipation and leading to thermal discomfort. In contrast, moderate insulation paired with high PCM content appears to offer a more balanced thermal response. The 4 cm EPS layer in V14 provides adequate resistance against solar gains during the day while still allowing effective night cooling. Concurrently, the thicker PCM layer operates efficiently under extended temperature peaks, storing and releasing heat in sync with daily thermal cycles.

Table 4.
Annual Heating and Cooling Energy Demand (kWh/m²) for Configurations V12–V15 Combining EPS Insulation and Phase Change Materials (PCM) under 2020 and 2050 (RCP 8.5) Climate Scenarios.

				2020		2050	
configuration	**Insulation EPS**	**glazing**	**PCM**	**Heating (kWh/m²)**	**Cooling (kWh/m²)**	**Heating (kWh/m²)**	**Cooling (kWh/m²)**
V12	0.5	0	0.5	4.394	8.755	1.994	12.886
V13	1	0	0.5	3.613	8.127	1.608	12.057
V14	0.5	0	1	4.269	8.457	1.150	11.275
V15	1	0	1	3.554	7.945	1.583	11.791

Across both time horizons, PCM-enhanced envelopes demonstrate consistently strong performance. Configuration V15 remains the best performer in 2020, while V14 becomes more optimal under 2050 climate conditions. A comparative analysis of configurations V12 to V15 further confirms these trends. While PCM performance clearly improves with increased thickness from 1 cm to 4 cm, additional gains beyond this point may diminish or require complementary ventilation strategies to prevent overheating. Furthermore, the data indicate that the thermal priority shifts from insulation-dominant strategies in 2020 to PCM-driven control in 2050. This reflects a broader transition in passive envelope design, where the emphasis evolves from reducing heat loss to actively managing thermal loads and delay mechanisms in response to prolonged heat events.

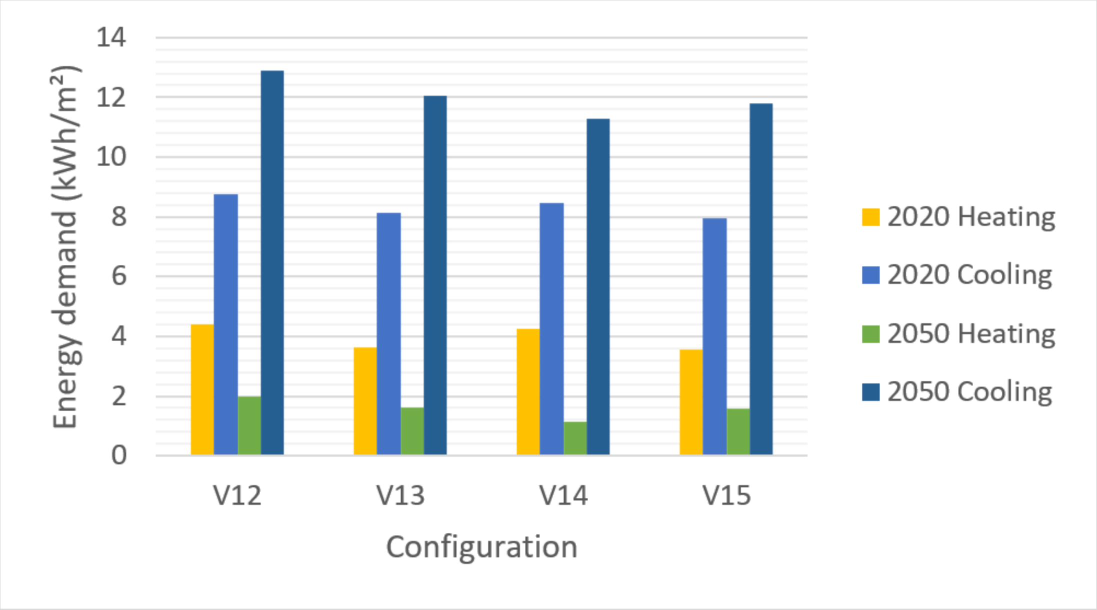

Figure 6.
Cooling and heating energy demand across two combined parameters (EPS Insulation-PCM).

3.1.4. Combined Effects: Glazing and PCM

The integration of advanced glazing systems with phase change materials (PCM), without the support of additional thermal insulation (Table 5), reveals pronounced seasonal asymmetries and critical design limitations. As evidenced in Table 5 and Figure 7, these configurations can effectively mitigate cooling demand during hot periods but simultaneously incur significant penalties in heating energy consumption. This thermal imbalance is primarily due to the combined effect of reduced solar gains through high-performance glazing and the delayed heat release characteristics of PCM, particularly in the absence of thermal insulation to retain interior warmth.

3.1.4.1. Energy Demand Under 2020 Climate Conditions

Under the 2020 climate conditions, configuration V19, comprising double Low-E glazing combined with 4 cm of PCM, demonstrated the best cooling performance within this group, achieving a 36.2% reduction in cooling energy demand relative to the baseline configuration V1. Nevertheless, this gain came at a considerable cost; heating energy demand for V19 increased by 111.7% compared to the baseline. Similarly, configuration V18, which combined double-tinted glazing with the same PCM thickness, reduced cooling demand by 34.1% but still exhibited an 89.7% increase in heating energy consumption. These figures underscore a critical shortcoming of glazing-PCM combinations when deployed without complementary insulation: while effective in limiting summer thermal loads, they impair passive solar utilization in winter.

The underlying cause of this heating penalty lies in the reduced solar transmittance of double glazing, especially Low-E variants, which block winter solar radiation that would otherwise contribute to passive heating. Furthermore, PCM materials, though effective in absorbing and delaying daytime heat gains, also delay the release of stored thermal energy, thereby limiting their benefit during cooler periods when immediate heat delivery is desirable. In the absence of envelope insulation, these effects are exacerbated by uncontrolled night-time heat losses.

3.1.4.2. Energy Demand Under 2050 Climate Projections (RCP 8.5)

Under the projected 2050 climate scenario, the same trade-off becomes even more pronounced. Configuration V19 remained the most effective for cooling, reducing demand by 32.7% compared with the reference case. However, all glazing–PCM configurations exhibited a doubling of heating energy demand relative to the baseline, with increases ranging from 101% to 118%. This outcome indicates that while the combination of solar-control glazing and PCM provides tangible benefits for mitigating summer overheating, it is insufficient to maintain adequate winter performance in the absence of complementary insulation.

Table 5.
Annual Heating and Cooling Energy Demand (kWh/m²) for Configurations V15–V19 Combining Glazing Types and PCM under 2020 and 2050 (RCP 8.5) Climate Scenarios.

				2020		**2050**	
Configuration	**Insulation EPS**	**glazing**	**PCM**	**Heating (kWh/m²)**	**Cooling (kWh/m²)**	**Heating (kWh/m²)**	**Cooling (kWh/m²)**
V16	0	0.5	0.5	7.313	11.104	3.668	16.531
V17	0	1	0.5	7.985	10.861	4.177	16.161
V18	0	0.5	1	6.984	9.336	3.517	14.148
V19	0	1	1	7.788	9.051	4.134	13.728

The key finding is that combining PCM with advanced glazing, without insulation, does not improve thermal performance. While glazing slightly reduces summer cooling demand, it significantly worsens winter performance. Configuration V7, which uses only 1 cm of PCM without advanced glazing or insulation, results in lower heating demand than V18 and V19. This confirms that glazing alone cannot compensate for the lack of insulation and may even block useful winter solar gains.

This pattern is even more evident under 2050 RCP 8.5 conditions. V7 shows a cooling demand of 13.88 kWh/m² and a heating demand of 2.24 kWh/m². Although V18 and V19 reduce cooling slightly (−1.73 and −3.15 kWh/m² compared to V7), they exhibit significantly higher heating demands (3.52 and 4.13 kWh/m², respectively). The simple PCM-only configuration outperforms more complex glazing-PCM combinations in winter energy efficiency.

Altogether, these results highlight that the glazing-PCM combination without insulation is thermally unbalanced. The modest summer gains do not justify the winter penalties. By contrast, PCM used alone, even in minimal thickness, delivers more stable seasonal results. For PCM to function effectively, it must be incorporated into an envelope system that includes insulation and enables both solar gain management and heat retention.

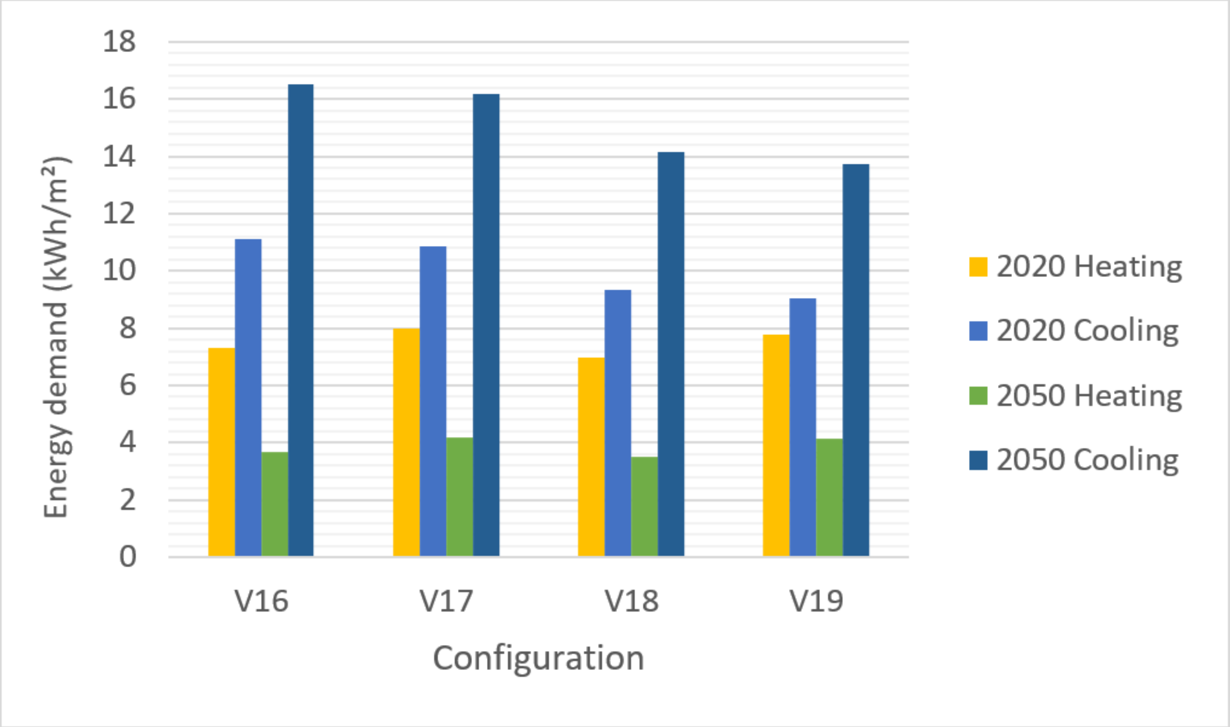

Figure 7.
Cooling and heating energy demand across two combined parameters (Glazing type-PCM).

3.1.4.3. Comprehensive Integration Of EPS, Glazing, And PCM

This section evaluates the combined impact of EPS insulation, glazing type, and PCM thickness on annual energy performance. Configurations V20–V27 constitute a full factorial matrix integrating these three envelope strategies (Table 6).

3.1.4.4. Energy Demand Under 2020 Climate Conditions

The 2020 results, as presented in Figure 8, show that configuration V27 (EPS 10 cm, Low-E glazing, PCM 4 cm) achieves the lowest cooling demand at 5.29 kWh/m², corresponding to a 62.7% reduction from the reference case (V1). Close behind, V25 (EPS 10 cm, AL-Tint glazing, PCM 4 cm) records 5.81 kWh/m², or a 59.0% reduction. These outcomes confirm that high insulation levels significantly reduce transmission gains, while thicker PCM layers effectively smooth daily thermal peaks. Low-E glazing slightly outperforms AL-Tint for cooling due to superior solar control.

Regarding the heating demand, none of the combined strategies outperforms the baseline heating demand (V1: 3.68 kWh/m^2). V25 performs best among the group, with 5.02 kWh/m^2 (+36.4%), while V27 exhibits 6.51 kWh/m^2 (+76.9%). These penalties are mainly due to the reduced solar transmittance of Low-E glazing and PCM's delayed heat release.

3.1.4.5. Energy Demand Under 2050 Climate Projections (RCP 8.5)

Looking ahead to projected 2050 climate conditions, configuration V23, integrating 4 cm of EPS insulation, Low-E glazing, and 4 cm of PCM, exhibited the best performance in terms of cooling demand, achieving 6.98 kWh/m^2, a reduction of 65.8% compared to V1 (20.40 kWh/m^2). In contrast, configuration V21 recorded the lowest heating energy requirement in 2050, at 1.90 kWh/m^2, which nonetheless represents an increase of approximately 9.0% compared to the 2050 baseline (1.743 kWh/m^2). This marginal increase highlights the persistent challenge of balancing winter thermal performance when solar gains are reduced by spectrally selective materials.

These results underscore the importance of climate-responsive building envelope strategies. While high insulation thicknesses may yield optimal results under current climate conditions, moderate insulation levels combined with advanced glazing and latent thermal storage appear to offer better thermal balance under future warming scenarios.

Table 6.
Annual Heating and Cooling Energy Demand (kWh/m^2) for Configurations V20–V27 Combining both EPS Insulation, Glazing Types, and PCM under 2020 and 2050 (RCP 8.5) Climate Scenarios.

				2020		**2050**	
Configuration	**Insulation EPS**	**Glazing**	**PCM**	**Heating (kWh/m^2)**	**Cooling (kWh/m^2)**	**Heating (kWh/m^2)**	**Cooling (kWh/m^2)**
V20	0.5	0.5	0.5	5.790	6.869	2.849	10.372
V21	0.5	0.5	1	5.673	6.540	1.902	7.747
V22	0.5	1	0.5	6.972	6.504	3.696	9.836
V23	0.5	1	1	6.898	6.169	3.270	6.986
V24	1	0.5	0.5	5.086	5.576	2.423	8.565
V25	1	0.5	1	5.020	5.806	2.372	8.876
V26	1	1	0.5	6.536	5.573	3.463	8.499
V27	1	1	1	6.514	5.293	3.437	8.093

The data reveal several important interaction dynamics. EPS and PCM show strong synergy under 2020 conditions, with insulation reducing conduction and PCM contributing thermal inertia. However, in 2050, over-insulation limits PCM effectiveness, as heat becomes trapped. The glazing–PCM interaction is also climate-dependent: in winter, Low-E glazing blocks passive solar gains while PCM absorbs heat that is not effectively released, increasing heating demand. In summer, the same combination performs well by minimizing gains and modulating indoor temperatures.

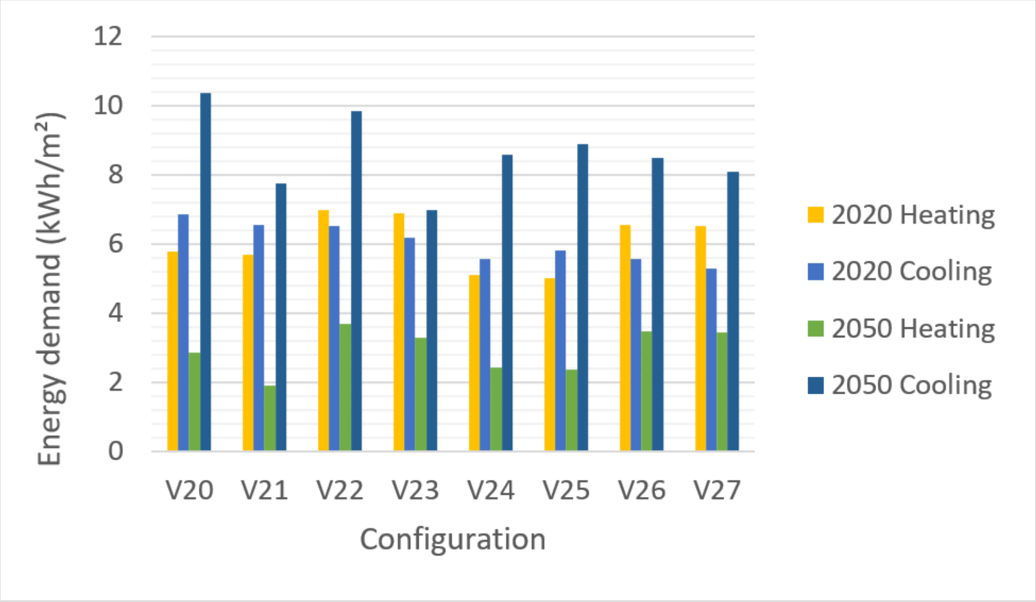

Figure 8.
Cooling and heating energy demand across three combined parameters (EPS Insulation-Glazing type-PCM).

In 2020, strategies prioritizing maximum insulation, moderate solar control (AL-Tint), and 4 cm PCM (e.g., V25) deliver the best balance between cooling and heating demands. However, in 2050, where cooling dominates, moderate insulation (4 cm EPS) combined with high solar control (Low-E) and PCM becomes more effective (e.g., V23, V21), as it prevents heat buildup while enabling night-time cooling.

The results also highlight a paradigm shift: from insulation-driven envelopes in cooler or transitional climates (2020) to glazing- and PCM-driven strategies in future hot climates (2050). This shift calls for design strategies that are not only high-performing under current conditions but also adaptable to future thermal stressors.

3.2. Parametric Trends and Interaction Dynamics Under Climate Change Scenarios

A detailed trend analysis was conducted to evaluate the individual and combined impacts of the three key passive design parameters, EPS insulation, glazing type, and PCM, on annual heating and cooling energy demand under current (2020) and future (2050, RCP 8.5) climatic scenarios. The evolution of their influence and interdependencies highlights the non-static nature of envelope performance in a changing climate.

EPS insulation exhibits a persistent ability to reduce energy consumption across both heating and cooling seasons, confirming its consistent role in thermal resistance [36]. However, the magnitude and direction of its impact shift with climatic conditions. While in 2020, high insulation levels reduce both heating and cooling loads, in 2050, the cooling benefit intensifies due to longer and hotter summers. Conversely, its influence on heating demand diminishes under milder winter conditions, where thermal retention is less critical.

Glazing demonstrates a moderate impact with limited interaction effects. In winter, Low-E glazing increases heating demand due to its low solar heat gain coefficient, which blocks beneficial radiation. In summer, its contribution is more favorable, helping to reduce cooling loads through solar control. However, its relative influence decreases slightly under future climate conditions, possibly due to diminishing returns when combined with highly insulated and PCM-integrated envelopes.

PCM integration reveals a seasonally reversed behavior. In the 2020 scenario, PCM reduces heating demand by storing solar gains and releasing heat during nighttime. However, in 2050, PCM contributes to increased heating demand, as milder winters reduce the amplitude of daily temperature fluctuations, weakening the material's thermal cycling capacity. For cooling, PCM performs positively in both scenarios, with enhanced performance under future conditions due to extended cooling seasons and higher daytime peaks.

Evolution of Parametric Interactions: The interactions between parameters are also climate-sensitive. Notably, the synergy between EPS insulation and PCM observed in 2020 for both heating and cooling becomes more complex in 2050. For heating, their combination may be counterproductive, as high insulation prevents effective PCM discharge, limiting winter comfort. For cooling, however, their synergy persists; insulation stabilizes internal temperatures while PCM buffers peak loads.

In contrast, glazing shows minimal interactive behavior with other parameters, acting as an independent modulator of solar gains. This finding suggests that glazing performance should be strategically aligned with seasonal solar control goals, rather than used as a compensatory measure for other envelope weaknesses.

These findings demonstrate that the performance of envelope parameters is dynamic, not static, and that their relative importance evolves under climate change. Consequently, envelope design should prioritize adaptability and future climate responsiveness, rather than rely on fixed performance assumptions.

4. Conclusion

This paper presents a comprehensive evaluation of passive envelope strategies under both current and future climatic contexts in Marrakech. By integrating EPS insulation, glazing types, and PCM layers within a parametric simulation framework, the results demonstrate that while insulation remains dominant under current conditions, its effectiveness diminishes under 2050 climate projections, where PCM and glazing become more influential.

Configurations using moderate insulation (4 cm EPS), Low-E glazing, and 4 cm PCM achieved the best cooling reductions in future scenarios, while AL-Tinted glazing offered a better balance with less winter heating penalty. Notably, excessive insulation coupled with high thermal inertia led to overheating risks, suggesting that over-insulated designs may be counterproductive in future climates.

Furthermore, glazing-PCM combinations without insulation were shown to be thermally unbalanced, particularly during winter, underscoring the need for holistic envelope design. The shift from insulation-led to glazing–PCM-dominant strategies highlights the importance of adaptable, climate-responsive building envelopes in semi-arid zones facing rapid climate change.

Future work should explore hybrid systems and dynamic thermal controls to optimize seasonal performance further. These findings contribute to developing resilient passive strategies tailored for hot, dry regions under long-term climate change.

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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