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Energy and Thermal Comfort Assessment of Insulation Strategies in Moroccan Residential Buildings: A Multi-Zone Simulation Study Based on the Moroccan Thermal Construction Regulation

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Abstract.

This study investigates the impact of thermal insulation strategies on annual energy demand and indoor thermal comfort in a typical Moroccan residential building. A two-storey dwelling with a floor area of 100.05 m² was simulated in the six climatic zones defined by the Moroccan Thermal Construction Regulation. Dynamic simulations were performed using DesignBuilder coupled with EnergyPlus. Six conventional insulation materials, namely extruded polystyrene, expanded polystyrene, glass wool, rock wool, hemp wool, and wood fiber, were assessed for different thicknesses and envelope configurations, including wall insulation, roof insulation, and combined wall–roof insulation. A phase change material, BioPCM M51/Q23, was also investigated separately. The results show that the uninsulated reference building exceeds the regulatory performance limits in all climatic zones, confirming the need for envelope improvement. Among the tested scenarios, combined wall–roof insulation using extruded polystyrene at 6/6 cm consistently provides the highest reduction in annual heating and cooling demand in all six climatic zones, ranging from 9.58% in Agadir to 24.71% in Ifrane. However, full regulatory compliance is not achieved by insulation alone, mainly because of the unchanged single glazing and, in some zones, the insufficient thermal performance of the slab-on-ground floor. The comfort analysis further indicates that the lowest annual energy demand does not always correspond to the best thermal comfort performance: in Marrakech and Agadir, the energy-optimal and comfort-optimal scenarios diverge, and in Marrakech wood fiber at 6/6 cm provides the greatest reduction in discomfort hours, highlighting the relevance of dynamic thermal behavior in hot semi-arid climates. These findings demonstrate that insulation strategies in Morocco should be selected according to climatic zone, envelope component, regulatory requirements, and comfort objectives rather than based only on thermal conductivity. By applying a single building model and a common regulation-based simulation framework to all six Moroccan climatic zones, three envelope configurations, and four families of insulation material simultaneously, this study provides a unified comparative basis for climate-specific envelope design in Moroccan residential buildings that previous single-zone or single-material studies could not offer.

Keywords: building energy simulation; thermal insulation; Moroccan Thermal Construction Regulation; EnergyPlus; DesignBuilder; Moroccan climatic zones; thermal comfort.

1. Introduction

The building sector is now at the center of energy transition, carbon reduction, and climate adaptation challenges. At the international level, buildings account for a significant share of energy consumption and associated emissions, making the improvement of their thermal performance one of the key

strategies for reducing energy demand and environmental impacts [1,2]. In Morocco, rapid urbanization, the growth of the residential building stock, rising comfort requirements, and the increasing use of heating and air-conditioning systems reinforce the need to better control residential energy demand [3–6].

In this context, the Moroccan Thermal Construction Regulation (RTCM) represents an important step toward the integration of energy efficiency requirements into building design [3,4]. Based on the division of the national territory into six climatic zones, the RTCM combines two complementary approaches: a prescriptive approach, which defines minimum thermal requirements for the building envelope, and a performance-based approach, which limits annual heating and cooling demand [3,4,7]. This dual regulatory framework is particularly relevant in Morocco, where climatic diversity requires construction solutions adapted to each geographical context rather than a single uniform approach [5–8]. Compliance can be demonstrated through either route; both approaches are therefore examined in parallel for every scenario considered here, following the evaluation protocol described in Section 5.

Among the available passive strategies, the insulation of the opaque building envelope remains one of the most effective measures for improving thermal performance. Wall and roof insulation can reduce heat losses in winter, limit solar heat gains in summer, and influence indoor thermal comfort [9–11]. However, the effectiveness of an insulation strategy depends not only on thermal conductivity or thickness, but also on the local climate, the thermophysical properties of the material, the thermal inertia of the envelope, and the position of the insulation within the construction assembly [12–17]. This explains the growing interest in comparing different families of insulation materials, including conventional mineral and polymer materials, bio-based insulation, and phase change materials (PCM) [9–19]. In addition to reducing energy demand, insulation significantly affects indoor thermal comfort by moderating indoor temperature fluctuations and reducing discomfort periods, which reinforces the practical relevance of assessing energy demand and thermal comfort jointly rather than sequentially.

The literature devoted to the Moroccan context confirms the potential of passive strategies, while showing that their effectiveness varies greatly depending on the climatic zone, building type, and construction scenario considered. Gargab et al. compared, across the six Moroccan climatic zones, passive envelope improvement solutions and active solutions related to domestic hot water production, highlighting the need for an integrated reading of building performance [5]. Lamrani Alaoui et al. showed that local construction configurations and certain geometric choices, such as wall composition or roof slope, significantly influence energy demand in the different Moroccan climates [6]. At the scale of localized case studies, Eddib and Lamrani assessed the effect of several insulation materials and their optimum thicknesses for a dwelling in Marrakech [20], Kaddouri et al. studied the interest of bio-based materials and then the contribution of hemp concrete combined with passive strategies in the context of Al-Hoceima [21,22], while Abidouche et al. showed, in Tangier, that regulatory compliance in the RTCM sense does not by itself exhaust the question of occupants' thermal comfort [7]. Likewise, Bouchark et al. compared, for a building in Meknes, solutions based on polystyrene, hemp concrete, and PCM, confirming that the choice of material remains strongly dependent on the climate and the mode of integration into the envelope [23]. Other Moroccan works have also emphasized the interest of ecological materials, multilayer walls filled with insulation, and thickness optimization in semi-arid, cold, or hot contexts [8,12,24–27].

Beyond the Moroccan context, several review studies have emphasized that the selection of insulation materials should not be based only on thermal conductivity. Other criteria, such as dynamic thermal response, durability, fire resistance, moisture behavior, implementation constraints, and

environmental impacts, must also be considered [9–11]. Bio-based insulation materials are increasingly studied because of their lower embodied energy and their hygrothermal properties, which can be beneficial for building envelopes [18,19]. Phase change materials have also been widely investigated for their ability to reduce indoor temperature fluctuations, shift thermal peaks, and improve summer comfort, especially when combined with appropriate ventilation strategies [13–17]. These findings support the need for a comparative assessment of conventional, bio-based, and PCM solutions under different climatic conditions.

Dynamic building simulation tools are widely used to assess the thermo-energetic performance of buildings under realistic operating conditions. Software environments such as TRNSYS, EnergyPlus, and DesignBuilder make it possible to analyze the combined effects of climate, envelope composition, insulation material, thickness, occupancy schedules, and operating assumptions [4,20,28–31]. Recent studies have shown that the effectiveness of an insulation strategy depends not only on the material itself, but also on its thickness, its location in the envelope, and its application to walls, roofs, or both components [23,28–33].

Despite these contributions, several research gaps remain. Many existing studies are limited to a single location, a specific climatic zone, or one family of insulation materials. In addition, few studies have simultaneously compared mineral, polymer, bio-based, and PCM insulation solutions within an explicit Moroccan regulatory framework. Finally, limited attention has been given to integrated assessments combining the six RTCM climatic zones, both prescriptive and performance-based approaches, several insulation thicknesses, and different envelope configurations, including walls, roof, and combined wall–roof insulation [3–8,21–23,28,32–35]. No previous study, however, has jointly examined seven insulation solutions from four material families (polymer, mineral, bio-based, and phase-change), five thicknesses, three envelope configurations, and both RTCM compliance routes across all six Moroccan climatic zones within a single, internally consistent simulation framework.

Recent contributions continue to refine this picture. In Tehran's hot-summer continental climate, dynamic DesignBuilder/EnergyPlus simulations of roof and wall insulation have proposed numerical frameworks for ranking insulation materials and thicknesses [36,37], a modeling approach directly comparable to the one adopted here. In arid North African contexts, palm-fiber-reinforced adobe has been shown to substantially improve both the mechanical and thermal performance of earthen envelope components, reinforcing the relevance of bio-based alternatives to petrochemical insulation in hot climates [38]. For Morocco specifically, a large-scale simulation campaign covering more than 1000 residential configurations across the RTCM climatic zones has confirmed wide variability in regulatory compliance and highlighted the sensitivity of thermal comfort, not only energy demand, to construction practice [39], while an optimization-based lifecycle-cost analysis applied to the same six climatic zones adopted in the present work has shown that RTCM compliance alone captures only part of the energy-saving potential available once glazing, air leakage, lighting, and HVAC efficiency are optimized jointly with insulation [40]. Phase-change materials integrated into building envelopes have also been the subject of a recent critical review with a dedicated assessment of Moroccan research, underlining the sensitivity of PCM performance to phase-change temperature, layer position, and ventilation strategy [41]. Finally, comparative evaluations of adaptive thermal-comfort models (ASHRAE 55, EN 16798-1, ISSO 74) in Mediterranean and North African residential contexts confirm that comfort-model choice materially affects discomfort-hour outcomes, which motivates the explicit description of the comfort model given in Section 4 [42].

This study addresses these gaps by assessing the impact of insulation strategies on annual heating and cooling demand and thermal comfort in a typical Moroccan residential building. Dynamic simulations are carried out using DesignBuilder coupled with EnergyPlus for the six RTCM climatic zones. Six conventional insulation materials, namely XPS, EPS, glass wool, rock wool, hemp wool, and wood fiber, are evaluated for five thicknesses and three envelope configurations: walls, roof, and combined wall–roof insulation. BioPCM M51/Q23 is also analyzed separately. The study aims to identify the most suitable insulation strategies according to climatic zone, regulatory compliance, energy demand reduction, and thermal comfort performance [3–8,21–23,28–35].

2. Description of the studied climate

The climatic assessment was carried out for the six climatic zones defined by the Moroccan Thermal Construction Regulation (RTCM). Each zone was represented by a reference city: Agadir for Z1, Tangier for Z2, Fez for Z3, Ifrane for Z4, Marrakech for Z5, and Errachidia for Z6 [3–8]. This selection covers the main Moroccan climatic conditions, including coastal, Mediterranean, inland, mountainous, hot semi-arid, and desert climates (Table 1). Using the same building model in all climatic zones makes it possible to isolate the influence of climate on annual heating demand, cooling demand, and thermal comfort.

The dynamic simulations were driven by the complete hourly EnergyPlus Weather (EPW) files of the six selected cities, which include dry-bulb temperature, relative humidity, wind speed and direction, sky temperature, and direct and diffuse solar radiation, among other parameters; all of these variables are fully accounted for in the hourly simulations. For the purpose of describing and comparing the six climates in this section specifically, monthly outdoor air temperature and global solar irradiation are reported (Figures 1 and 2) because they are the two variables that most directly and intuitively govern envelope heat losses, solar gains, cooling needs, and the relative effectiveness of insulation strategies.

Table 1: Climatic characteristics of the main cities of Morocco

Location	Climatic description
Agadir	Coastal climate with a subtropical and semi-arid dominance. Atlantic influence keeps winters mild and limits summer extremes, while sunshine remains high and relatively regular throughout the year.
Tangier	Mediterranean climate with maritime influence. Winters are moderate and more humid, summers are warm without being extreme, and the annual thermal amplitude remains among the lowest in the sample.
Fez	Inland climate with Mediterranean and continental influence. The city shows a more marked seasonal contrast than coastal cities, with a relatively cool winter, a hot summer, and substantial sunshine.
Ifrane	Cold mountainous climate, humid-temperate. Ifrane is the coldest thermal profile in the panel, with harsh winters, high heating demand, and markedly milder summers.
Marrakech	Hot semi-arid climate. The city combines a generally mild winter with a very hot summer, resulting in high exposure to cooling demand and a high level of solar irradiation.
Errachidia	Hot desert climate. This city is distinguished by very hot summers, marked thermal contrasts between seasons, and one of the highest solar potentials among the cities studied.

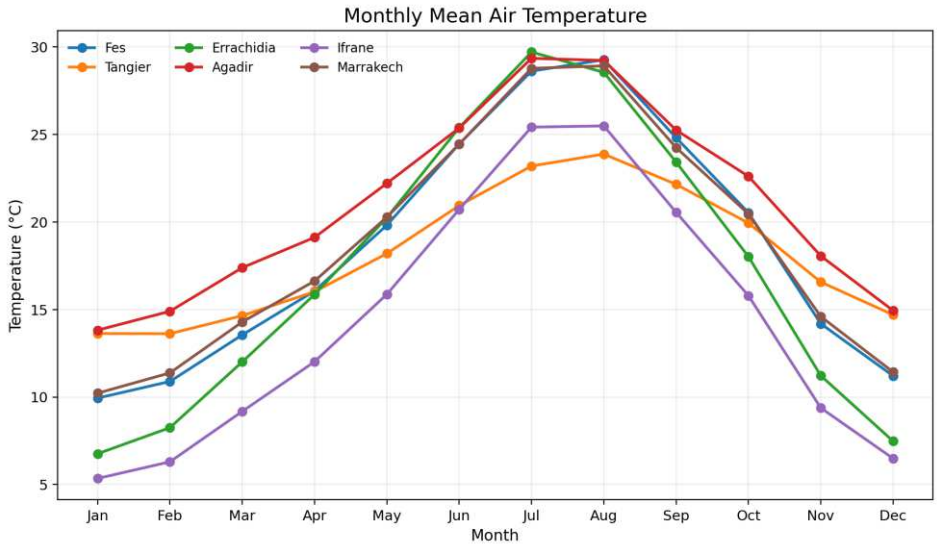


Figure 1: Monthly Mean Air Temperature of the Six Selected Moroccan Cities.

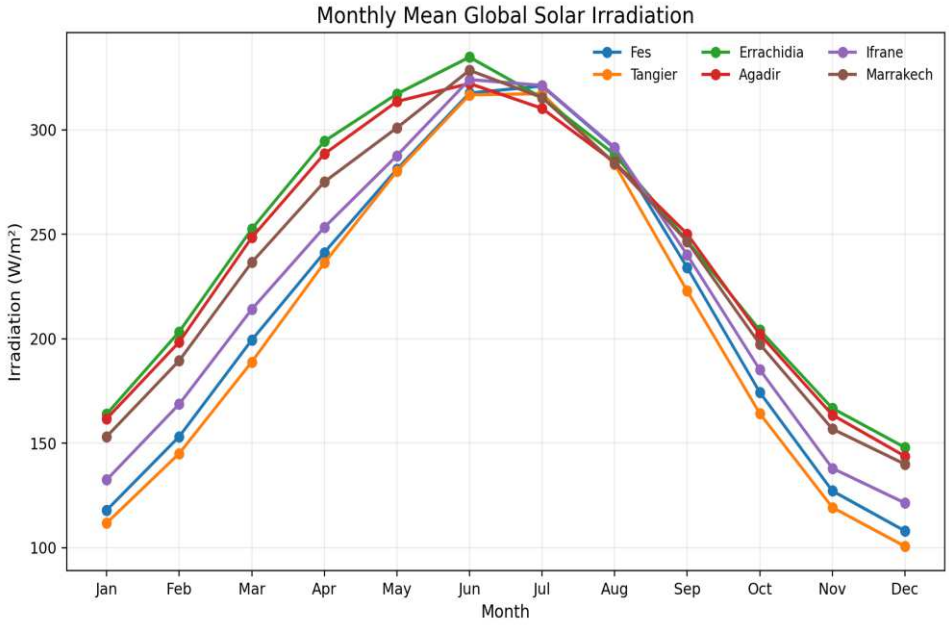


Figure 2: Monthly Mean Global Solar Irradiation of the Six Selected Moroccan Cities.

3. Description of the studied building

The case study is a two-storey residential villa (R+1) with a total floor area of 100.05 m² and a floor-to-ceiling height of 3 m. The building is occupied by a five-person household and includes the main functions of a typical Moroccan dwelling, namely living spaces, a kitchen, bedrooms, bathrooms, and storage areas. The same geometry, orientation, envelope composition, occupancy assumptions, and internal loads were used for all climatic zones in order to ensure a consistent comparison between the simulated cases.

The main façade of the building is oriented to the south, while the rear, left lateral, and right lateral façades are oriented to the north, west, and east, respectively (Table 2); this orientation corresponds to the actual orientation of the reference dwelling on which the architectural plans are based (Figure 3) and was therefore kept unchanged across all climatic zones, consistent with the objective of isolating the effect of climate and insulation rather than architectural design choices such as orientation. The building was modeled in DesignBuilder according to the architectural plans, and the three-dimensional model was used to perform the dynamic simulations with EnergyPlus (Figure 4).

Table 2: Orientation of the building facades

Facade	Orientation
Front facade	South
Rear facade	North
Left lateral	West
Right lateral	East

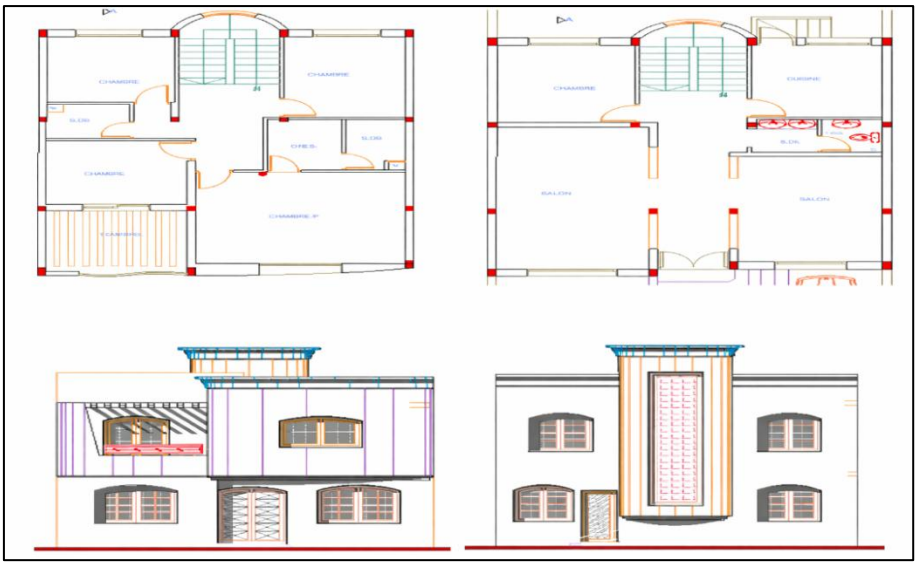


Figure 3: Architectural plans of the studied residential building.

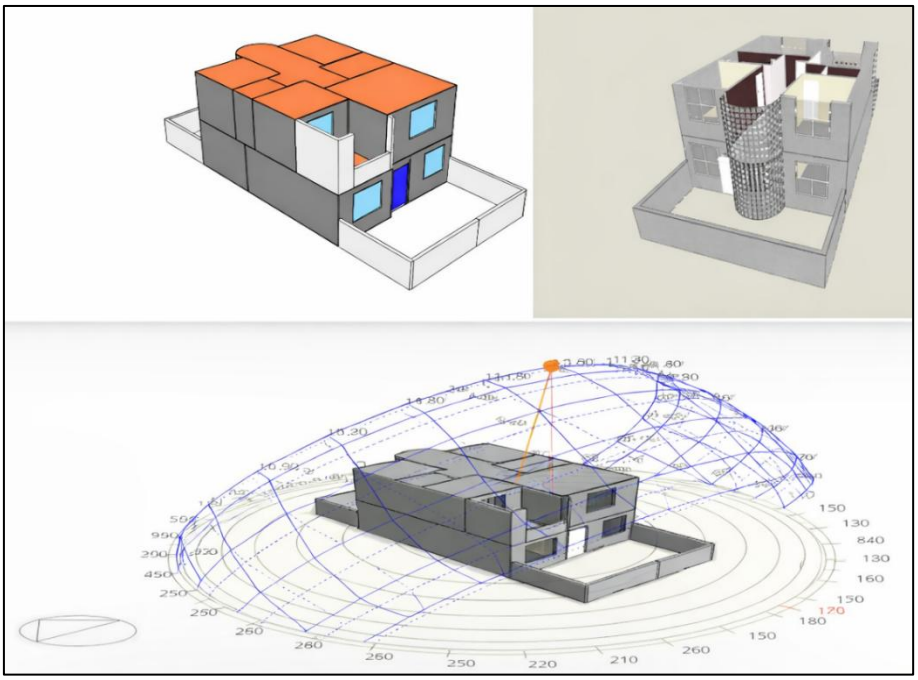


Figure 4: 3D model and solar analysis of the studied building in DesignBuilder.

The thermal properties of the building envelope were defined according to the initial construction layers of the reference building. The external walls, internal partitions, roof, and slab-on-ground floor were modeled using the material thicknesses, thermal conductivities, and densities presented in Tables 3–6. These properties were used to calculate the thermal transmittance of the envelope components and to define the baseline case before the integration of insulation materials. The windows were modeled as single glazing, with a thermal transmittance of U_glazing ≈ 5.88 $W \cdot m^{-2} \cdot K^{-1}$ (Table 11),

representative of common existing residential construction in Morocco; the doors were considered as wooden doors. The glazing corresponds to the generic single clear 3 mm glazing dataset of DesignBuilder/EnergyPlus, with a solar heat gain coefficient of approximately 0.86 and a visible transmittance of approximately 0.90. The glazing system was kept unchanged in all scenarios in order to isolate the specific effect of the insulation materials on the opaque envelope.

Table 3: Exterior wall compositions

Materials	Mortar	Brick (8holes)	Brick (8holes)	Mortar
Thickness (cm)	1	10	10	1
Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	1.4	1.15	1.15	1.4
Density ($kg \cdot m^{-3}$)	2000	743	743	2000

Table 4: Interior wall compositions

Materials	Mortar	Brick (8holes)	Mortar
Thickness (cm)	1	10	1
Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	1.4	1.15	1.4
Density ($kg \cdot m^{-3}$)	2000	743	2000

Table 5: Roof compositions

Materials	Plaster	Concrete slabs	Slab	Mortar	Tiles
Thickness (cm)	1	16	4	10	5
Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	0.351	1.23	1.65	1	1
Density ($kg \cdot m^{-3}$)	1500	1300	2150	1700	2500

Table 6: Floor-on-ground compositions

Materials	Exposed aggregate concrete	Form	Slab	Sand	Gravel
Thickness (cm)	2	6	12	3	20
Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	1	0.39	1.7	0.39	0.47
Density ($kg \cdot m^{-3}$)	2000	600	2400	750	570

4. Energy simulation and physical model

Dynamic thermal simulations were performed using DesignBuilder coupled with the EnergyPlus calculation engine. The building geometry was created from the architectural plans and divided into thermal zones according to space use. The envelope components were defined using the construction layers and thermophysical properties presented in the previous section. For all simulated cities, the same building geometry, orientation, occupancy, internal loads, ventilation mode, glazing type, and temperature setpoints were maintained in order to ensure a consistent comparison between climatic zones and insulation scenarios.

The building was assumed to be naturally ventilated and occupied by a five-person household. LED lighting and typical residential electrical equipment were considered. Heating and cooling setpoints were fixed at 20 °C and 26 °C, respectively. The window-to-wall ratio was 10.69%, and the windows were modeled as single glazing. Annual heating demand, annual cooling demand, and total energy demand were extracted directly from the EnergyPlus simulation output for each scenario; the thermal transmittance (U-value) of each envelope component was calculated from the modeled construction

layers; RTCM compliance was subsequently determined by comparing these simulated U-values and annual energy indicators against the prescriptive and performance-based thresholds defined in Section 5, rather than being an output directly extracted from the simulations; and annual discomfort hours were obtained from the ASHRAE 55-2004 Simple comfort indicator described below.

Outdoor air renewal was represented by a constant infiltration rate of 0.35 air changes per hour (ACH), applied continuously (24 h/day, 7 days/week) to all thermal zones; no mechanical ventilation system was modeled, consistent with the naturally ventilated operation of typical Moroccan dwellings, and linear thermal bridges were not explicitly modeled. Surface convection was computed with the TARP correlation for internal surfaces and the DOE-2 correlation for external surfaces in the heating design, cooling design, and annual simulation calculations. Internal gains were assigned from the DesignBuilder residential activity templates associated with each zone. Occupancy followed the hourly domestic schedules of these templates: on weekdays, the occupancy fraction rises from zero before 07:00 to full occupancy between 08:00 and 09:00, drops to zero during the middle of the day (10:00–17:00), and increases progressively in the evening to full occupancy between 20:00 and 22:00 before decreasing overnight, while at weekends and on holidays the dwelling is fully occupied from 09:00 to 21:00. The metabolic activity corresponds to light manual work with a metabolic factor of 0.90, and clothing insulation is 1.0 clo in winter and 0.5 clo in summer. General lighting was modeled as suspended LED luminaires with a normalized power density of 5.0 $W \cdot m^{-2}$ per 100 lux of design illuminance (radiant fraction 0.42, visible fraction 0.18), operated from 07:00 to 10:00 and from 17:00 to 24:00 on weekdays and from 09:00 to 21:00 at weekends and on holidays; miscellaneous electrical equipment gains were taken from the same residential templates. All of these assumptions were kept strictly identical across the six climatic zones and all insulation scenarios, so that they affect every case equally and do not bias the comparative results.

Thermal discomfort was quantified using the built-in EnergyPlus/DesignBuilder indicator “Time Not Comfortable Based on Simple ASHRAE 55-2004,” a simplified method that classifies each occupied hour as comfortable or not according to the combination of zone operative temperature and humidity ratio, evaluated against two fixed comfort regions defined by ASHRAE Standard 55-2004 for “summer clothes” (approximately 0.5 clo) and “winter clothes” (approximately 0.9–1.0 clo) [43,44]. Unlike the Fanger PMV/PPD model, this simplified method does not require the modeler to specify a numerical air speed, metabolic rate, or clothing insulation for each simulated hour; instead, comfort is assessed directly against the two psychrometric comfort zones defined by the standard, for which the minimum winter-clothes comfort temperature is approximately 21.7 °C at low humidity and the maximum summer-clothes comfort temperature is approximately 26.8 °C at low humidity [44]. This indicator was selected because it is the default discomfort-hour output reported by DesignBuilder for naturally ventilated residential buildings and enables a direct, standardized comparison across the six climatic zones and all insulation scenarios. Because this is a fixed-band method rather than an adaptive or PMV-based model, the discomfort hours reported here are not directly comparable in absolute terms with studies using adaptive comfort standards such as EN 16798-1 or ISSO 74, which define comfort bands as a function of the running-mean outdoor temperature and can therefore yield different discomfort-hour estimates for the same climate and building [42].

Table 7: Thermo-energetic simulation conditions of the building studied.

Simulation Condition	Description
Location	Agadir, Tangier, Fez, Ifrane, Marrakech, Errachidia (six RTCM climatic zones)

Weather data	Full hourly EPW weather file for each of the six cities (see Section 2)
Simulation Period	Full-year (annual) simulation
Occupancy	5 people in a residential R+1 building
Occupancy schedule	Hourly weekday/weekend/holiday residential profiles (see Section 4)
Lighting Sources	LED lighting, 5.0 W·m⁻² per 100 lux (suspended luminaires)
Thermal Insulation	Uninsulated baseline envelope (non-compliant with the RTCM)
Ventilation	Natural ventilation (no mechanical system)
Infiltration	Constant 0.35 ACH, applied 24 h/day, 7 days/week
Window Type	Single glazing
Electrical Equipment	Gains from the DesignBuilder residential activity templates
Envelope Conditions	Walls, roof, and floors as built (Tables 3–6)
WWR	10.69%
Simulation Software	DesignBuilder coupled with EnergyPlus
Temperature setpoint	heating: 20°C, cooling: 26°C

For all cities, the simulations retain the same residential geometry (100.05 m²), the same single glazing, the same occupancy, the same internal loads, and the same setpoints (20 °C for heating and 26 °C for cooling). Comparisons are therefore climatic and material-related rather than architectural. Unless otherwise stated, λ is expressed in $W \cdot m^{-1} \cdot K^{-1}$, U in $W \cdot m^{-2} \cdot K^{-1}$, R in $m^2 \cdot K \cdot W^{-1}$, ρ in $kg \cdot m^{-3}$, Cp in $J \cdot kg^{-1} \cdot K^{-1}$, thickness in cm, annual demand in $kWh \cdot m^{-2} \cdot year^{-1}$, and discomfort in h/year.

4.1. Mathematical formulation used in DesignBuilder/EnergyPlus

DesignBuilder was used as the graphical interface for building modeling, while EnergyPlus was used as the dynamic thermal simulation engine. EnergyPlus calculates building thermal behavior using the heat balance method, which accounts for heat transfer through the envelope, internal gains, solar radiation, ventilation, infiltration, and HVAC system response.

At the zone level, the air heat balance considers internal convective gains, convective exchanges with internal surfaces, interzone airflow, infiltration, and heating or cooling system input. The thermal response of the envelope is calculated by considering transient conduction through walls and roofs, as well as long-wave and short-wave radiative exchanges at internal and external surfaces. This approach makes it possible to evaluate hourly heating and cooling demand, surface heat transfer, indoor temperature evolution, and thermal comfort indicators.

In the present study, the same physical model and calculation assumptions were used for all insulation scenarios and climatic zones. Therefore, the differences observed in the results are mainly attributed to climatic conditions, insulation material properties, insulation thickness, and envelope configuration.

The main governing equations used by EnergyPlus are briefly recalled below to clarify the physical basis of the dynamic thermal simulation.

The thermal balance of the zone air is written as:

$$C_z \frac{dT_z}{dt} = \sum \dot{Q}_i + \sum h_i A_i (T_{si} - T_z) + \sum \dot{m}_i C_p (T_{zi} - T_z) + \dot{m}_{inf} C_p (T_\infty - T_z) + \dot{Q}_{sys} \qquad (1)$$

where $C_z$is the sensible heat capacity of the zone air, $T_z$the zone air temperature, $\sum \dot{Q}_i$the internal convective gains, $h_i A_i (T_{si} - T_z)$the convective heat exchange with the surfaces, $\dot{m}_i$the interzone

airflow rates, $\dot{m}_{inf}$the infiltration, $T_{\infty}$the outdoor temperature, and $\dot{Q}_{sys}$the HVAC system input. EnergyPlus also expresses the sensible effect of the air system as:

$$\dot{Q}_{sys} = \dot{m}_{sys} C_p (T_{sup} - T_z) \qquad (2)$$

with $\dot{m}_{sys}$the supply airflow rate and $T_{sup}$the supply air temperature.

The balance at the inner face of a wall is formulated as:

$$q''_{LWX} + q''_{SW} + q''_{LWS} + q''_{ki} + q''_{sol} + q''_{conv} = 0 \qquad (3)$$

where $q''_{LWX}$is the infrared radiative exchange between surfaces, q''_{SW} the short-wave radiation from lighting, $q''_{LWS}$the long-wave radiation from equipment, $q''_{ki}$the conduction through the wall, q''_{sol} the transmitted solar radiation absorbed by the surface, and q''_{conv} the convective heat flux to the air. The convective term is given by:

$$q''_{conv} = h_c (T_s - T_a) \qquad (4)$$

With h_c the internal convection coefficient, T_S the surface temperature, and T_a the zone air temperature.

For transient conduction in walls, EnergyPlus uses the Conduction Transfer Functions (CTF) method:

$$q''_{ki}(t) = -Z_0 T_{i,t} - \sum_{j=1}^{n_z} Z_j \; T_{i,t-j\delta} + Y_0 T_{o,t} + \sum_{j=1}^{n_z} Y_j \; T_{o,t-j\delta} + \sum_{j=1}^{n_q} \Phi_j \; q''_{ki,t-j\delta} \qquad (5)$$

Where T_i and T_o are the temperatures of the inner and outer faces, Z_j, Y_j, and $\Phi_j$are the CTF coefficients, $\delta$is the time step, and $q''_{ki}$is the inner conductive heat flux.

Finally, for infiltration in the most common simple model:

$$\dot{V}_{inf} = I_{design} F_{schedule} \left[A + B \mid T_{zone} - T_{odb} \mid + C \, V_{wind} + D \, V_{wind}^2 \right] \qquad (6)$$

Where I_{design} is the nominal infiltration rate, $F_{schedule}$ the schedule factor, T_{odb} the outdoor dry-bulb temperature, V_{wind} the wind speed, and A, B, C, and Dempirical coefficients. For indoor convection, DesignBuilder/EnergyPlus can use several correlations; one of the most commonly used is the TARP correlation for a vertical surface:

$$h = 1.31 \mid \Delta T \mid^{1/3} \qquad (7)$$

With: $\Delta T = T_s - T_a$.

5. Regulatory framework and evaluation protocol

The regulatory assessment was based on the two complementary approaches defined by the Moroccan Thermal Construction Regulation (RTCM). The first is the prescriptive approach, which verifies the thermal characteristics of the envelope components against the regulatory thresholds for walls, roofs, glazing, and, depending on the climatic zone, the slab-on-ground floor. The second is the performance-based approach, which compares the annual heating and cooling demand of the building with the RTCM limits expressed in kWh·m^{-2}·year^{-1} [3,4,7]. Figure 6 illustrates how the two approaches are first read separately and then combined in the final analysis.

In this study, the analysis focused on seven insulation materials belonging to four families: polymer materials, mineral materials, bio-based materials, and phase change materials. The objective was to

assess the specific effect of these insulation solutions on the thermal and energy performance of the building envelope.

Glazing was kept unchanged in all scenarios in order to isolate the effect of insulation materials on the opaque envelope. Consequently, the remaining non-compliance observed in some scenarios is partly related to the unchanged single-glazing system [3].

5.1. Simulation matrix and insulation scenarios

The simulation matrix (Table 8) was designed to evaluate the influence of insulation material, insulation thickness, envelope location, and climatic zone on building performance. First, the uninsulated reference building was simulated in the six RTCM climatic zones. Then, six conventional insulation materials were tested: XPS, EPS, glass wool, rock wool, hemp wool, and wood fiber. For each material, five insulation thicknesses were considered: 2, 4, 6, 8, and 10 cm. Three envelope configurations were evaluated: insulation applied to the external walls, insulation applied to the roof, and combined wall–roof insulation.

BioPCM M51/Q23 was analyzed separately at a fixed thickness of 2.08 cm. This material was not considered as a direct substitute for conventional insulation materials because its function is mainly related to latent heat storage rather than low thermal conductivity. Therefore, the PCM scenarios were used to assess the potential contribution of thermal storage to energy demand and comfort.

Overall, the simulation campaign included the reference case, wall insulation cases, roof insulation cases, combined wall–roof insulation cases, and PCM cases for the six reference cities, resulting in a total of 564 simulations (Figure 5).

Table 8: Simulation matrix used in this work.

Simulation block	Description	Number of cases
Baseline case	Uninsulated reference building	6
Walls – conventional insulation materials	6 materials × 5 thicknesses × 6 cities	180
Roof – conventional insulation materials	6 materials × 5 thicknesses × 6 cities	180
Combined wall–roof – conventional insulation materials	6 materials × 5 combinations × 6 cities	180
PCM – walls	BioPCM 2.08 cm in six cities	6
PCM – roof	BioPCM 2.08 cm in six cities	6
PCM – combined wall–roof	BioPCM 2.08/2.08 cm in six cities	6
Total used	Total number of simulations	564

Table 9: RTCM prescriptive and performance thresholds used in the comparison (WWR ≤ 15%). U-values in $W \cdot m^{-2} \cdot K^{-1}$; floor-on-ground requirements expressed as thermal resistance R in $m^2 \cdot K \cdot W^{-1}$; performance limits in $kWh \cdot m^{-2} \cdot year^{-1}$.

Zone	Reference location	Performance limit ($kWh \cdot m^{-2} \cdot year^{-1}$)	U_wall max	U_roof max	floor on ground requirement	U_glazing max
Z1	Agadir	40	1.20	0.75	NE	5.80
Z2	Tangier	46	0.80	0.75	NE	5.80
Z3	Fez	48	0.80	0.65	R ≥ 0.75	3.30
Z4	Ifrane	64	0.60	0.55	R ≥ 1.25	3.30
Z5	Marrakech	61	0.80	0.65	R ≥ 1.00	3.30
Z6	Errachidia	65	0.80	0.65	R ≥ 1.00	3.30

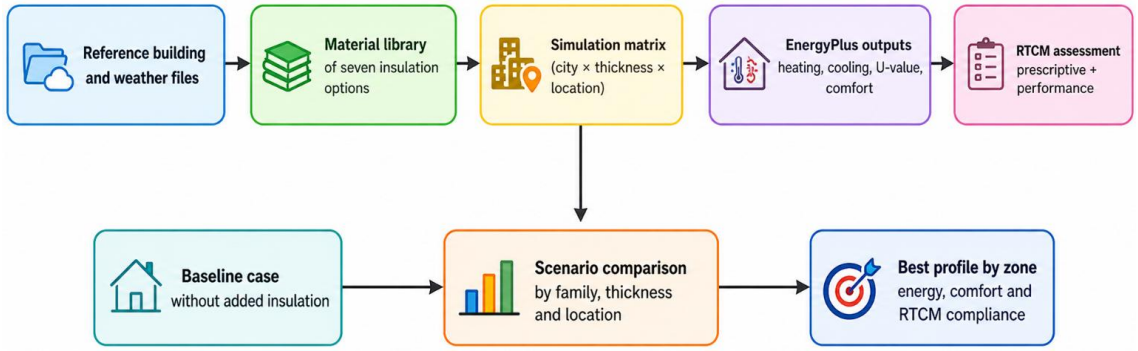


Figure 5: Synthetic diagram of the simulation protocol and result extraction.

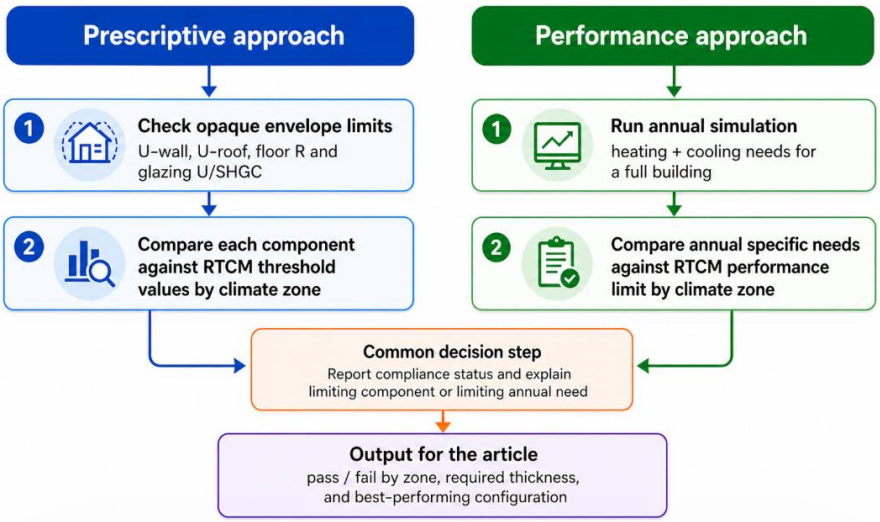


Figure 6: Separate reading of the prescriptive and performance-based approaches, then articulation in the final analysis.

Table 10: Thermophysical properties of the insulation materials studied

Material	Family	Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	Heat capacity ($J \cdot kg^{-1} \cdot K^{-1}$)
XPS	Polymer	0.03	1400
EPS	Polymer	0.04	1400
Glass wool	Mineral	0.04	840
Rock wool	Mineral	0.04	840
Hemp wool	Bio-based	0.04	1600
Wood fiber	Bio-based	0.04	1380
BioPCM M51/Q23	PCM	0.20	1970

6. Results and discussion

The results were analyzed using several indicators: annual heating demand, annual cooling demand, total annual energy demand, relative reduction compared with the reference case, wall and roof thermal transmittance values, RTCM compliance, and annual discomfort hours. Thermal discomfort was evaluated using the "Time Not Comfortable Based on Simple ASHRAE 55-2004" indicator.

Before analyzing the insulation scenarios, the simulated reference (uninsulated) building — hereafter the "simulated reference case" — was compared with the simplified baseline case provided in the official RTCM guide, hereafter the "RTCM guide baseline," which is distinct from the RTCM

performance limit discussed below. This comparison (Figure 7) was used as a consistency check rather than a full experimental validation: it verifies that the present DesignBuilder/EnergyPlus model reproduces the order of magnitude of the simplified guide's own reference calculation, without claiming equivalence to a measured benchmark. Differences between the simulated reference case and the RTCM guide baseline may be explained by differences in weather files (complete hourly EPW data here versus the simplified guide's own method), modeling assumptions, occupancy schedules, internal loads, and simulation time step. The simulated reference case was then positioned with respect to the official RTCM prescriptive and performance-based thresholds.

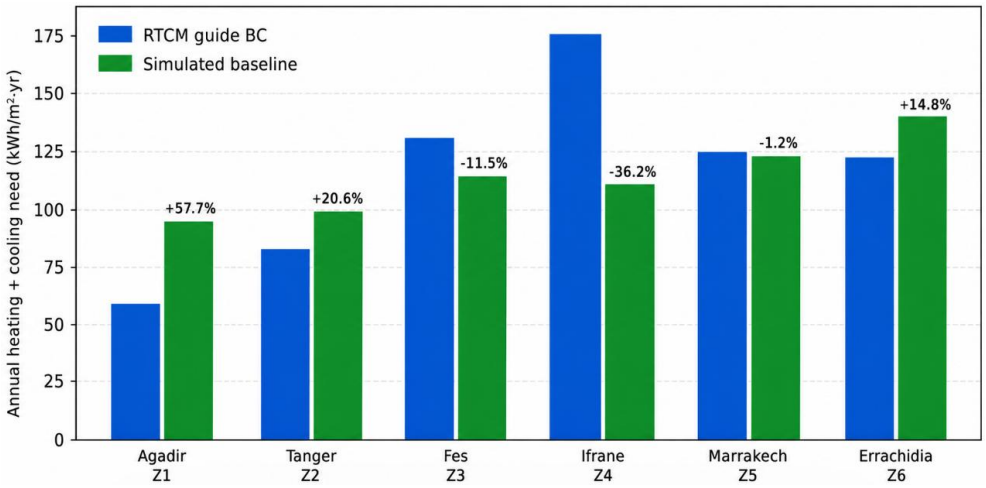


Figure 7: Baseline consistency check: simulated reference case versus RTCM guide baseline case.

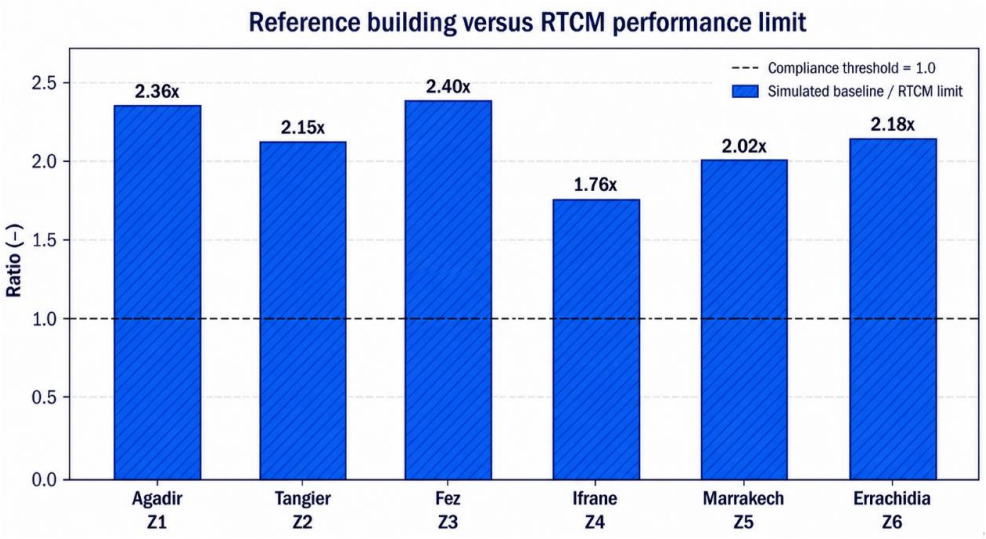


Figure 8: Ratio between the simulated annual demand of the reference building and the tabulated RTCM performance limit (a ratio > 1 indicates non-compliance).

After the baseline consistency check (Table 11a), the simulated reference case was positioned with respect to the RTCM performance limit — the regulatory pass/fail threshold expressed in kWh·m^{-2}·year^{-1} — rather than the RTCM guide baseline (Figure 8). The simulated reference case remains non-compliant with the RTCM performance limit in all six climatic zones. Cooling demand clearly dominates in Agadir, Tangier, Marrakech, and Errachidia. In Ifrane, heating demand becomes significant, although it does not exceed annual cooling demand in the simulated model. The uninsulated wall, with U ≈ 2.96 W·m^{-2}·K^{-1}, and the uninsulated roof, with U ≈ 2.13–2.18 W·m^{-2}·K^{-1}, remain far above RTCM requirements, confirming the structural non-compliance of the reference envelope.

Table 11a quantifies this comparison explicitly for each city, with the relative difference defined as the deviation of the present model from the RTCM guide baseline. The simulated reference case deviates from the guide baseline by −36.2% to +57.7% depending on the zone, with the closest agreement obtained in Marrakech (−1.2%) and the largest deviations in Agadir (+57.7%, dynamic model above the guide baseline) and Ifrane (−36.2%, dynamic model below the guide baseline). Deviations of this magnitude are expected given the differences in weather data, occupancy schedules, internal loads, and calculation method between a complete hourly EnergyPlus simulation and the simplified method underlying the guide, and they confirm that this comparison should be read as an order-of-magnitude consistency check rather than as a validation against a measured benchmark; the regulatory positioning of the reference building is therefore based exclusively on the official RTCM thresholds (Table 9).

City	RTCM guide baseline ($kWh \cdot m^{-2} \cdot yr^{-1}$)	Present model ($kWh \cdot m^{-2} \cdot yr^{-1}$)	Difference (%)
Agadir	59.8	94.25	+57.7
Tangier	82.1	99.07	+20.6
Fez	129.9	115.00	−11.5
Ifrane	176.7	112.72	−36.2
Marrakech	124.4	122.95	−1.2
Errachidia	123.5	141.79	+14.8

In Table 11, the RTCM ratio is defined as the ratio of the simulated total annual energy demand to the RTCM performance limit for the corresponding climatic zone (dimensionless); a ratio greater than 1 indicates non-compliance with the performance-based approach, and the magnitude of the ratio reflects how far the uninsulated reference building deviates from the regulatory target.

Table 11: Reference building: annual results, thermal discomfort, and positioning with respect to the RTCM (Heating, Cooling, Total, and Difference in $kWh \cdot m^{-2} \cdot year^{-1}$; RTCM ratio dimensionless; Discomfort in h/year; U-values in $W \cdot m^{-2} \cdot K^{-1}$).

Location	Zone	Heating	Cooling	Total	RTCM Limit	Difference	RTCM ratio	Discomfort (h/year)	U_wall	U_roof	U_glazing
Agadir	Z1	0.10	94.15	94.25	40	54.25	2.36	2526.50	2.96	2.18	5.88
Tangier	Z2	2.73	96.34	99.07	46	53.07	2.15	2831	2.96	2.18	5.88
Fez	Z3	7.34	107.66	115	48	67	2.40	2851	2.96	2.18	5.88
Ifrane	Z4	21.88	90.84	112.72	64	48.72	1.76	3080.50	2.96	2.18	5.88
Marrakech	Z5	1.49	121.46	122.95	61	61.95	2.02	2839.50	2.96	2.18	5.88
Errachidia	Z6	3.29	138.50	141.79	65	76.79	2.18	3024	2.96	2.13	5.88

6.1. Prescriptive approach: U-values and RTCM compliance

The effect of insulation materials on envelope thermal transmittance is clearly observed. In the uninsulated reference case, the wall thermal transmittance is about $U_wall \approx 2.96\ W \cdot m^{-2} \cdot K^{-1}$, while the roof thermal transmittance ranges from $U_roof \approx 2.13$ to $2.18\ W \cdot m^{-2} \cdot K^{-1}$. With 4 cm of insulation, several materials already satisfy the RTCM thresholds for walls and roofs in zones Z1, Z2, Z3, Z5, and Z6 (Tables 12 and 13). Zone Z4, represented by Ifrane, is the most demanding zone and generally requires 6 cm of insulation to meet the prescribed U-value limits. Figure 9 illustrates the decrease in thermal transmittance with increasing insulation thickness, together with the RTCM thresholds for each climatic zone.

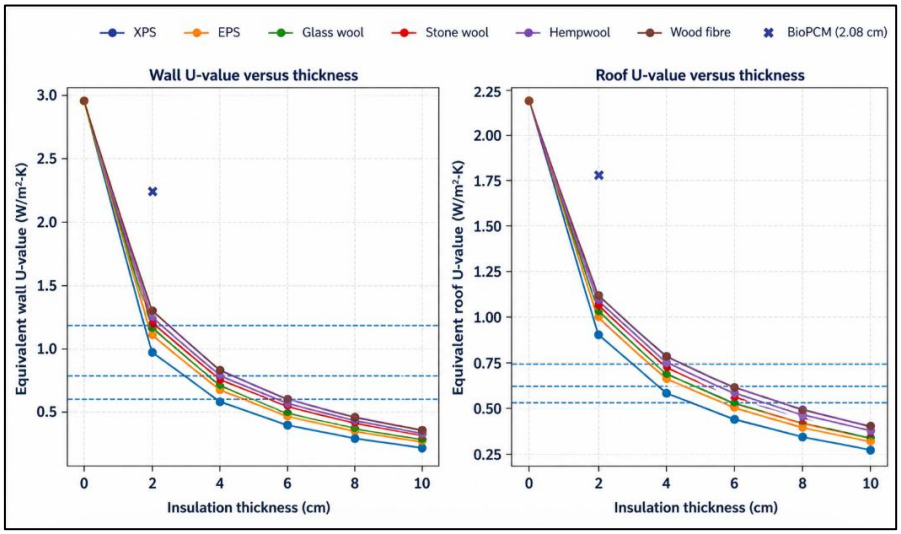


Figure 9: Evolution of wall and roof U-values according to material and thickness, with reminder of RTCM thresholds.

Table 12: Comparison of wall U-values without insulation and with insulation materials at different thicknesses.

Material	without insulation	2 cm	2.08 cm	4 cm	6 cm	8 cm	10 cm
XPS	2.96	0.99	—	0.60	0.43	0.33	0.27
EPS	2.96	1.10	—	0.67	0.49	0.38	0.31
Glass wool	2.96	1.12	—	0.69	0.50	0.39	0.32
Rock wool	2.96	1.16	—	0.72	0.52	0.41	0.34
Hemp wool	2.96	1.19	—	0.75	0.54	0.43	0.35
Wood fiber	2.96	1.25	—	0.79	0.58	0.46	0.38
BioPCM M51/Q23	2.96	—	2.26	—	—	—	—

Table 13: Comparison of roof U-values without insulation and with insulation materials at different thicknesses.

Material	without insulation	2 cm	2.08 cm	4 cm	6 cm	8 cm	10 cm
XPS	2.17	0.89	—	0.56	0.41	0.32	0.26
EPS	2.17	0.97	—	0.62	0.46	0.36	0.30
Glass wool	2.17	0.98	—	0.64	0.47	0.37	0.31
Rock wool	2.17	1.02	—	0.66	0.49	0.39	0.32
Hemp wool	2.17	1.04	—	0.69	0.51	0.41	0.34
Wood fiber	2.17	1.08	—	0.72	0.54	0.43	0.36
BioPCM M51/Q23	2.17	—	1.78	—	—	—	—

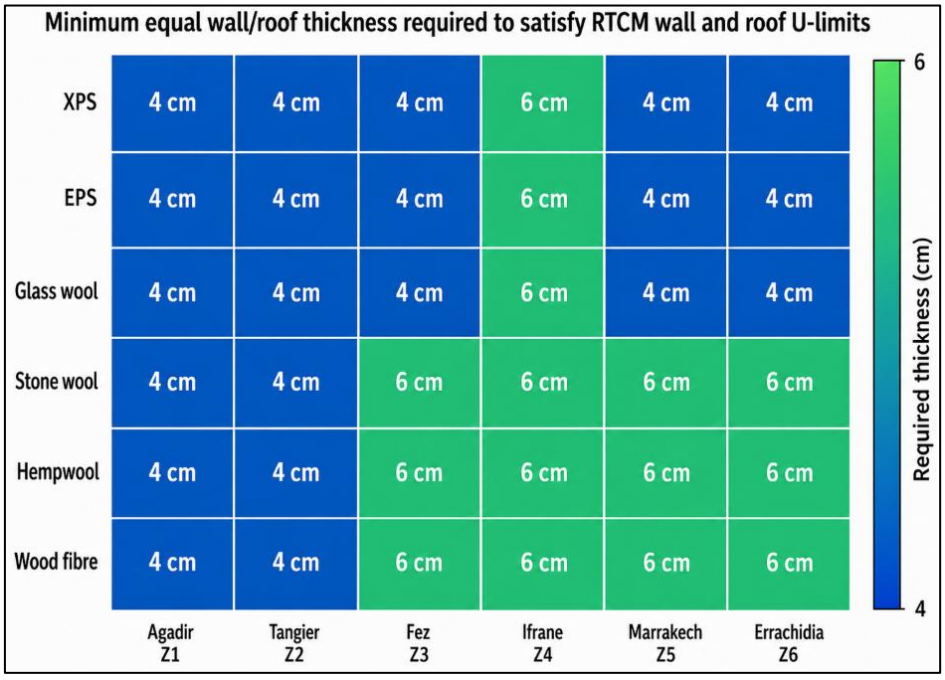


Figure 10: Minimum equal wall/roof thickness allowing the RTCM thresholds on U_wall and U_roof to be satisfied.

The detailed prescriptive analysis leads to three main conclusions. First, several 4/4 cm or 6/6 cm scenarios make the combined wall–roof envelope compliant with RTCM requirements (Figure 10). Second, when the slab-on-ground floor is included, zones Z4, Z5, and Z6 remain non-compliant because the thermal resistance of the initial floor is insufficient. Third, full prescriptive compliance is not achieved because the single glazing retained in all scenarios remains non-compliant: U_glazing $\approx$ 5.88 $W \cdot m^{-2} \cdot K^{-1}$ exceeds the limit of 5.80 $W \cdot m^{-2} \cdot K^{-1}$ in Z1–Z2 and especially the limit of 3.30 $W \cdot m^{-2} \cdot K^{-1}$ in Z3–Z6.

6.2. Performance-based approach: energy demand and reduction

At low thicknesses, namely 2 cm for conventional insulation materials and 2.08 cm for BioPCM M51/Q23, XPS provides the highest annual energy demand reduction among the conventional materials (Figure 11), mainly because of its lower thermal conductivity. EPS and glass wool show very close performance, while bio-based materials provide slightly lower reductions in annual energy demand. However, bio-based insulation may offer advantages in terms of dynamic thermal response and thermal comfort. BioPCM shows lower energy savings than conventional insulation materials, which is expected because its main function is latent heat storage rather than resistance to heat transfer.

In every zone, combined wall–roof insulation provides greater energy savings than wall-only or roof-only insulation. This confirms the importance of treating the opaque envelope as an integrated system. BioPCM does not outperform conventional insulation at the tested thickness, but its results remain useful for assessing the potential contribution of thermal storage to indoor comfort.

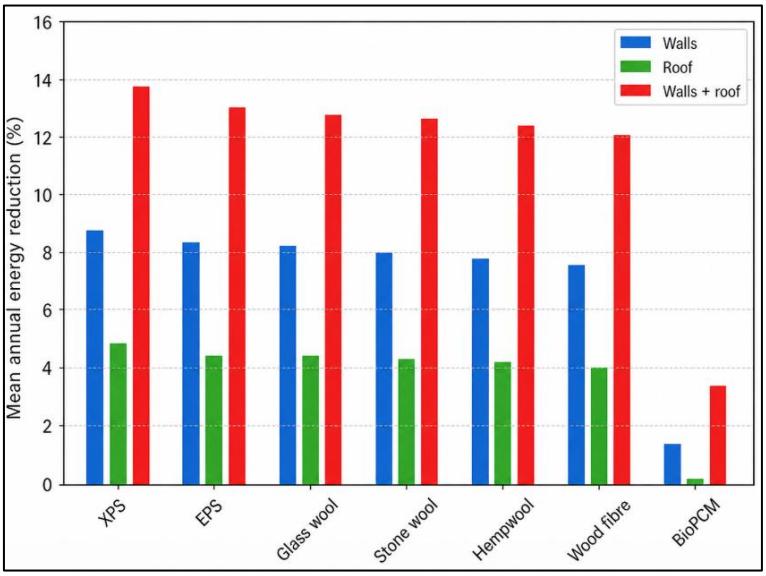


Figure 11: Comparison of insulation materials at low thickness (2 cm / 2.08 cm).

6.2.1. Agadir (Z1 – temperate semi-arid coastal)

In Agadir, the reference building is almost entirely cooling-dominated, with a total annual demand of 94.25 kWh·m^{-2}·year^{-1}, of which 94.15 kWh·m^{-2}·year^{-1} corresponds to cooling. The best energy performance is obtained with XPS applied to both walls and roof at 6/6 cm, reducing annual demand by 9.58% (Tables 14 and 15, Figure 12). However, the best comfort result is achieved with XPS applied only to the roof at 10 cm, which reduces discomfort hours by 6.08%. This indicates that, in this coastal climate, roof insulation has a stronger influence on summer comfort than wall insulation alone.

Table 14: Best-performing insulation scenarios by configuration in Agadir.

Material	Best wall (thick./gain/total)	Best roof (thick./gain/total)	Best combined wall–roof case (thick./gain/total)
XPS	2.00 cm / 3.61% / 90.85	10.00 cm / 6.12% / 88.48	6.00/6.00 cm / 9.58% / 85.22
EPS	2.00 cm / 3.51% / 90.94	10.00 cm / 5.99% / 88.60	6.00/6.00 cm / 9.32% / 85.47
Glass wool	2.00 cm / 3.48% / 90.97	10.00 cm / 5.97% / 88.62	6.00/6.00 cm / 9.25% / 85.53
Rock wool	2.00 cm / 3.45% / 91.00	10.00 cm / 5.92% / 88.67	6.00/6.00 cm / 9.19% / 85.59
Hemp wool	2.00 cm / 3.44% / 91.01	10.00 cm / 5.87% / 88.72	6.00/6.00 cm / 9.15% / 85.63
Wood fiber	2.00 cm / 3.38% / 91.06	10.00 cm / 5.80% / 88.78	6.00/6.00 cm / 9.03% / 85.74
BioPCM M51/Q23	2.08 cm / 1.27% / 93.05	2.08 cm / 0.50% / 93.78	2.08/2.08 cm / 2.83% / 91.58

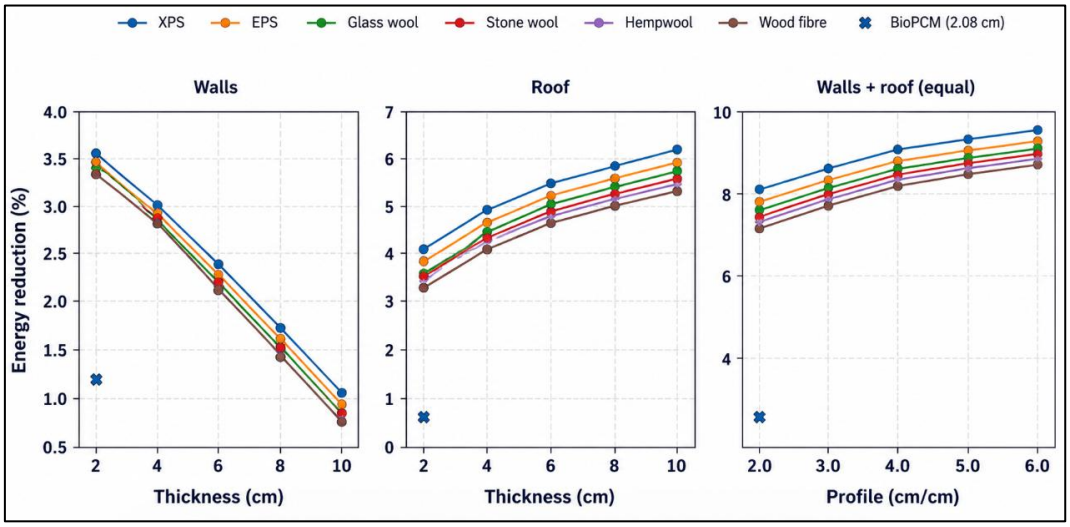


Figure 12: Agadir: evolution of demand reductions according to insulation material, thickness, and configuration.

Table 15: Energy performance and regulatory feasibility of equal wall–roof insulation profiles in Agadir.

Equal wall/roof thickness (cm)	Best material	Max reduction (%)	Corresponding total demand (kWh·m⁻²·year⁻¹)	RTCM Combined wall–roof compliance	Full opaque-envelope compliance
2	XPS	8.55	86.19	False	False
4	XPS	9.40	85.39	True	True
6	XPS	9.58	85.22	True	True

6.2.2. Tangier (Z2 – Mediterranean maritime)

In Tangier, the reference building has an annual energy demand of 99.07 kWh·m⁻²·year⁻¹, mainly dominated by cooling demand. The best energy performance is obtained with XPS applied to both walls and roof at 6/6 cm, leading to a reduction of 9.96% (Tables 16 and 17, Figure 13). This configuration also provides the best thermal comfort performance. Compared with Agadir, the combined wall–roof insulation strategy becomes slightly more effective, although the additional gain beyond 4/4 cm remains limited.

Table 16: Best-performing insulation scenarios by configuration in Tangier.

Material	Best wall (thick./gain/total)	Best roof (thick./gain/total)	Best combined wall–roof case (thick./gain/total)
XPS	2.00 cm / 5.20% / 93.92	10.00 cm / 5.75% / 93.37	6.00/6.00 cm / 9.96% / 89.20
EPS	4.00 cm / 5.02% / 94.10	10.00 cm / 5.63% / 93.49	6.00/6.00 cm / 9.76% / 89.40
Glass wool	4.00 cm / 4.98% / 94.14	10.00 cm / 5.60% / 93.52	6.00/6.00 cm / 9.71% / 89.45
Rock wool	4.00 cm / 4.97% / 94.15	10.00 cm / 5.56% / 93.56	6.00/6.00 cm / 9.56% / 89.60
Hemp wool	4.00 cm / 4.96% / 94.16	10.00 cm / 5.52% / 93.60	6.00/6.00 cm / 9.54% / 89.62
Wood fiber	4.00 cm / 4.90% / 94.22	10.00 cm / 5.46% / 93.66	6.00/6.00 cm / 9.44% / 89.72
BioPCM M51/Q23	2.08 cm / 1.24% / 97.84	2.08 cm / 0.25% / 98.82	2.08/2.08 cm / 2.78% / 96.32

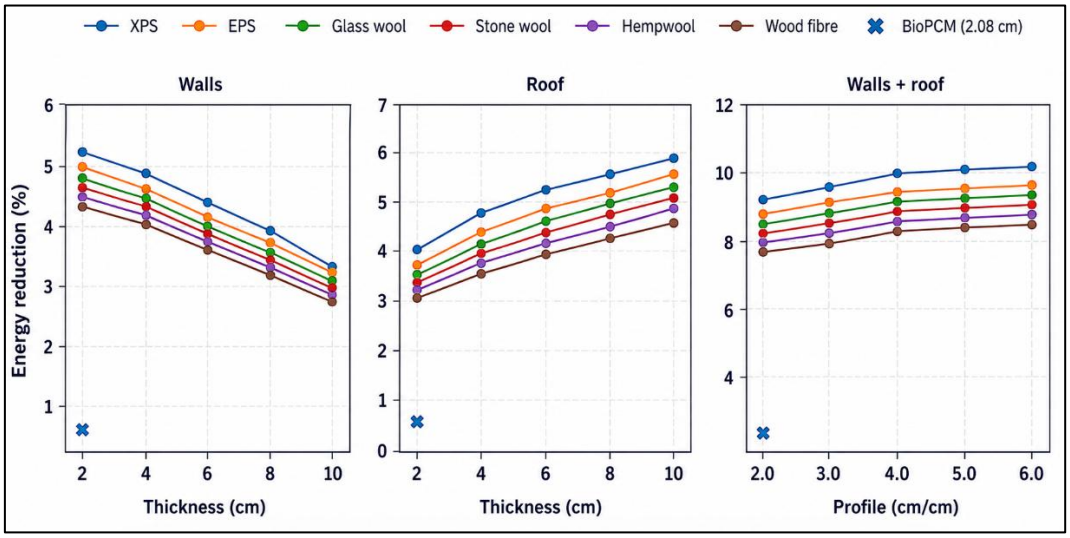


Figure 13: Tangier: evolution of demand reductions according to insulation material, thickness, and configuration.

Table 17: Energy performance and regulatory feasibility of equal wall–roof insulation profiles in Tangier.

Equal wall/roof thickness (cm)	Best material	Max reduction (%)	Corresponding total demand (kWh·m^{-2}·year^{-1})	RTCM Combined wall–roof compliance	Full opaque-envelope compliance
2	XPS	9.19	89.97	False	False
4	XPS	9.88	89.28	True	True
6	XPS	9.96	89.20	True	True

6.2.3. Fez (Z3 – contrasted inland)

In Fez, the reference building reaches an annual energy demand of 115.00 kWh·m^{-2}·year^{-1}. The best energy performance is obtained with XPS applied to both walls and roof at 6/6 cm, resulting in a reduction of 19.83% (Tables 18 and 19, Figure 14). Unlike the coastal zones, wall insulation becomes more influential in Fez because of the stronger seasonal thermal amplitude of this inland climate. The same combined wall–roof configuration also provides the best thermal comfort performance.

Table 18: Best-performing insulation scenarios by configuration in Fez.

Material	Best wall (thick./gain/total)	Best roof (thick./gain/total)	Best combined wall–roof case (thick./gain/total)
XPS	6.00 cm / 11.76% / 101.48	10.00 cm / 8.10% / 105.68	6.00/6.00 cm / 19.83% / 92.20
EPS	6.00 cm / 11.48% / 101.80	10.00 cm / 7.94% / 105.87	6.00/6.00 cm / 19.37% / 92.72
Glass wool	6.00 cm / 11.42% / 101.87	10.00 cm / 7.90% / 105.91	6.00/6.00 cm / 19.26% / 92.85
Rock wool	6.00 cm / 11.33% / 101.97	10.00 cm / 7.83% / 105.99	6.00/6.00 cm / 19.10% / 93.03
Hemp wool	6.00 cm / 11.26% / 102.05	10.00 cm / 7.77% / 106.07	6.00/6.00 cm / 18.98% / 93.17
Wood fiber	6.00 cm / 11.10% / 102.23	10.00 cm / 7.68% / 106.17	6.00/6.00 cm / 18.70% / 93.49
BioPCM M51/Q23	2.08 cm / 1.65% / 113.10	2.08 cm / -0.31% / 115.36	2.08/2.08 cm / 3.72% / 110.72

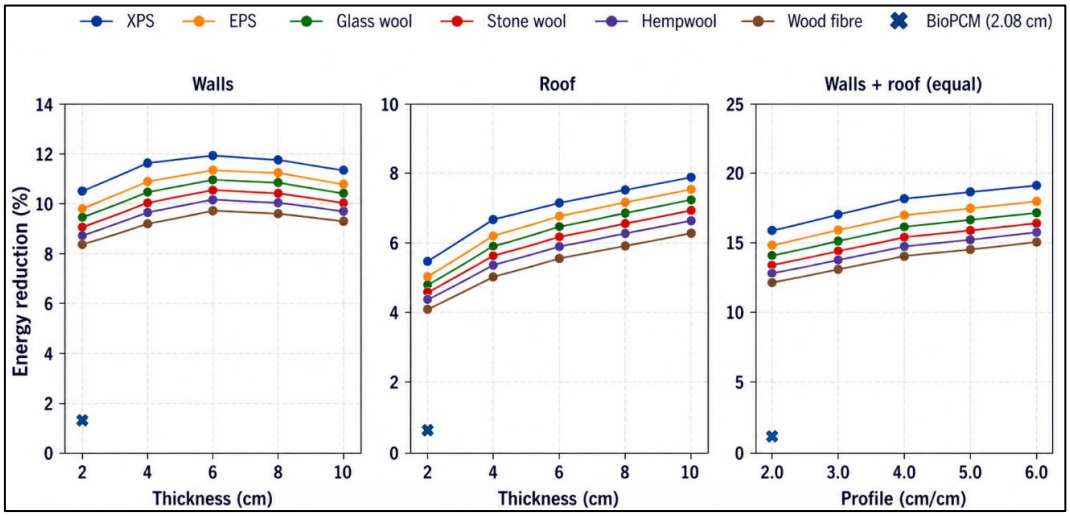


Figure 14: Fez: evolution of demand reductions according to insulation material, thickness, and configuration.

Table 19: Energy performance and regulatory feasibility of equal wall–roof insulation profiles in Fez.

Equal wall/roof thickness (cm)	Best material	Max reduction (%)	Corresponding total demand (kWh·m^{-2}·year^{-1})	RTCM Combined wall–roof compliance	Full opaque-envelope compliance
2	XPS	16.38	96.16	False	False
4	XPS	19.03	93.12	True	True
6	XPS	19.83	92.20	True	True

6.2.4. Ifrane (Z4 – cold mountainous)

In Ifrane, the reference building shows the highest heating demand among the studied cities, reflecting the cold mountainous climate of this zone. However, cooling demand remains dominant in the annual balance of the simulated model. The best energy performance is obtained with XPS applied to both walls and roof at 6/6 cm, leading to a reduction of 24.71%, which is the highest improvement among all climatic zones (Tables 20 and 21, Figure 15). This confirms that insulation is particularly effective in cold mountainous climates, where both winter heat losses and summer heat gains must be controlled.

Table 20: Best-performing insulation scenarios by configuration in Ifrane.

Material	Best wall (thick./gain/total)	Best roof (thick./gain/total)	Best combined wall–roof case (thick./gain/total)
XPS	6.00 cm / 14.55% / 96.32	10.00 cm / 10.50% / 100.88	6.00/6.00 cm / 24.71% / 84.87
EPS	8.00 cm / 14.17% / 96.75	10.00 cm / 10.27% / 101.14	6.00/6.00 cm / 24.30% / 85.33
Glass wool	8.00 cm / 14.08% / 96.85	10.00 cm / 10.22% / 101.20	6.00/6.00 cm / 24.20% / 85.44
Rock wool	8.00 cm / 13.98% / 96.96	10.00 cm / 10.13% / 101.30	6.00/6.00 cm / 24.04% / 85.62
Hemp wool	8.00 cm / 13.89% / 97.06	10.00 cm / 10.04% / 101.40	6.00/6.00 cm / 23.90% / 85.78
Wood fiber	8.00 cm / 13.69% / 97.29	10.00 cm / 9.92% / 101.54	6.00/6.00 cm / 23.62% / 86.10
BioPCM M51/Q23	2.08 cm / 1.97% / 110.50	2.08 cm / -0.29% / 113.05	2.08/2.08 cm / 4.23% / 107.95

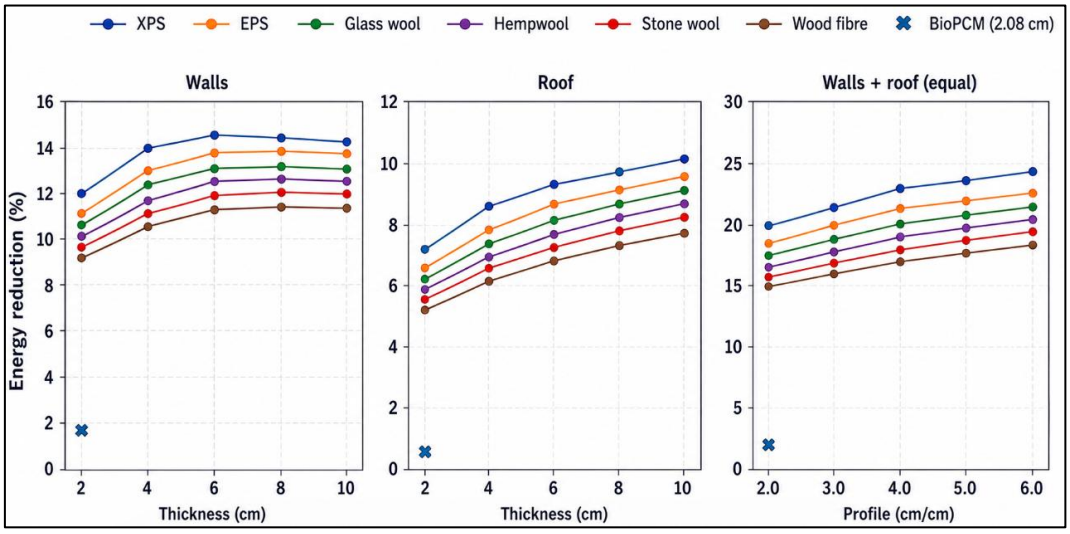


Figure 15: Ifrane: evolution of demand reductions according to insulation material, thickness, and configuration.

Table 21: Energy performance and regulatory feasibility of equal wall–roof insulation profiles in Ifrane.

Equal wall/roof thickness (cm)	Best material	Max reduction (%)	Corresponding total demand (kWh·m^{-2}·year^{-1})	RTCM Combined wall–roof compliance	Full opaque-envelope compliance
2	XPS	20.10	90.06	False	False
4	XPS	23.90	85.78	False	False
6	XPS	24.71	84.87	True	False

6.2.5. Marrakech (Z5 – hot semi-arid)

In Marrakech, the reference building reaches an annual energy demand of 122.95 kWh·m^{-2}·year^{-1}, mainly due to cooling demand. The best energy performance is obtained with XPS applied to both walls and roof at 6/6 cm, resulting in a reduction of 19.12% (Tables 22 and 23, Figure 16). However, the best thermal comfort performance is achieved with wood fiber at 6/6 cm. This result suggests that bio-based insulation may provide a more favorable dynamic thermal response under hot semi-arid conditions, even when it does not achieve the lowest annual energy demand.

Table 22: Best-performing insulation scenarios by configuration in Marrakech.

Material	Best wall (thick./gain/total)	Best roof (thick./gain/total)	Best combined wall–roof case (thick./gain/total)
XPS	6.00 cm / 11.13% / 109.26	10.00 cm / 6.19% / 115.34	6.00/6.00 cm / 19.12% / 99.44
EPS	6.00 cm / 10.83% / 109.64	10.00 cm / 6.06% / 115.50	6.00/6.00 cm / 18.46% / 100.25
Glass wool	6.00 cm / 10.74% / 109.74	10.00 cm / 6.03% / 115.53	6.00/6.00 cm / 18.32% / 100.42
Rock wool	6.00 cm / 10.65% / 109.85	10.00 cm / 5.99% / 115.59	6.00/6.00 cm / 18.02% / 100.80
Hemp wool	6.00 cm / 10.58% / 109.94	10.00 cm / 5.93% / 115.66	6.00/6.00 cm / 17.82% / 101.04
Wood fiber	6.00 cm / 10.41% / 110.15	10.00 cm / 5.86% / 115.74	6.00/6.00 cm / 17.49% / 101.45
BioPCM M51/Q23	2.08 cm / 1.50% / 121.11	2.08 cm / -0.48% / 123.54	2.08/2.08 cm / 3.11% / 119.13

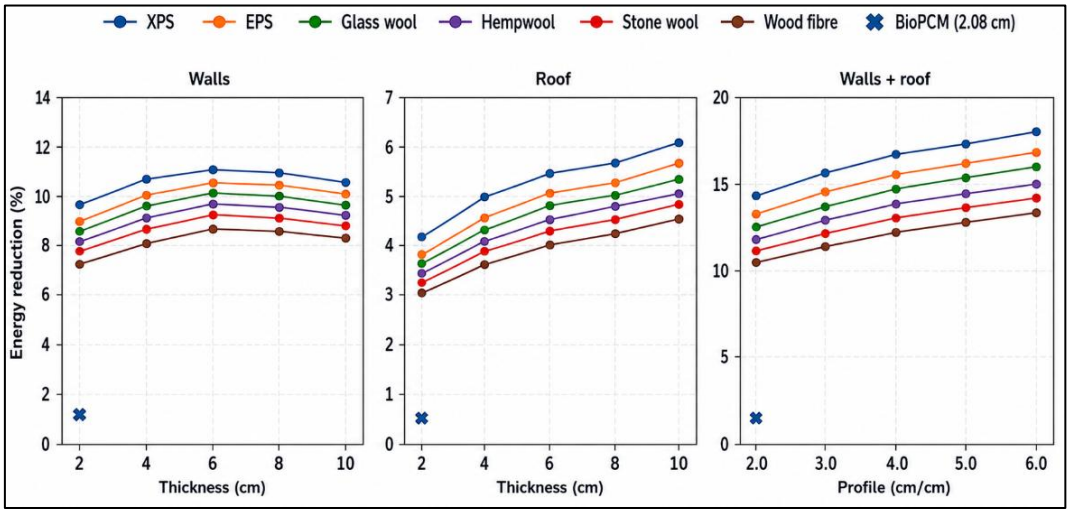


Figure 16: Marrakech: evolution of demand reductions according to insulation material, thickness, and configuration.

Table 23: Energy performance and regulatory feasibility of equal wall–roof insulation profiles in Marrakech.

Equal wall/roof thickness (cm)	Best material	Max reduction (%)	Corresponding total demand ($kWh \cdot m^{-2} \cdot year^{-1}$)	RTCM Combined wall–roof compliance	Full opaque-envelope compliance
2	XPS	14.84	104.70	False	False
4	XPS	17.77	101.10	True	False
6	XPS	19.12	99.44	True	False

6.2.6. Errachidia (Z6 – hot desert)

In Errachidia, the reference building shows the highest annual energy demand among the studied cities, reaching 141.79 $kWh \cdot m^{-2} \cdot year^{-1}$. The best energy performance is obtained with XPS applied to both walls and roof at 6/6 cm, leading to a reduction of 22.69% (Tables 24 and 25, Figure 17). In this hot desert climate, wall insulation plays a major role because of the high outdoor temperatures and strong thermal amplitude, while roof insulation alone remains less effective than combined wall–roof insulation.

Table 24: Best-performing insulation scenarios by configuration in Errachidia.

Material	Best wall (thick./gain/total)	Best roof (thick./gain/total)	Best combined wall–roof case (thick./gain/total)
XPS	8.00 cm / 15.13% / 120.34	10.00 cm / 5.60% / 133.85	6.00/6.00 cm / 22.69% / 109.62
EPS	8.00 cm / 14.72% / 120.92	10.00 cm / 5.48% / 134.02	6.00/4.00 cm / 21.02% / 111.99
Glass wool	8.00 cm / 14.92% / 120.64	10.00 cm / 5.44% / 134.07	6.00/6.00 cm / 21.74% / 110.97
Rock wool	8.00 cm / 14.48% / 121.26	10.00 cm / 5.40% / 134.13	6.00/6.00 cm / 21.28% / 111.61
Hemp wool	10.00 cm / 14.37% / 121.42	10.00 cm / 5.37% / 134.18	6.00/6.00 cm / 21.03% / 111.97
Wood fiber	10.00 cm / 14.15% / 121.72	10.00 cm / 5.29% / 134.29	6.00/6.00 cm / 20.62% / 112.55
BioPCM M51/Q23	2.08 cm / 0.56% / 141.00	—	2.08/2.08 cm / 2.14% / 138.76

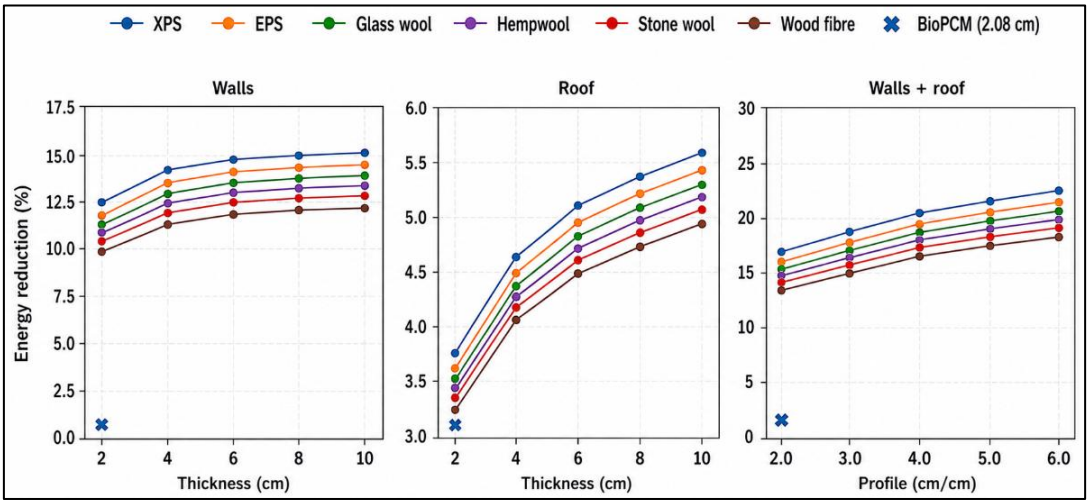


Figure 17: Errachidia: evolution of demand reductions according to insulation material, thickness, and configuration.

Table 25: Energy performance and regulatory feasibility of equal wall–roof insulation profiles in Errachidia.

Equal wall/roof thickness (cm)	Best material	Max reduction (%)	Corresponding total demand (kWh·m^{-2}·year^{-1})	RTCM Combined wall–roof compliance	Full opaque-envelope compliance
2	XPS	17.06	117.60	False	False
4	XPS	20.88	112.18	True	False
6	XPS	22.69	109.62	True	False

6.3. Effect of thickness and diminishing returns

The effect of insulation thickness is not strictly linear and depends strongly on the climatic zone and envelope component. For roof insulation, increasing thickness generally improves energy performance, although the marginal gains decrease beyond 6 cm (Table 26, Figure 18). For wall insulation, the trend is more climate-dependent. In Agadir and Tangier, increasing wall insulation beyond 4 cm provides limited additional benefits and may even become less favorable for annual total demand: in Agadir, for example, the average wall-only reduction of the six conventional materials decreases from 3.48% at 2 cm to 2.25% at 6 cm and 0.80% at 10 cm (Table 26). In contrast, in Fez, Ifrane, Marrakech, and Errachidia, wall insulation remains effective up to approximately 6 cm, after which the additional gains become relatively small.

From a practical point of view, 4 cm appears to be the first robust insulation level in most climatic zones, in the sense that it simultaneously satisfies most of the RTCM wall and roof U-value limits (Figure 10) and captures the greater part of the achievable energy demand reduction. The use of 6 cm is more justified in Ifrane, Marrakech, and Errachidia, or when the objective is to maximize opaque-envelope compliance and energy savings. Thicknesses of 8 and 10 cm may still improve roof performance, but their marginal benefit should be evaluated against additional construction cost and implementation constraints.

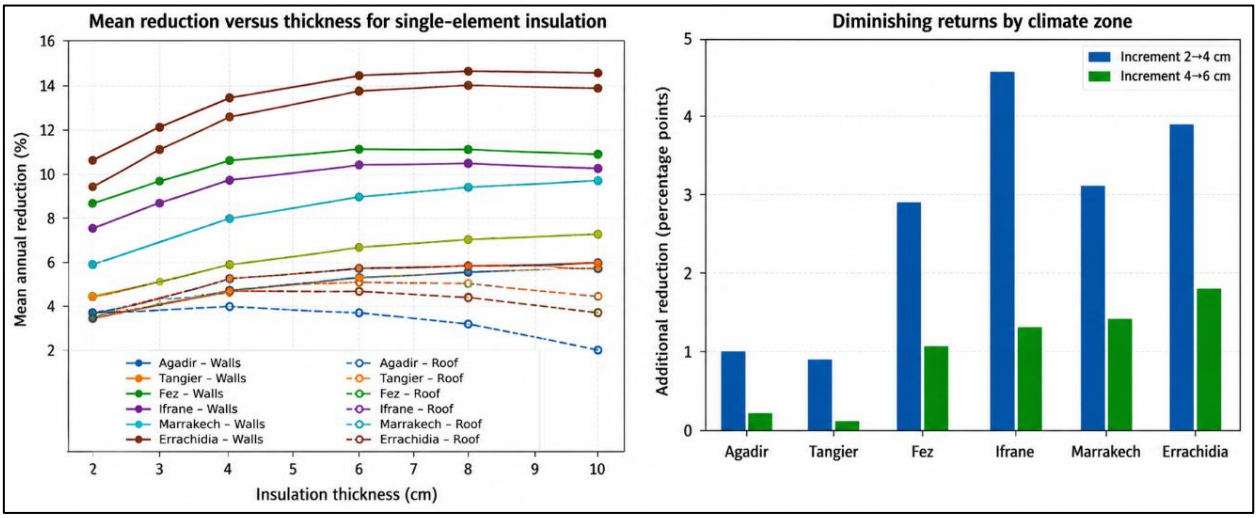


Figure 18: Average effect of thickness on demand reductions for walls and roofs.

All insulation simulations in this study are deterministic: the dispersion described in Tables 26–28 as "marginal gain" and "spread" therefore reflects variation across material, thickness, and location choices rather than statistical or probabilistic uncertainty, a point developed further after Table 28.

Table 26: Average reductions by thickness and marginal gains 2→4 cm and 4→6 cm (average of the six conventional insulation materials).

Location	Configuration	2 cm	4 cm	6 cm	8 cm	10 cm	Marginal gain 2→4	Marginal gain 4→6
Agadir	Walls	3.48	3.00	2.25	1.51	0.80	-0.48	-0.76
Agadir	Roof	3.83	4.87	5.40	5.73	5.95	1.04	0.53
Tangier	Walls	4.93	4.98	4.52	3.94	3.34	0.05	-0.47
Tangier	Roof	3.60	4.58	5.09	5.39	5.59	0.99	0.51
Fez	Walls	9.57	11.13	11.39	11.24	10.93	1.56	0.26
Fez	Roof	4.99	6.42	7.14	7.58	7.87	1.43	0.72
Ifrane	Walls	10.99	13.25	13.97	14.05	13.87	2.26	0.72
Ifrane	Roof	6.23	8.22	9.20	9.79	10.18	1.99	0.98
Marrakech	Walls	8.94	10.42	10.73	10.63	10.36	1.48	0.30
Marrakech	Roof	3.86	4.91	5.46	5.79	6.01	1.05	0.54
Errachidia	Walls	11.00	13.53	14.38	14.62	14.58	2.53	0.85
Errachidia	Roof	3.35	4.39	4.91	5.22	5.43	1.05	0.52

From the point of view of practical feasibility limited to 2, 4, and 6 cm, the 4 cm level appears to be the first truly robust one in almost all zones. The move to 6 cm is justified especially for Ifrane, Marrakech, and Errachidia, or when a maximum opaque-envelope compliance objective is sought. Thicknesses of 8 and 10 cm remain useful on roofs, but their interest decreases sharply relative to the additional construction effort required.

6.4. Effect of insulation location: walls, roof, and then combination

The location of the insulation strongly affects the performance hierarchy of the tested solutions. In warm coastal zones such as Agadir and Tangier, roof insulation provides higher benefits than wall insulation alone, mainly because the roof is strongly exposed to solar radiation. In inland, mountainous, semi-arid, and desert climates, wall insulation becomes more influential because of larger daily and seasonal temperature variations. Nevertheless, combined wall–roof insulation

remains the most effective strategy in all climatic zones (Figure 19), as it reduces both heat losses in winter and heat gains in summer through the main opaque components of the envelope.

From a practical renovation perspective, roof insulation should be prioritized when only one component can be treated in Agadir and Tangier. In Fez, Ifrane, Marrakech, and Errachidia, wall insulation already provides significant energy savings, but the best overall performance is achieved when walls and roof are insulated together.

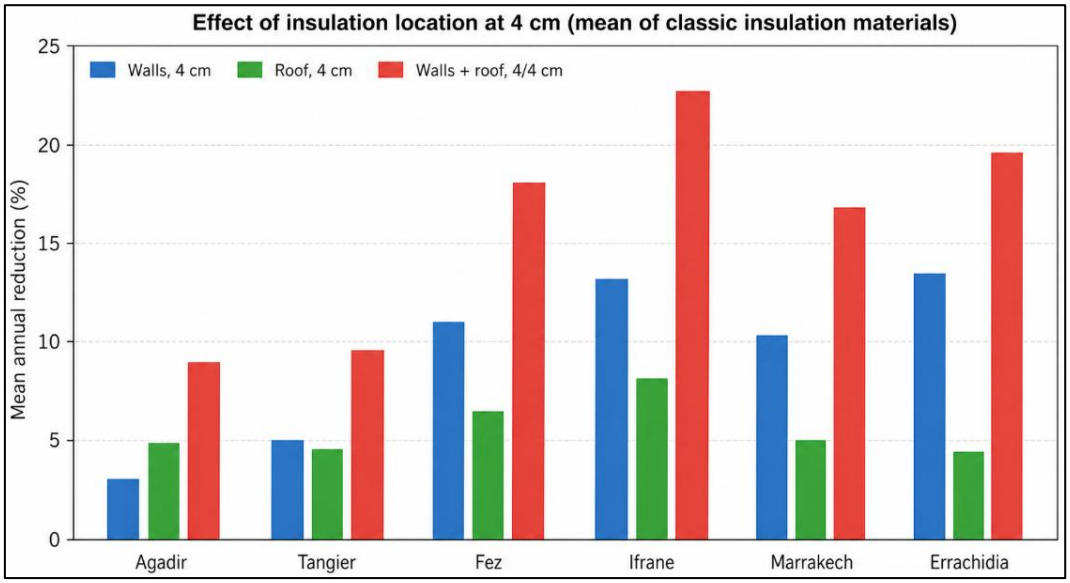


Figure 19: Effect of insulation location at 4 cm (average of the conventional insulation materials).

This result makes it possible to rank interventions in light renovation: if only one element can be treated in Agadir or Tangier, the roof must be prioritized. In Fez, Ifrane, Marrakech, and Errachidia, walls alone already provide a substantial gain, but the maximum objective is always reached by combined insulation.

6.5. Annual thermal comfort

Annual thermal comfort was assessed using the "Time Not Comfortable Based on Simple ASHRAE 55-2004" indicator and the unmet cooling setpoint hours. The reference building shows a high number of discomfort hours in all climatic zones, ranging from 2526.5 h/year in Agadir to 3080.5 h/year in Ifrane. This confirms that the uninsulated envelope is not sufficient to ensure acceptable indoor comfort under the studied climatic conditions.

The comparison between the best energy scenarios and the best comfort scenarios (Figure 20) shows that reducing annual energy demand does not always lead to the highest comfort improvement. In most zones, combined wall–roof insulation improves both energy performance and comfort. However, in Marrakech, wood fiber at 6/6 cm provides better comfort performance than the lowest-energy scenario. This suggests that dynamic thermal behavior and heat storage capacity may play an important role in hot semi-arid climates.

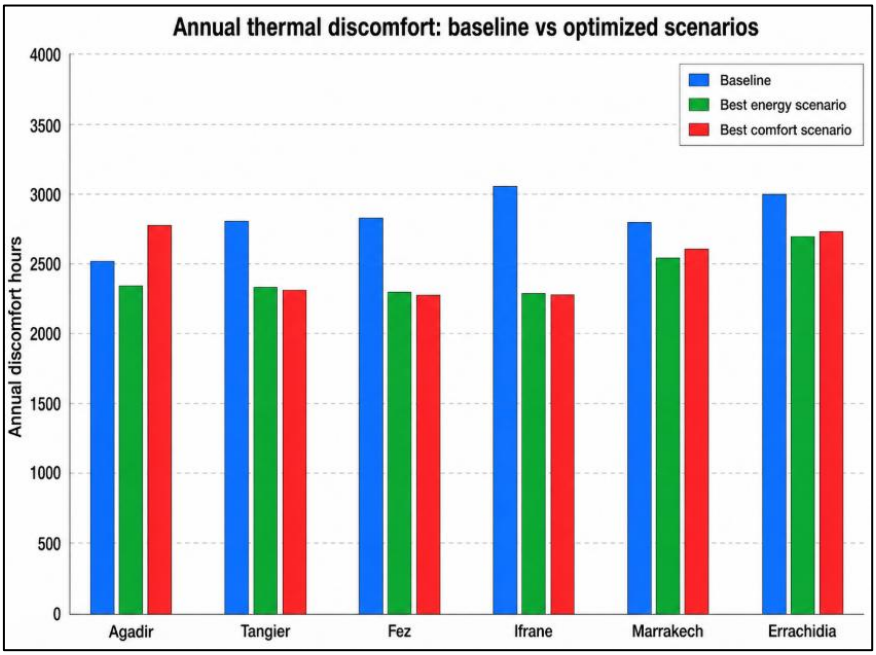


Figure 20: Annual discomfort hours: comparison between the reference case, the best energy scenario, and the best comfort scenario.

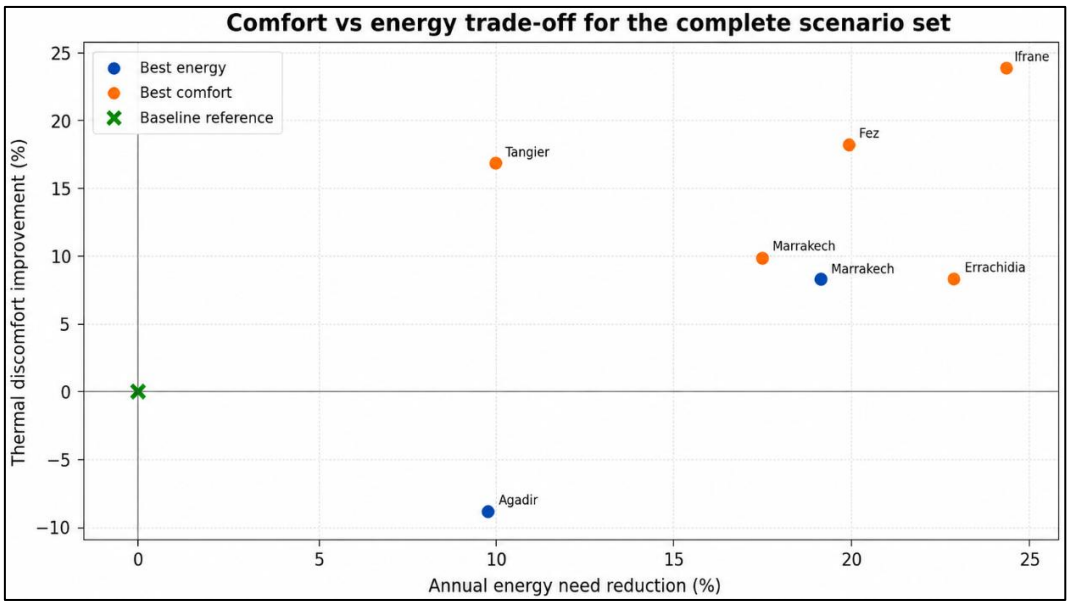


Figure 21: Comfort vs energy trade-off for the complete scenario set.

Table 27: Comparison between the best energy scenario and the best comfort scenario by zone.

Location	Best energy	Discomfort hours (best energy)	Comfort improvement (best energy)	Best comfort	Discomfort hours (best comfort)	Comfort improvement (best comfort)
Agadir	XPS – combined wall–roof– 6.00/6.00	2810	-11.22	XPS – Roof – 0.00/10.00	2373	6.08
Tangier	XPS – combined wall–roof – 6.00/6.00	2352.50	16.90	XPS – combined wall–roof – 6.00/6.00	2352.50	16.90
Fez	XPS – combined wall–roof – 6.00/6.00	2328	18.34	XPS – combined wall–roof – 6.00/6.00	2328	18.34

Ifrane	XPS – combined wall–roof – 6.00/6.00	2329.50	24.38	XPS – combined wall–roof – 6.00/6.00	2329.50	24.38
Marrakech	XPS – combined wall–roof – 6.00/6.00	2604.50	8.28	Wood fiber – combined wall–roof – 6.00/6.00	2563	9.74
Errachidia	XPS – combined wall–roof – 6.00/6.00	2771	8.37	XPS – combined wall–roof – 6.00/6.00	2771	8.37

Two lessons emerge. First, the improvement in comfort broadly follows the improvement in energy performance in the inland and cold zones, where XPS 6/6 cm in combined wall–roof also remains the best comfort scenario. Second, differences appear in climates dominated by summer overheating: in Agadir, the roof alone in XPS 10 cm improves comfort more than the global best energy scenario; in Marrakech, wood fiber 6/6 cm achieves the best result in terms of discomfort hours, suggesting an inertial benefit of the bio-based material that is not entirely reflected by annual demand alone.

Across the six climatic zones, the energy-optimal and comfort-optimal scenarios coincide in four zones (Tangier, Fez, Ifrane, and Errachidia) and diverge in the remaining two (Agadir and Marrakech), as shown in Table 27. This 2-of-6 divergence rate is itself a notable finding: it indicates that a single climate-independent design rule ("always choose the lowest-energy scenario") would be adequate in two-thirds of the RTCM climatic zones but insufficient in the two zones where passive summer comfort is most sensitive to envelope thermal inertia.

The comfort improvement (%) reported in Table 27 is defined analogously to the energy demand reduction, as: Comfort improvement (%) = [($\text{Discomfort}_{h,\text{reference}} - \text{Discomfort}_{h,\text{scenario}}$) / $\text{Discomfort}_{h,\text{reference}}$] × 100, where $\text{Discomfort}_{h,\text{reference}}$ is the annual discomfort duration of the uninsulated reference building for the corresponding city (Table 11) and $\text{Discomfort}_{h,\text{scenario}}$ is the annual discomfort duration of the insulation scenario considered. A positive value indicates fewer discomfort hours (an improvement), while a negative value, as observed for the best-energy scenario in Agadir, indicates that the scenario increases annual discomfort hours relative to the uninsulated reference case.

The negative comfort improvement recorded in Agadir for the best-energy scenario (XPS 6/6 cm combined wall–roof, Table 27) deserves explicit physical interpretation, since a scenario that reduces energy demand can, in principle, still worsen occupant comfort in a naturally ventilated building. The building is not mechanically cooled (Table 7); annual cooling "demand" is therefore an ideal-loads indicator representing the energy that would be required to maintain the 26 °C setpoint, whereas discomfort hours describe the actual free-running indoor operative temperature. In Agadir's mild, ocean-buffered coastal climate, the uninsulated envelope allows a substantial part of the internal and solar heat gains accumulated during the day to escape through the walls and roof once outdoor temperatures fall at night. A thick, low-thermal-mass insulation layer such as XPS (specific heat capacity ≈ 1400 $J \cdot kg^{-1} \cdot K^{-1}$, Table 10) suppresses this nocturnal heat loss almost as effectively as it suppresses daytime heat gain, which can trap accumulated heat inside the building and raise the operative temperature during occupied hours even though the notional cooling-energy indicator improves. This mechanism is consistent with the more favourable comfort outcome obtained with roof-only XPS at 10 cm in Agadir — a lighter intervention that limits solar gains through the roof without as strongly restricting nocturnal heat loss through the walls — and it helps explain why the comfort-optimal and energy-optimal scenarios diverge specifically in the two zones with the mildest thermal amplitude and the greatest reliance on passive night cooling (Agadir and, to a lesser extent, Marrakech).

Wood fiber's comfort advantage in Marrakech is likewise consistent with its material properties (Table 10): although its thermal conductivity (0.04 $W \cdot m^{-1} \cdot K^{-1}$) is marginally higher than that of XPS (0.03 $W \cdot m^{-1} \cdot K^{-1}$), its combination of density and specific heat capacity (1380 $J \cdot kg^{-1} \cdot K^{-1}$) gives it a higher volumetric heat capacity and, consequently, a longer time lag and lower decrement factor than lightweight polymer foams of equal thickness [45]. In Marrakech's hot semi-arid climate, characterized by a very hot summer superimposed on a large diurnal temperature range, this thermal-inertia advantage delays and damps the transmission of the daytime heat wave through the envelope, which reduces peak indoor operative temperatures and hence ASHRAE 55-2004 discomfort hours, even though it does not translate into the lowest ideal-loads cooling-energy indicator. The discomfort-hour indicator used throughout this section is itself derived from the simulated indoor operative temperature and humidity of each zone (Section 4), so the reductions in discomfort hours reported for the insulated scenarios directly reflect a moderation of indoor temperature extremes.

The comfort-energy cloud confirms that the Pareto front is dominated by conventional scenarios, especially polymers and minerals, whereas PCM remains grouped in the zone of low energy gains and modest comfort benefits. An important nuance nevertheless appears in Marrakech, where wood fiber offers the best comfort compromise, which suggests that a discussion strictly based on annual energy alone would be incomplete.

Quantitatively, BioPCM's own energy demand reduction at the 2.08/2.08 cm combined configuration ranges from about 2.1% in Errachidia to about 4.2% in Ifrane (Tables 14, 16, 18, 20, 22 and 24), well below the 9.6–24.7% achieved by combined XPS at 6/6 cm in the same cities, which substantiates its position in the low-energy-gain region of the comfort–energy plane (Figure 21). The PCM scenarios never constitute the best-energy or the best-comfort option in any zone and therefore do not appear in Table 27; their position in the comfort–energy plane (Figure 21) nevertheless shows that their comfort benefit remains modest and of the same order as their limited energy benefit.

The normalized demand–thickness curves (Figure 22) show that the combined wall–roof configuration systematically delivers the best average level, with a marginal return that decreases sharply beyond 4 to 6 cm, while, once demand is normalized by the baseline case of each city, the decrease in the equivalent opaque-envelope U-value is accompanied by a quasi-monotonic decrease in annual energy (Figure 23).

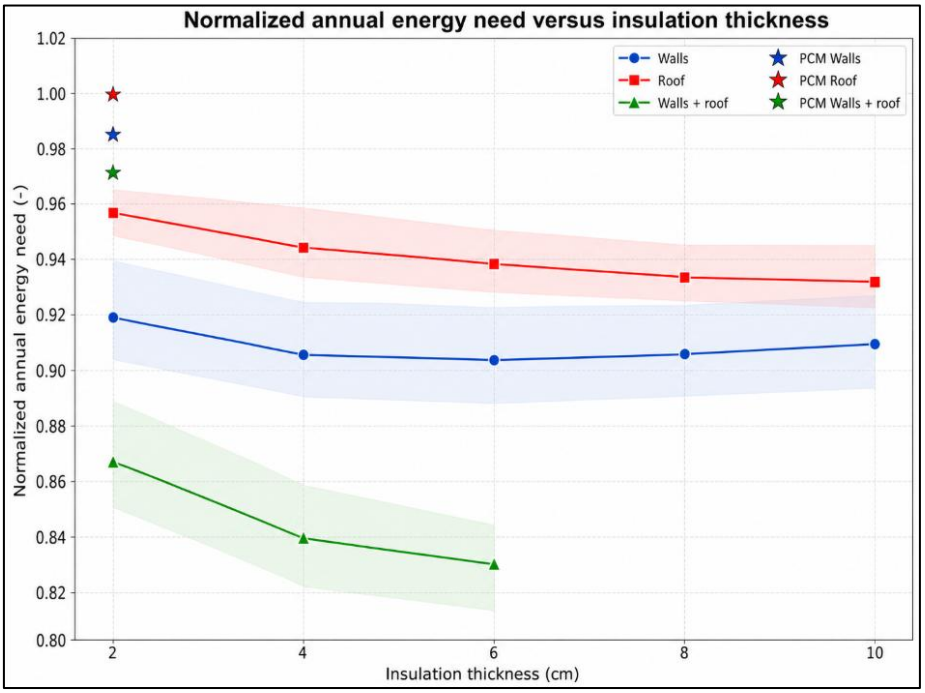


Figure 22: Normalized annual energy demand versus insulation thickness.

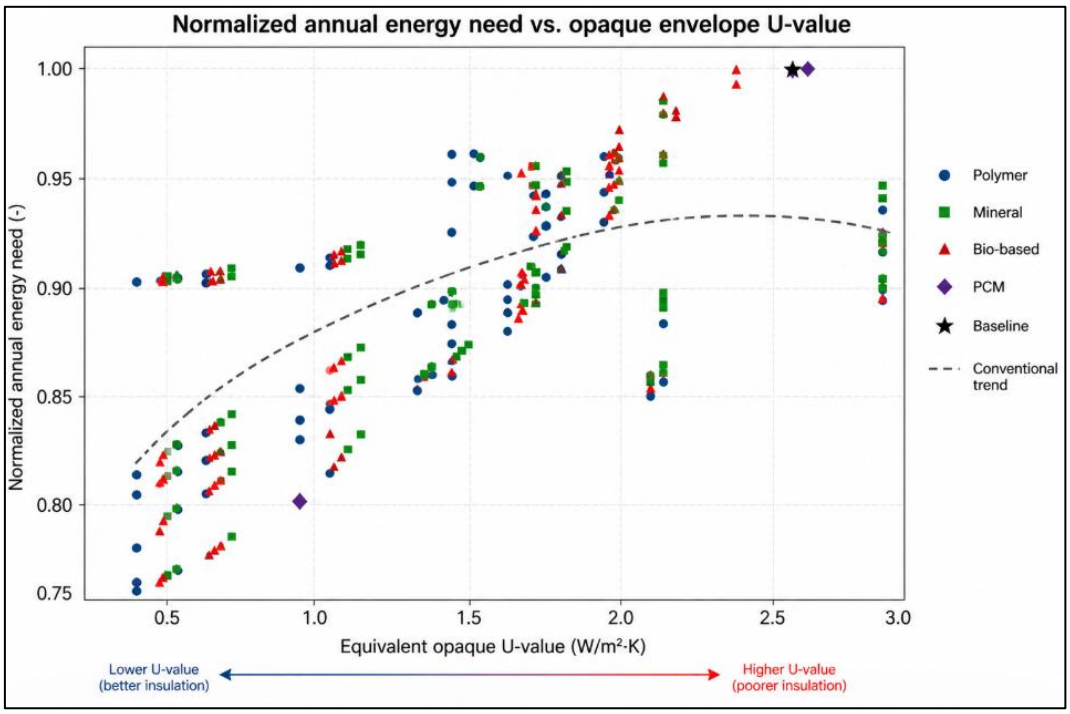


Figure 23: Normalized annual energy demand versus equivalent opaque-envelope U-value.

Two signatures stand out. On the one hand, sensitivity to thickness is maximal between 2 and 4 cm in inland and extreme climates: +4.47 reduction points in Ifrane and +3.96 points in Errachidia, compared with +0.99 point in Agadir and +0.89 point in Tangier. On the other hand, the inter-material spread at combined 4 cm remains low in the coastal zones (0.54 to 0.64 point) and becomes wider in continental and desert climates (1.55 to 2.14 points), which shows that climate amplifies inter-material dispersion.

Table 28: Indicators of thickness sensitivity and inter-material dispersion for conventional insulation materials.

Location	Combined 4 cm mean reduction (%)	Δ2→4 (pp)	Δ4→6 (pp)	Material spread at 4 cm (range, pp)	Best single element at 4 cm
Agadir	9.03	0.99	0.22	0.64	Roof (4.87%)
Errachidia	19.68	3.96	1.79	2.14	Walls (13.52%)
Fez	18.14	2.92	1.07	1.55	Walls (11.13%)
Ifrane	22.87	4.47	1.26	1.91	Walls (13.24%)
Marrakech	16.79	3.12	1.41	1.74	Walls (10.41%)
Tangier	9.56	0.89	0.09	0.54	Walls (4.97%)

Since the simulations are deterministic, the variability discussed here should not be interpreted as probabilistic uncertainty. It rather corresponds to the dispersion of results induced by the choice of insulation material, insulation location, and thickness. Sensitivity is therefore assessed through three complementary indicators: (i) the marginal gains obtained when increasing insulation thickness from 2 to 4 cm and from 4 to 6 cm; (ii) the inter-material dispersion observed at 4 cm; and (iii) the global relationship between annual energy demand, equivalent opaque-envelope U-value, and nominal insulation thickness.

The first mechanism explaining the results is conductive heat transfer through the opaque envelope. For a given building geometry, the heat flux through walls and roofs is mainly governed by the relationship between the U-value, the envelope area, and the indoor–outdoor temperature difference. Therefore, reducing both wall and roof U-values directly limits heat losses in winter and heat gains in summer. This explains why the combined wall–roof configuration systematically gives the highest energy reduction.

The second mechanism is climatic. In coastal zones such as Agadir and Tangier, the annual demand is strongly dominated by cooling, and the roof plays an important role because of direct solar exposure. In contrast, in inland, mountainous, and desert climates such as Fez, Ifrane, Marrakech, and Errachidia, wall insulation becomes more influential due to larger outdoor temperature variations and stronger heat exchanges through façades.

The third mechanism concerns the location of the insulation. Roof insulation alone is particularly relevant in coastal climates, while wall insulation becomes more effective in continental and extreme climates. However, the best performance is obtained when both components are treated simultaneously, because this configuration reduces heat transfer through the two main opaque envelope elements.

The fourth mechanism is the diminishing return of insulation thickness. The results show that the gain obtained when increasing thickness from 2 to 4 cm is generally higher than the additional gain from 4 to 6 cm. Beyond this range, the residual demand becomes increasingly controlled by other building components that were kept unchanged in this study, such as glazing, floor construction, ventilation, infiltration, and internal gains.

Finally, BioPCM does not follow the same physical behavior as conventional insulation materials. Its thermal conductivity is higher than that of the other tested insulation materials, which limits its effect on U-value reduction. Its potential benefit is more related to latent heat storage, peak temperature attenuation, and thermal phase shifting than to steady-state insulation. This explains why BioPCM remains less effective in terms of annual energy demand reduction in the scenarios tested.

6.6. Comparison with previous studies

The results obtained in this study are consistent with previous Moroccan studies showing that the effectiveness of passive envelope strategies depends strongly on climatic conditions, building configuration, and envelope composition [5,6,8]. The differences observed between coastal zones, inland climates, mountainous areas, semi-arid regions, and desert climates confirm that a single insulation strategy cannot be generalized to all Moroccan climatic zones. Compared with previous works, the present study extends the analysis by applying the same building geometry, simulation assumptions, and RTCM-based evaluation framework to the six Moroccan climatic zones.

The strong energy performance of XPS is consistent with the general literature on building insulation materials, where thermal conductivity is identified as one of the main parameters controlling conductive heat transfer through the envelope [9–11]. Since XPS has the lowest thermal conductivity among the conventional insulation materials tested in this study, its higher energy performance is physically expected. However, the results also confirm that thermal conductivity alone is not sufficient to describe overall building performance, since comfort and energy savings also depend on climatic zone, treated envelope component, insulation thickness, and material dynamic behavior.

The results obtained for Marrakech are particularly relevant when compared with studies conducted in hot or semi-arid Moroccan climates [20]. Although XPS provides the lowest annual energy demand, wood fiber gives the best comfort performance in this zone. This confirms that bio-based materials may offer advantages in terms of dynamic thermal response and summer comfort, as also suggested by previous studies on bio-sourced insulation materials in Moroccan buildings [21,22]. More broadly, the divergence between the energy-optimal and comfort-optimal scenarios observed in Agadir and Marrakech (Section 6.5) extends these earlier Moroccan studies, which generally reported energy indicators only.

Regarding PCM, the limited reduction in annual energy demand observed in this study is consistent with previous works showing that PCM performance depends strongly on the phase-change temperature, the position of the PCM layer, the climatic context, and the possibility of thermal discharge through natural or night ventilation [28,32–35]. Therefore, PCM should not be interpreted as a direct substitute for conventional insulation materials. Its potential contribution is more related to peak temperature reduction, thermal phase shifting, and overheating mitigation than to a strong reduction in annual energy demand.

Overall, this comparison confirms the relevance of a climate-specific approach to envelope insulation in Morocco. The main contribution of the present work is to provide a unified multi-climatic, multi-material, and RTCM-based comparison of insulation strategies applied to walls, roofs, and combined wall–roof configurations.

To make this comparison more explicit, it is useful to contrast the magnitude of the present energy savings with those reported in closely related recent studies. Applying a sequential-search, multi-parameter optimization (envelope, glazing, air leakage, lighting, and HVAC efficiency) to the same six Moroccan climatic zones and RTCM framework, Boumlik et al. reported cost-effective annual energy savings of 51–67% relative to current construction practice [40] — substantially higher than the 9.58–24.71% obtained here for insulation alone. This difference is expected and, in fact, corroborates the present results: because the present study isolates the effect of opaque-envelope insulation while holding glazing, air leakage, lighting, and HVAC efficiency constant, it quantifies the specific contribution of one measure among the many that a full multi-parameter optimization can combine, and the gap between the two figures is consistent with the present finding that the unchanged single glazing and, in some zones, the slab-on-ground floor are the main remaining barriers to larger

savings. Likewise, a 2025 building-stock-scale simulation of over 1000 Moroccan residential configurations found RTCM compliance ranging from full compliance in milder climates to complete non-compliance in the harshest zones [39], mirroring the present finding that the uninsulated reference building fails the RTCM performance limit in all six zones and that non-compliance becomes progressively more severe from the coastal zones (Agadir, Tangier) toward the continental and desert zones (Ifrane, Errachidia).

Regarding the methodology adopted for insulation ranking, the DesignBuilder-based numerical framework used here to compare materials and thicknesses is methodologically consistent with recent applications of the same simulation environment to residential roof and wall insulation in Tehran's hot-summer continental climate [36,37], which similarly identified an optimal insulation-thickness range of a few centimeters beyond which marginal energy gains diminish sharply — the same diminishing-returns pattern reported in Section 6.3 for all six Moroccan zones. Regarding bio-based materials, the comfort advantage of wood fiber identified here in Marrakech is consistent with the broader literature on the dynamic thermal response of bio-based insulation, and is reinforced by recent evidence that fiber-reinforced earthen materials can deliver substantial thermal improvements in hot and arid climates while remaining compatible with local construction practice [38].

6.7. Optimization synthesis by zone and recommendations

Based on the energy results, RTCM compliance analysis, and comfort assessment, an optimization synthesis was established for each climatic zone. The objective is not only to identify the scenario with the lowest annual energy demand, but also to highlight the most practical insulation level and the remaining envelope improvements required to approach full RTCM compliance. Table 29 summarizes the recommended insulation profiles, the corresponding demand reductions, the practical interpretation of 2/4/6 cm insulation levels, and the remaining regulatory limitations.

Table 29: Ideal profiles by zone, 2/4/6 cm feasibility reading, and remaining conditions to target full RTCM compliance.

Location	Recommended ideal profile	Demand reduction	2–4–6 cm reading	Remaining RTCM condition
Agadir (Z1)	XPS 6/6 cm combined wall–roof	9.58%	4/4 cm already very close to the maximum; roof priority if only one intervention is possible	Combined wall–roof OK from 4/4 cm; glazing must be replaced for total compliance
Tangier (Z2)	XPS 6/6 cm combined wall–roof	9.96%	4/4 cm constitutes the best compromise; marginal gains are very small beyond this level	Combined wall–roof OK from 4/4 cm; glazing must be replaced for total compliance
Fez (Z3)	XPS 6/6 cm combined wall–roof	19.83%	4/4 cm is a strong threshold; 6/6 cm for maximization and additional margin	Combined wall–roof–floor OK from 4/4 cm; glazing must be replaced
Ifrane (Z4)	XPS 6/6 cm combined wall–roof	24.71%	6/6 cm recommended; 4/4 cm remains insufficient with regard to cold-zone U requirements	Combined wall–roof OK at 6/6 cm but floor and glazing remain non-compliant
Marrakech (Z5)	XPS 6/6 cm combined wall–roof	19.12%	4/4 cm is relevant, 6/6 cm is preferable to maximize cooling reduction	Combined wall–roof OK from 4/4 cm; floor and glazing must be improved for total compliance

Errachidia (Z6)	XPS 6/6 cm combined wall–roof	22.69%	4/4 cm is the first robust level; 6/6 cm recommended for desert climate	Combined wall–roof OK from 4/4 cm; floor and glazing block full compliance

In summary, from the perspective of annual heating and cooling demand reduction, the best-performing scenario among those tested is combined wall–roof insulation using XPS at 6/6 cm in all climatic zones. However, this result should not be interpreted as a general superiority of XPS for all building performance criteria. The present comparison focuses on simulated annual energy demand and thermal comfort, while other important criteria, such as cost, embodied energy, fire behavior, moisture sensitivity, acoustic performance, durability, and implementation constraints, were not assessed.

The higher energy performance of XPS is mainly explained by its lower thermal conductivity, which reduces the overall heat transfer through the opaque envelope. This effect is particularly important in the most demanding climates, where indoor–outdoor temperature differences and solar gains increase heat exchanges through walls and roofs. However, increasing insulation thickness leads to diminishing marginal returns. Beyond a certain level, the remaining energy demand is increasingly influenced by other components, especially glazing, the slab-on-ground floor, and air exchanges. In this context, bio-based materials remain relevant for improving summer comfort through their dynamic thermal behavior, while PCM acts more as a thermal modulation material than as a conventional insulation layer.

This energy-based ranking should not, however, be read as an unconditional recommendation of XPS over bio-based alternatives. Across the six climatic zones at the combined wall–roof configuration, wood fiber trails XPS by as little as 0.52 percentage points in Tangier to about 2.07 percentage points in Errachidia in annual demand reduction (Tables 14, 16, 18, 20, 22 and 24), while offering markedly higher decrement factor and time lag due to its higher specific heat capacity and density — properties known to improve summer comfort and reduce reliance on mechanical cooling in naturally ventilated buildings [45]. Wood fiber and hemp wool are also bio-based materials with substantially lower embodied energy and a lower environmental footprint than petrochemical-derived polymer insulation such as XPS or EPS [18,19], a point reinforced by recent work on bio-based earthen envelope components in arid climates [38]. For sustainability-minded designers, the marginal energy penalty of choosing wood fiber over XPS may therefore be an acceptable trade-off against embodied-energy and end-of-life benefits, particularly in Marrakech where wood fiber additionally delivers the best thermal comfort outcome (Section 6.5). The present comparison deliberately excludes cost, embodied energy, fire behavior, and moisture performance (see Section 7), and this exclusion should be read as a scope limitation rather than as evidence that XPS is the preferable material once these criteria are considered.

To complement this zone-by-zone reading, Tables 30 and 31 synthesize the overall rankings that emerge from Tables 14, 16, 18, 20, 22 and 24; no new simulations were performed to construct them. Table 30 ranks the seven insulation materials by their average annual demand reduction at the best combined wall–roof configuration, averaged across the six climatic zones.

Rank	Material	Family	Average reduction across six zones (%)
1	XPS	Polymer	17.65
2	Glass wool	Mineral	17.08
3	EPS	Polymer	17.04
4	Rock wool	Mineral	16.87
5	Hemp wool	Bio-based	16.74

6	Wood fiber	Bio-based	16.48
7	BioPCM M51/Q23	PCM	3.14

Table 31 ranks the six climatic zones by the average annual demand reduction achieved by the six conventional insulation materials (excluding BioPCM) at the best combined wall–roof configuration.

Rank	City (RTCM zone)	Average reduction, conventional materials (%)
1	Ifrane (Z4)	24.13
2	Errachidia (Z6)	21.40
3	Fez (Z3)	19.21
4	Marrakech (Z5)	18.21
5	Tangier (Z2)	9.66
6	Agadir (Z1)	9.25

Finally, Table 32 summarizes the comparison with the recent literature discussed in Section 6.6.

Reference	Scope	Reported result	Relation to present study
Boumlik et al. [40], Buildings 2024	Multi-parameter LCC optimization, six Moroccan RTCM zones	51–67% annual energy savings vs. reference design	Higher than the 9.58–24.71% found here because it jointly optimizes glazing, air leakage, lighting, and HVAC efficiency in addition to insulation
Boumlik et al. [39], J. Building Eng. 2025	>1000 residential configurations, six Moroccan RTCM zones	RTCM compliance ranges from full compliance to complete non-compliance depending on zone	Consistent with the present finding that the uninsulated reference fails the RTCM limit in all six zones, worsening from coastal to desert zones
Hassani & Bahramani [36,37], J. Thermal Eng. 2025–2026	DesignBuilder wall/roof insulation, Tehran	Diminishing marginal energy gains beyond a few cm of insulation	Same diminishing-returns pattern as Section 6.3 of the present study
Bassoud et al. [38], J. Thermal Eng. 2026	Palm-fiber-reinforced adobe, arid Algeria	Up to 133% higher thermal insulation, 53% lower energy use	Supports the discussion of bio-based alternatives to XPS in Sections 6.6 and 6.7
Tellache et al. [42], Buildings 2025	ASHRAE 55 / EN 16798-1 / ISSO 74 comparison, Algiers	Comfort-model choice materially changes discomfort-hour estimates	Consistent with the explicit ASHRAE 55-2004 Simple model description given in Section 4

7. Limitations and future work

This work has several limitations that should be kept in mind when interpreting the results. First, the analysis is based exclusively on numerical simulation: the model was checked for consistency against the simplified baseline of the official RTCM guide (Table 11a) but was not calibrated against in-situ measurements for the specific building studied, so the absolute values of energy demand and discomfort hours carry the usual uncertainties of uncalibrated dynamic simulation. Second, the comparison of insulation materials is restricted to simulated energy demand, regulatory compliance, and thermal comfort; cost, embodied energy, carbon emissions, moisture transfer, fire behavior, acoustic performance, and long-term durability were not assessed, although these criteria can modify the final material choice, particularly between polymer and bio-based solutions. Third, the glazing system, the slab-on-ground construction, the infiltration rate, and the internal-gain assumptions were deliberately held constant in all scenarios in order to isolate the effect of opaque-envelope insulation, so the results quantify the specific contribution of insulation and cannot be extrapolated to buildings in which these parameters differ substantially. Finally, discomfort hours are reported with the fixed-band ASHRAE 55-2004 Simple model only, and the absolute comfort results are therefore not directly comparable with studies based on adaptive comfort standards such as EN 16798-1 or ISSO 74 [42].

Several extensions follow directly from these limitations. Future work should combine dynamic simulation with experimental monitoring of an instrumented dwelling in order to calibrate the model and validate the comfort predictions, and should couple the energy and comfort indicators reported here with economic optimization and life-cycle assessment so that operational savings, investment cost, and embodied impacts can be weighed within a single decision framework. On the design side, the priorities are the improvement of the components identified as the remaining barriers to full RTCM compliance, namely the single glazing and, in some zones, the slab-on-ground floor, together with the investigation of night-ventilation strategies and alternative PCM integration methods (phase-change temperature, layer position, and coupling with ventilation) that could unlock the comfort potential of latent heat storage in the hot Moroccan climates.

8. Conclusion

This study assessed the impact of thermal insulation strategies on annual energy demand and thermal comfort in a typical Moroccan residential building located in each of the six climatic zones defined by the Moroccan Thermal Construction Regulation (RTCM). Dynamic simulations were performed using DesignBuilder coupled with EnergyPlus. Six conventional insulation materials, including extruded polystyrene (XPS), expanded polystyrene (EPS), glass wool, rock wool, hemp wool, and wood fiber, were evaluated for different thicknesses and envelope configurations. BioPCM M51/Q23 was also analyzed separately in order to assess the potential contribution of latent heat storage.

The results show that the uninsulated reference building exceeds the RTCM performance limits in all climatic zones, confirming the need for envelope improvement. Among the tested scenarios, combined wall–roof insulation gives the highest energy savings in all zones. XPS at 6/6 cm provides the greatest reduction in annual energy demand in all six zones, with gains ranging from 9.58% in Agadir to 24.71% in Ifrane, while not necessarily delivering the best thermal comfort performance, as shown explicitly in Marrakech and Agadir (Section 6.5). These results confirm that insulation effectiveness depends strongly on climatic conditions and that the combined treatment of walls and roof is more effective than insulating only one envelope component. By applying a single building model and a common simulation and RTCM-based evaluation framework to all six Moroccan climatic zones, three envelope configurations, and four families of insulation material, this study provides a unified comparative basis for climate-specific envelope design in Moroccan residential buildings, extending previous single-zone or single-material Moroccan case studies toward a nationally consistent, regulation-anchored comparison.

However, insulation alone does not ensure full RTCM compliance in the studied building. Although several wall–roof insulation scenarios satisfy the prescriptive requirements for opaque envelope components, the unchanged single glazing and, in some zones, the insufficient slab-on-ground thermal resistance remain limiting factors. The comfort analysis also shows that the lowest annual energy demand does not always correspond to the best thermal comfort performance. In Marrakech, for example, wood fiber at 6/6 cm provides better comfort results, suggesting that bio-based materials may offer advantages under hot semi-arid conditions. Taken together, these results provide climate-specific, regulation-anchored guidance for envelope insulation in Moroccan residential dwellings and a quantified starting point for the multi-criteria and experimental extensions outlined in Section 7.

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Data availability The data supporting the findings of this study are included in the article. The DesignBuilder/EnergyPlus model files and the complete simulation output used to generate the tables and figures are available from the corresponding author on reasonable request.

Ethics approval Not applicable. This study is based exclusively on numerical simulation and did not involve human participants or animals.