

**THE IMPACT OF INTEGRATING PHASE CHANGE MATERIALS
(PCM) IN BUILDING ENVELOPES ON ENERGY PERFORMANCE IN
EXTREME CLIMATIC CONDITIONS**

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DEDICATION

“Alhamdulillah Rabbil ‘Alamin” to the Most Merciful, whose boundless grace has illuminated my path, granted me wisdom, and guided me through every step of this journey. I humbly offer my deepest gratitude for the blessings of knowledge, perseverance, and faith that have shaped my life and this work. May every word written here honor your divine light and the teachings of our beloved Rasul (SAW), who remains my eternal guide toward truth and humility.

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LIST OF ABBREVIATIONS

PCM	:	Phase Change Materials
ASHRAE Engineers	:	American Society of Heating Refrigerating and Air-Conditioning
HVAC	:	Heating Ventilation and Air Conditioning
KSA	:	Kingdom of Saudi Arabia
XPS	:	Extruded Polystyrene
ΔH	:	Latent heat capacity
WWR	:	Window to Wall Ratio
SBC	:	Saudi Building Codes
NMBE	:	Non-Mean Bias Error
CVMBE	:	Coefficient of Variation of Mean Bias Error (CVMBE)
BIM	:	Building Information Model
BEM	:	Building Energy Modeling
CondFD	:	Conduction Finite Differences
OT	:	Operative Temperature
INT	:	Interior
EXT	:	Exterior
CST	:	Cooling Set Point
EUI	:	Energy Utilization Index
TES	:	Thermal Energy Storage
ATD	:	Annual Thermal Discomfort
GA	:	Genetic Algorithm
TMY	:	Typical Metrological Year

ABSTRACT

Full Name : Rashid Kanu
Thesis Title : The Impact of Integrating Phase Change Materials (PCM) In Building Envelopes on Energy Performance in Extreme Climatic Conditions
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Buildings in extreme climates, such as Saudi Arabia, face increasing cooling demands that strain energy infrastructure and amplify carbon emissions. While phase change materials (PCMs) offer latent heat storage to regulate indoor temperatures, previous studies lack whole-building evaluations under extreme climatic diversity and fail to optimize PCM parameters (melting temperature, thickness, position) for region-specific applications. This study bridges these gaps by analyzing PCM-integrated exterior walls across Saudi Arabia's contrasting climates: Al-Ahsa (extremely hot and dry) and Taif (hot and dry) using EnergyPlus/DesignBuilder simulations coupled with genetic algorithm optimization. A residential villa model was calibrated against Saudi Building Code (SBC 601) standards, evaluating macro-encapsulated InfiniteR PCMs (21–39°C melting temperature range, 6–24 mm thickness) in code-compliant and retrofit wall assemblies. Results demonstrated that PCM integration reduced peak cooling loads by 17.4% in Al-Ahsa and 26.7% in Taif, shifting demand by 2–4 hours and enabling HVAC system downsizing (20% capacity reduction). Optimal interior placement of 24 mm PCM with climate-specific melting temperatures (27°C and 25°C for Al-Ahsa, 25°C for Taif) reduced total energy consumption by 12.6–18.4% while maintaining thermal discomfort below 20% of annual hours. The optimized configurations

lowered cooling loads by 12.6–34.2% and heating demand by 35–80%, with CO₂ emissions reduced by 1,526–3,640 kg/year for the studied building. The findings emphasize PCM's efficacy in extreme climates when synchronized with HVAC setpoints and regional diurnal patterns. Recommendations prioritize inorganic PCMs for fire resistance and thermal stability, interior positioning for direct thermal buffering, and 24 mm thickness for cost-effective latent storage. This research advances actionable guidelines for Saudi Arabia's construction sector, supporting Vision 2030 sustainability goals through climate-responsive envelope design.

ملخص الرسالة

الاسم الكامل : رشيد كانو

عنوان الرسالة: تأثير دمج المواد متغيرة الحالة (PCMs) في أغلفة المباني على أداء الطاقة في الظروف المناخية

القاسية

المجال الرئيسي: الهندسة المعمارية

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تواجه المباني في المناخات القاسية، مثل المملكة العربية السعودية، طلبات تكيف متزايدة تُجهد البنية التحتية للطاقة وتزيد من انبعاثات الكربون. وعلى الرغم من أن المواد متغيرة الحالة (PCMs) توفر تخزينًا حراريًا كاملاً يساعد على تنظيم درجات الحرارة الداخلية، فإن الدراسات السابقة كانت تفتقر إلى التقييم الشامل لاستخداماتها في المباني تحت تنوع مناخي قاسي، كما لم تقم تلك الدراسات بتحسين معايير المواد متغيرة الحالة (مثل درجة حرارة الانصهار، السماكة، وموقعها في الحائط) وفقًا لخصائص كل منطقة مناخية.

وتهدف هذه الدراسة إلى سد هذه الثغرات من خلال تحليل الحوائط الخارجية المدمجة مع المواد متغيرة الحالة عبر مناخات مختلفة في السعودية ممثلة بالأحساء (حار جدًا وجاف)، والطائف (معتدل)، باستخدام المحاكاة بواسطة EnergyPlus/DesignBuilder بالتزامن مع استخدام خوارزميات الأمثلة متعددة الأهداف لتجويد الأداء الحراري. حيث تمت معايرة نموذج فيلا سكنية وفقًا لمتطلبات "الكود السعودي للبناء (SBC 601)"، وتم تقييم مواد PCMs والمُغلّفة كليًا (بنطاق درجات حرارة انصهار بين 21-39 درجة مئوية، وسماكة تتراوح بين 6-24 ملم) ضمن أنظمة الحوائط المتوافقة مع الكود. وقد أظهرت النتائج أن دمج المواد متغيرة الحالة قلل من أحمال التكييف القصوى بنسبة 17.4% في الأحساء و26.7% في الطائف، مع تحويل ذروة الطلب بمدة تتراوح بين ساعتين إلى أربع ساعات، مما سمح بتقليل حمولة نظام تكييف الهواء بنسبة 20%. كما حققت التركيبة المثلى للوضع الداخلي لطبقة PCM بسماكة 24 ملم ودرجات حرارة انصهار مخصصة لكل منطقة (27°م و25°م للأحساء، و25°م للطائف) تخفيضًا في استهلاك الطاقة الإجمالي بنسبة 12.6-18.4%، مع الحفاظ على فترة عدم الراحة الحرارية تحت 20% من الساعات السنوية.

كما أدت المكونات المُحسنة إلى تخفيضات في أحمال التكييف بنسبة 12.6–34.2%، وفي متطلبات التدفئة بنسبة 35–80%، مع تقليل انبعاثات ثاني أكسيد الكربون بمقدار 1,526–3,640 كجم/سنة لنموذج الفيلا السكنية المدروسة. وتؤكد نتائج البحث فعالية استخدام المواد متغيرة الحالة (PCMs) في المناخات القاسية عند مزامنتها مع نقاط ضبط نظام تكييف الهواء وأنماط درجات الحرارة اليومية الخاصة بكل منطقة. وتوصي الدراسة بإعطاء الأولوية للمواد غير العضوية من PCMs لمقاومتها للحريق وحفاظها على الاستقرار الحراري، ووضعها في الحائط لتكون أقرب للفراغ الداخلي لتعزيز تأثير العزل الحراري المباشر، وبسماكة 24 ملم لفعاليتها من حيث التكلفة في تخزين الطاقة الكامنة. وتسهم هذه الدراسة في وضع إرشادات عملية لقطاع الإنشاءات في المملكة العربية السعودية، دعمًا لأهداف رؤية 2030 المتعلقة بالاستدامة من خلال تصميم غلاف مبنى يستجيب للظروف المناخية المحلية.

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

Buildings account for over 40% of global energy consumption and greenhouse gas emissions, with cooling demands in extreme climates intensifying this trend (IPCC, 2020; Tollefson, 2018). In Saudi Arabia, residential buildings alone contribute up to 50% of national energy use, driven by air conditioning during summer months when temperatures exceed 45°C (Al-Homoud and Krarti, 2021; Felimban *et al.*, 2019).

This demand strains grid infrastructure and amplifies carbon emissions, underlining the urgency for energy-efficient building designs. Sustainable envelope technologies, particularly those integrating thermal energy storage, offer a viable pathway to reduce cooling loads while maintaining thermal comfort. This led to a critical need in regions with severe diurnal temperature swings (Dardouri, Mankai, *et al.*, 2023a; Gil-Lopez and Gimenez-Molina, 2013).

Conventional thermal mass materials, such as concrete, moderate indoor temperatures by absorbing heat, yet their effectiveness diminishes in hot-arid climates like Saudi Arabia, where excessive heat retention can unexpectedly increase cooling demands (Ajour *et al.*, 2022). Phase change materials (PCMs), however, present a transformative solution by leveraging latent heat storage during solid-liquid phase transitions. PCMs absorb surplus heat during peak daytime temperatures and release it during cooler nights, flattening indoor temperature fluctuations and reducing reliance on mechanical cooling (Mustafa *et al.*, 2022). Studies in moderate climates demonstrate PCMs can lower energy use by 10–30%, but their efficacy in extreme climates remains underexplored, particularly in whole-building analyses (Alam *et al.*, 2014; Al-Yasiri and Szabó, 2021a).

In Saudi Arabia, where summer temperatures rarely drop below 30°C at night, PCM integration demands meticulous optimization of phase-change temperatures, layer positioning, and thickness to avoid suboptimal performance (Al-Absi *et al.*, 2021). Prior research in the Kingdom has focused on homogenous climatic zones, achieving up to 30.4% annual energy savings with PCM-enhanced walls (Al-Absi *et al.*, 2021; Al-Absi, Hafizal, *et al.*, 2024; Bagazi *et al.*, 2021). However, these studies overlook regional climatic diversity, such as Taif's elevated, milder climate versus Al-Ahsa's arid extremes, limiting the applicability of their findings. Additionally, gaps persist in quantifying peak load reductions and optimizing PCM configurations (e.g., exterior vs. interior placement) for retrofitted versus new constructions (Dardouri, Mankai, *et al.*, 2023a; Wang *et al.*, 2023; Zhan *et al.*, 2023a).

This study addresses these gaps by evaluating PCM-integrated exterior walls across Saudi Arabia's contrasting climatic zones: Al-Ahsa (extremely hot and dry) and Taif (hot and dry). Using a genetic algorithm optimization simulation framework in EnergyPlus, it investigates the interplay of PCM melting temperatures (21–39°C), layer thicknesses (6–24 mm), and positions (exterior, middle, interior) within code-compliant and retrofit wall assemblies. By analyzing whole-building energy performance as a trade off with annual thermal discomfort, the research advances region-specific guidelines for PCM deployment, offering actionable insights for Saudi Arabia's construction sector. The findings aim to bridge the divide between theoretical PCM potential and practical, climate-responsive implementation, ultimately contributing to the Kingdom's 2030 Vision for sustainable urbanization.

1.2 Research Problem Statement

Saudi Arabia's extreme climate poses challenges for preserving indoor thermal comfort, with buildings constraint by excessive heat gain that overloads HVAC systems. Reliance on energy-intensive mechanical cooling has led to peak demand-straining electrical infrastructure. As energy rates rise, unsustainable residential air conditioning consumption jeopardizes affordability and environmental goals.

Traditional construction practices used thick, massive walls with insulation to regulate temperatures fluctuations. Substantial thicknesses of these walls increase material usage which also increases long-term costs. Simulation studies indicate their minimal thermal resistance and allowed continued internal heat flux worsening loads. Thermal lag fails to shift peak loads, overtaxing limited generation.

PCMs' thermal energy storage through phase transitions, composite wall systems could realize efficient thermal regulation with reduced thickness and embodied energy. Indoor comfort would be maintained while decreasing annual loads and peaks to ease grid stress. Optimizing wall envelopes with appropriate PCM selection and applications specific to regional practices offers the potential to greatly minimize residential energy usage. More efficient electricity consumption will result in lowering utility bills and carbon emissions. Through modeling, simulation, and optimization are the procedure needed to quantify PCM envelopes' effects on sustainable development in KSA under prevailing climatic extremes.

1.3 Research Gap

While previous research has advanced our understanding of Phase Change Materials (PCMs) as thermal energy storage technologies in buildings, significant gaps remain in comprehensively evaluating their performance potential regarding transition temperature, thickness, and positioning under extreme climatic conditions, particularly in Saudi Arabia. Much of the existing literature has focused on analyzing individual PCM-enhanced construction components or conducting proof-of-concept investigations, rather than optimizing and assessing the effects of PCMs at a whole-building scale (Biswas *et al.*, 2018a; Dardouri, Mankai, *et al.*, 2023a; Kishore *et al.*, 2021; Kosny *et al.*, 2012a).

Furthermore, relatively few studies have specifically examined the annual energy impacts of PCM integration using dynamic simulations that accurately represent Saudi Arabia's hot arid climate. Notable works (Ajour *et al.*, 2022; Al-Absi, Asif, *et al.*, 2024; Al-Absi *et al.*, 2021, 2022a, 2022b; Al-Absi, Hafizal, *et al.*, 2024; Farouk *et al.*, 2022a; Rawa *et al.*, 2022) have often evaluated PCM effects based on integration on one side or orientation of the building envelope, which tends to replicate prior research without addressing the nuanced differences in PCM effectiveness across distinct climatic zones. These regions exhibit unique climatic characteristics influenced by geographical location, elevation, and local microclimates; for instance, Al-Ahsa, with its extremely hot and dry climate, typically experiences higher average temperatures compared to Taif, which benefits from a more moderate climate due to its elevated mountainous terrain.

Additionally, there is a lack of clear guidelines concerning appropriate PCM selection and integration based on critical parameters such as melting temperature, position, and thickness within typical residential masonry wall assemblies. Current standards do not

provide adequate guidance on characterization methods, optimal integration strategies based on melting point ranges aligned with local weather data, or best practice application approaches tailored to the construction practices commonly found in Saudi Arabia's hot climatic zones.

This knowledge gap can be addressed by conducting annual energy simulations that evaluate optimized PCM envelope designs at a whole-building scale for residential villa constructions. Utilizing thermal energy modeling and simulation software will enable a quantitative assessment of impacts on annual cooling and heating energy demands, as well as thermal comfort, in comparison to a conventional base building model utilizing extruded polystyrene (XPS) insulation. Such research will not only advance technical understanding but also inform future building energy efficiency policies and codes tailored to the extreme climatic conditions of Saudi Arabia.

1.4 Aim and Objectives

This research seeks to assess the impact of integrating PCMs within residential building exterior walls envelope designs to optimize the energy performance for the selected representative climates of Saudi Arabia.

The key objectives to achieve this research aim are:

- To Identify, select and integrate the Identified PCM and exterior wall envelope into a residential building model under two selected representative climates.
- To quantify and compare energy savings potentials of PCM-integrated envelopes and conventional designs under selected representative climates of Saudi Arabia.
- To develop guidelines on the most suitable combination of wall assemblies incorporated with the proper PCM.

1.5 Significance of Research

Saudi Arabia depends so much on air conditioning during the hot summer months, Buildings contribute significantly to the rising levels of energy usage and the corresponding emitting greenhouse gases. As urbanization and climate change drive up cooling demands, creative strategies must be adopted to reduce demand and relieve pressure on already overworked electric systems. This work will help to:

- Progress the scientific and industrial knowledge of high-performance building envelopes using PCMs as passive thermal storage technologies.
- Motivate the exploration of alternative passive strategies through macro-encapsulation of PCM composite walls in residential buildings that can achieve comparable thermal regulation benefits with reduced thickness, weight, cost, and improved occupant comfort year-round under extreme climatic conditions.
- Lead to the provision of useful information on annual energy savings potential across two representative climates by carrying out energy simulations and optimization of PCM-integrated exterior wall envelopes.
- Further advance building industry practices with recommendations on optimum melting temperature, position/configuration and thickness/ quantity of an InfiniteR PCM application in the representative climates.
- Provide design guidelines, for the appropriate PCM integration particularly for Saudi Arabia's extreme climates this could encourage more people to use passive wall envelope design solutions to reduce emissions from the construction industry in compliance with sustainability goals and Saudi Arabi Vision 2030.

1.6 Scope and Limitations

This study focuses on the following key areas:

- The macro-encapsulation of InfiniteR PCMs exclusively within exterior wall envelopes, drawing insights from the three major classes of PCM and relevant literature (Sovetova *et al.*, 2019a; Yang, Zhu, *et al.*, 2018; Zahir *et al.*, 2023).
- The examination of a residential villa building typology integrated with PCM, specifically analyzed in two distinct climatic zones: Al-Ahsa (characterized as very hot and dry) and Taif (identified as hot and dry).
- The evaluation of energy performance for PCM-integrated walls in a typical Saudi Arabian residential villa, utilizing metrics such as fuel breakdown, total consumption, and thermal comfort. This analysis will employ software tools such as CAD, EnergyPlus simulation engine through DesignBuilder (V7.3), software to compare the effects of PCM integration.
- The research does not encompass field experimentation for the base case building's wall envelope. The integration of PCM in this study is limited to the layers within the wall assembly; other applications, such as those related to roofs or floors, are excluded and suggested for future research.

1.7 Organization of the Thesis

This thesis is structured into 5 chapters, each focusing on specific content. Chapter 1 offers an introduction to the study's context and background, its significance, aim and objectives, and research gap, related to the applications and energy-saving capacity of PCM in building envelope.

Chapter 2 focused on reviewing literature, beginning with key definition and classification of PCM, along with its characteristics. It explores the idea of storing thermal energy in building envelopes and discusses the properties of PCM. Additionally, this chapter highlights the criteria for PCM selection in passive cooling applications within building envelopes. The methods of integrating PCM into the building envelope are explored, along with the factors that impact PCM effectiveness in this setting. The chapter further explores the integration of PCM in whole building scale wall envelopes, specifically focusing on residential buildings' wall envelope systems in KSA.

Chapter 3 focuses on research methodology, including the selection of the two studied climatic locations and the identification of a baseline building model. It also identifies, selects and discusses the typical exterior walls system diversely used in the representative climatic zones and then outlines the simulation and optimization procedures. Moreover, this chapter addresses crucial aspects such as the determination of melting points, PCM position/configuration and thickness/quantity.

Chapter 4 presents the study's results discussion and analysis of the incorporated PCM on key objective function of total energy (kWh), seasonal impacts, monthly impact, annual thermal discomfort (ATD), operative temperature and the individual variable evaluation parameter such: PCM transition temperature, position and thickness in terms of energy and

comfort potentials. The savings by each of the optimal walls were then evaluated for environmental CO₂ emission reduction as compared to the base cases wall scenarios. It analyzed the energy storage potential derived from PCM-incorporated building envelopes compared to conventional buildings. This section provides a comprehensive analysis and evaluation of the effectiveness of PCM integration in enhancing energy performance and then backed by a concise summary of the study key findings.

Lastly, Chapter 5 concludes the thesis by summarizing the key findings and offering guidelines or recommendations for the integration of PCM in retrofitting existing buildings and or in constructing new buildings in extreme climates. Additionally, suggestions for future research are provided to further explore the potential benefits and applications of PCM in the built environment.

CHAPTER 2: LITERATURE REVIEW

Phase Change Materials (PCMs) have emerged as a potential solution to enhance energy efficiency in buildings, especially in extreme climatic conditions. This section of the study discusses various definitions of PCMs from relevant bodies of knowledge and explores their general classifications and types. Additionally, it focuses on the classification of PCMs used in external building wall envelopes, highlighting their different forms and applications (Al-Yasiri and Szabó, 2021b).

2.1 Concept of PCMs

PCM has a major concept of storing and releasing heat energy during a phase transition (Primarily transitioning between solid and liquid states and back again) at a comparatively stable temperature and enthalpy. Large quantities of thermal heat can be stored and released by these materials per finite unit volume. Because PCMs store heat during the melting/charging phase and release it during the solidification/discharging phase, this results in its effective management of energy in many applications (Biswas *et al.*, 2018b).

2.2 PCMs Definitions and Classifications

Phase change materials (PCMs) can be defined as "*materials with high heat of fusion which melt and solidify at certain temperatures, absorbing and releasing a large amount of energy during the phase transition*" (Mustafa et al., 2022, Mustafa et al., 2022) (Memon, 2014; Ramponi and Blocken, 2012). However, other key definitions of PCMs as shown in Figure 1 emphasize their "storage and release of thermal energy" capability. This phrase appears consistently as a keyword in definitions proposed by relevant bodies studying PCMs. (Biswas *et al.*, 2018c).

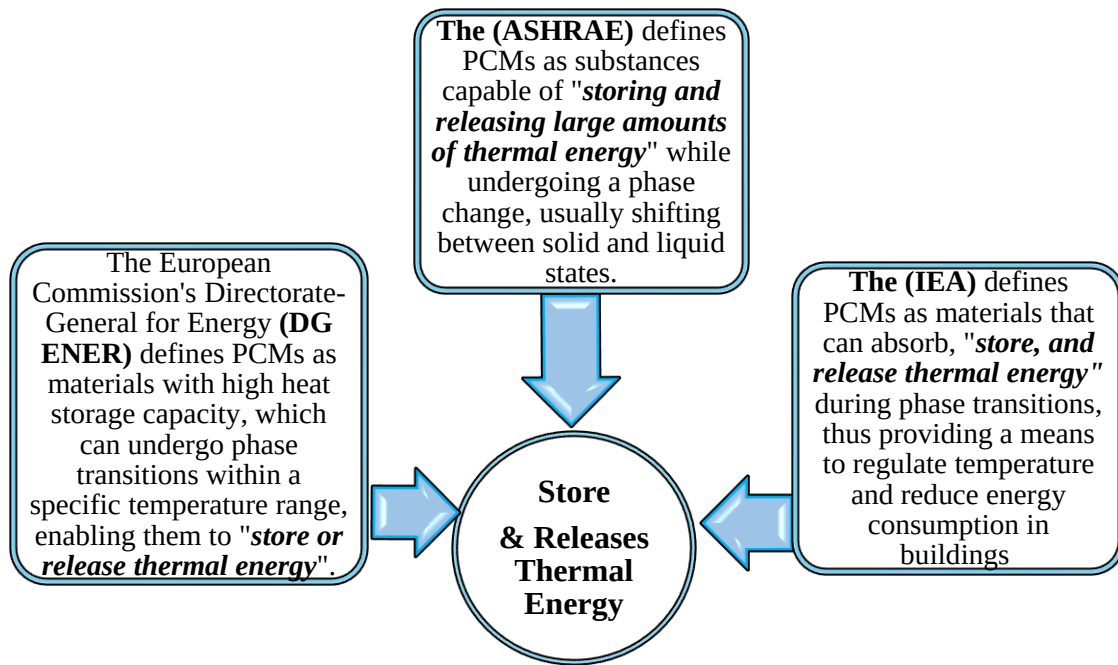


Figure 1: Definitions of PCM from related energy bodies

2.3 Classification and characteristics of PCMs

PCMs can be classified based on their phase change transition and chemical composition and properties (Zhan *et al.*, 2023b). Figure 2 shows the three-phase change sub-classification of PCMs which are: Solid-Solid PCMs, Solid-liquid PCMs, and Liquid-gas PCMs (Saeed, 2022).

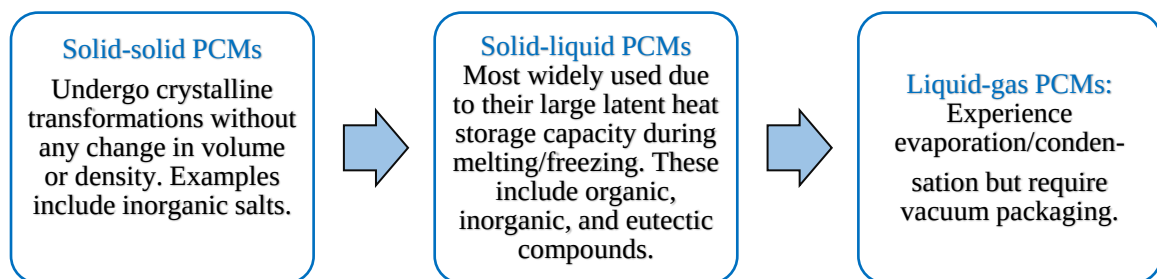


Figure 2: Phase change transition classifications of PCM

However, PCMs chemical composition classification such as organic, inorganic, and eutectic materials is depicted in Figure 3. The chemical composition classification of PCM with their common types commonly investigated for building envelope applications as studied by (Saeed, 2022) include:

Organic PCM: They are typically based on carbon-containing compounds, such as paraffin waxes, fatty acids nonadecane, and eicosane with melting points around 22-30°C. They usually have lower thermal conductivity and a narrower range of temperature stability.

Inorganic PCM: They often consist of salt or other inorganic compounds. They are generally characterized by: High thermal conductivity, higher latent heat of fusion compared to organic PCMs, stability over a wide range of temperatures. Examples include, InfiniteR PCM, Hydrated salts like calcium chloride hexahydrate, and sodium sulfate decahydrate.

Eutectic PCM mixtures: Combinations of organic or inorganic PCMs tailored for specific temperature ranges. However, in the building sector, Solid-liquid PCMs are predominantly used, due to their compatibility with typical construction materials and processes (Zahir *et al.*, 2023). Proper PCM selection depends on climatic conditions and integration within construction assemblies (Zhan *et al.*, 2023b).

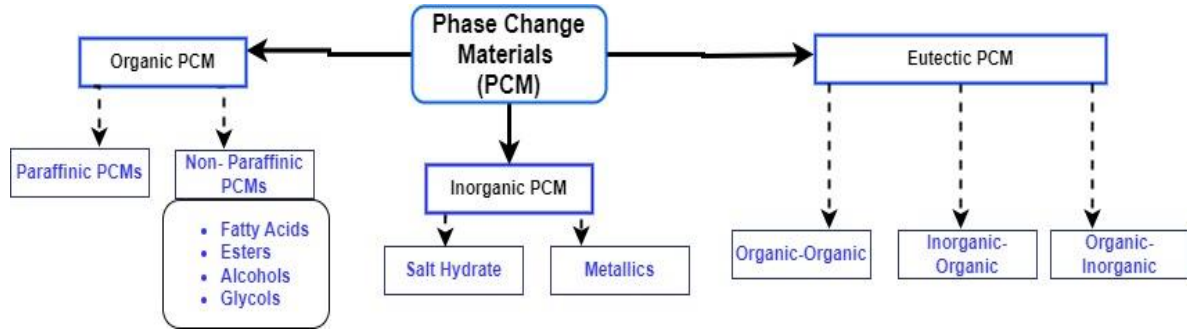


Figure 3: Chemical composition classification of PCMs.

Each of these PCM classes has a working temperature range and enthalpies as shown in Figure 4. Thus, some are more suitable for specific applications than others. However, (Kalnæs and Jelle, 2015) stated three common temperature ranges for the use of PCM as:

(i) Human thermal comfort: which focuses on maintaining indoor temperatures within a range that aligns with occupants' physiological needs (22–28°C). PCMs in this range buffer diurnal temperature fluctuations, absorbing excess heat during peak daytime temperatures and releasing it during cooler nights, thereby stabilizing indoor conditions without mechanical intervention (Panayiotou *et al.*, 2016; Zhou *et al.*, 2022)

(ii) Cooling applications ($\leq 21^\circ\text{C}$) involve PCMs designed to actively remove heat from environments, such as in refrigeration or radiant cooling systems. These PCMs absorb heat at lower temperatures to maintain sub-comfort conditions, often requiring integration with mechanical systems (De Gracia and Cabeza, 2015a)

(iii) For hot water applications from 29°C to 60 °C: are utilized primarily for thermal energy storage in domestic hot water (DHW) production, solar thermal systems, or industrial processes. These PCMs absorb excess heat during peak solar irradiation or waste heat generation and release it later to preheat water or maintain consistent temperatures in heating systems (De Gracia and Cabeza, 2015b; Lamrani *et al.*, 2021; Sharma *et al.*, 2015).

Investigating the common applications of phase change materials (PCMs) in buildings is essential for understanding their thermo-physical properties and types, particularly their subcategories and melting point ranges (Al-Absi *et al.*, 2020). PCMs are primarily used for temperature regulation, enhancing energy efficiency, and improving indoor comfort. During their phase change, they shift between solid and liquid states, allowing them to absorb and release heat effectively (Jha *et al.*, 2024). This behavior affects working temperature enthalpies, making them crucial for optimizing building performance. The diverse range of PCMs available enables tailored solutions for specific climate conditions and building requirements (Gao and Meng, 2023; Madhumathi and Sundarraja, 2014).

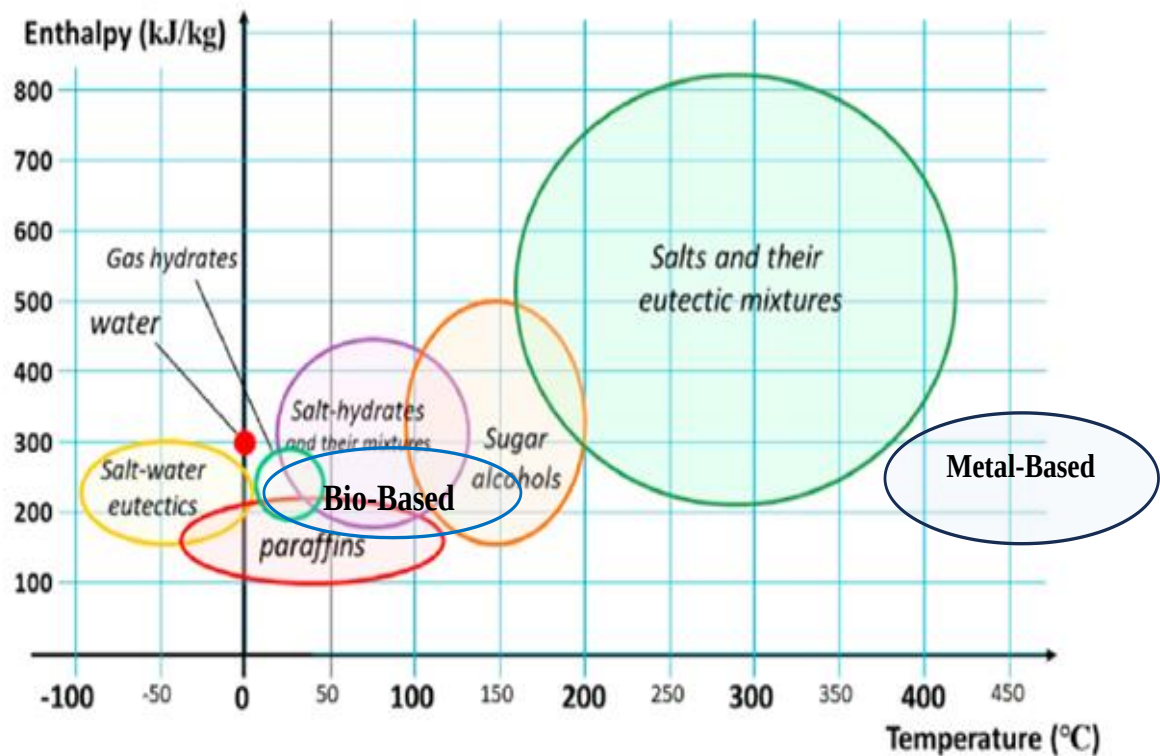


Figure 4: Different PCMs' working temperature range and enthalpy (Baetens *et al.*, 2010) (Zhan *et al.*, 2023b).

2.4 Inorganic InfiniteR PCMs Application in Exterior Building Envelopes.

Inorganic PCMs, such as salt hydrates and metallics, are increasingly applied to exterior building walls due to their high thermal conductivity and enhanced fire resistance, critical for extreme climates. Studies of (Zhou and Razaqpur, 2024a) demonstrated that inorganic PCMs like InfiniteR achieve 20–30% peak cooling load reductions in arid regions by leveraging rapid phase-change cycles, outperforming organic counterparts in high-temperature stability ($>45^{\circ}\text{C}$). (Ayadi *et al.*, 2024; Singh Rathore *et al.*, 2020a) further validated their efficacy in Saudi residential retrofits, noting 15–25% annual HVAC energy savings due to efficient diurnal heat buffering. Their non-flammable nature also addresses safety concerns in densely populated urban areas (Kosny *et al.*, 2012b), while cost analyses by (Ascione *et al.*, 2016, 2019) highlighted a 5–7-year return on investment (ROI) for inorganic PCMs in desert climates, justifying their upfront costs.

However, challenges like subcooling and phase segregation in inorganic PCMs necessitate macro-encapsulation or nano-additives to ensure durability. Research by (Sovetova *et al.*, 2019b) showed that encapsulated inorganic PCMs retained greater than 90% thermal efficiency over 10 years in harsh environments, mitigating degradation risks. (Al-Absi *et al.*, 2021; Al-Absi, Hafizal, *et al.*, 2024) emphasized their suitability for KSA's exterior walls, where reflectivity coatings combined with PCMs reduced surface temperatures by $8\text{--}12^{\circ}\text{C}$, enhancing synergy with passive cooling strategies. These findings collectively position inorganic PCMs as a resilient, scalable solution for energy-efficient buildings.

2.5 Thermal Energy Storage Systems in Building Envelopes

Heating and cooling account for over 40% of global building energy consumption, driving demand for thermal energy storage (TES) systems to manage load fluctuations and reduce operational costs (De Gracia and Cabeza, 2015a). TES technologies mitigate peak energy demands by decoupling supply and consumption, enhancing grid stability and efficiency (Cabeza *et al.*, 2011; Memon, 2014). Among TES methods, latent heat storage using phase change materials (PCMs) has emerged as the most effective for building envelopes due to its high energy density and ability to stabilize indoor temperatures (Cabeza *et al.*, 2011; Pomianowski *et al.*, 2013). The following section evaluates three TES approaches, which are: sensible, latent, and thermochemical contextualizing their relevance to energy-efficient building design in extreme climates.

2.5.1 Sensible Thermal Energy Storage (STES)

Sensible TES relies on materials absorbing or releasing heat without phase change, it is governed by the relationship $Q = M \cdot C \cdot \Delta T$, where Q is thermal energy, m is mass, C is specific heat, and ΔT is temperature difference. Common building materials like concrete and brick exhibit sensible storage, but their low energy density ($\sim 0.5\text{--}2$ kJ/kg) limits efficacy compared to latent systems (Sharma *et al.*, 2015). While cost-effective, sensible storage requires bulky volumes to match PCM performance, making it less viable for space-constrained retrofits (Friman Peretz *et al.*, 2019; Sharma *et al.*, 2015).

2.5.2 Latent Heat Energy Storage (LHES)

LHES cause PCM phase transitions (e.g., solid-liquid) to store 5–14 times more energy per unit mass than sensible methods (Kuznik and Virgone, 2009; Lamrani *et al.*, 2021). The total energy stored (Q) is governed by the equation, $Q = m \cdot (C_p \Delta T + L)$. Where m is mass,

and it combines sensible ($C_p\Delta T$) and latent (L) components, enabling compact solutions for building envelopes (Arıcı *et al.*, 2020). InfiniteR PCM, Paraffins, salt hydrates, and bio-based PCMs are widely studied for their ability to reduce cooling loads by 20–30% in arid climates (Al-Absi *et al.*, 2021). For instance, inorganic PCMs like salt hydrates achieve peak load shifting in desert regions by melting at 24–28°C, aligning with HVAC setpoints (Arıcı *et al.*, 2020; Zhou and Razaqpur, 2024b).

2.5.3 Thermochemical Energy Storage

Thermochemical systems store energy through reversible reactions (e.g., $XY + \Delta H \leftrightarrow X + Y$), offering high energy density but facing challenges like slow kinetics and material degradation (Farouk *et al.*, 2022b). While promising for long-term storage, their complexity and cost limit near-term adoption in buildings compared to latent systems.

It can be deduced from this whole section that PCM-based latent storage outperforms sensible and thermochemical methods in building applications, particularly in extreme climates, due to its balance of energy density, cost, and scalability. Studies in extreme climates like Saudi Arabia demonstrate PCMs reduce cooling loads by 10–30% while maintaining ASHRAE-compliant comfort (Amoatey *et al.*, 2022). This continues to position PCMs application as critical technology to achieving Vision 2030 energy resilience goals, warranting further research into material optimization.

2.6 PCM Selection Criteria for Integration in Building Envelopes

Phase Change Materials (PCMs) offer transformative potential for enhancing building energy efficiency in extreme climates, but their integration requires careful evaluation of thermophysical, chemical, and economic parameters. For instance, PCMs must exhibit a melting temperature range (10–30°C) aligned with local diurnal temperature swings to

optimize passive cooling and heating (Figueiredo *et al.*, 2017). For arid regions like Saudi Arabia, where peak daytime temperatures exceed 45°C, PCMs with phase-change thresholds near 24–29°C. are optimal to synchronize with HVAC setpoints and nighttime cooling (Al-Absi *et al.*, 2021). However, low thermal conductivity ($\sim 0.1\text{--}0.3\text{ W/m}\cdot\text{K}$) in organic PCMs like paraffin limits heat transfer rates, necessitating additives (e.g., graphene, metal foams) or encapsulation to enhance performance (Zhou and Razaqpur, 2024a). Table 1 records specific thermo-physical, chemical, kinetic, and economic characteristics necessary for selecting and implementing PCM in buildings envelopes. These characteristics are briefly enumerated below as follows:

a) Thermophysical Properties:

- **High latent heat capacity** ($\Delta H > 150\text{ kJ/kg}$) ensures sufficient energy storage per unit mass (Arıcı *et al.*, 2020).
- **Minimal subcooling** ($< 2^\circ\text{C}$) prevents incomplete phase transitions, which is critical for consistent thermal buffering (Lamrani *et al.*, 2021; Tunçbilek *et al.*, 2020).
- **Thermal durability** over $> 1,000$ cycles is essential for long-term efficacy in harsh climates (Sovetova *et al.*, 2019b).

b) Chemical Stability:

- **Non-flammability** and **low vapor pressure** are vital for safety in high-temperature environments (Cabeza *et al.*, 2011).
- **Compatibility** with construction materials (e.g., concrete, gypsum) this prevents degradation; salt hydrates like Glauber's Salt ($\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$) require corrosion-resistant encapsulation for structural integrity (Sharma *et al.*, 2015).

c) Economic Viability:

- **Cost-effectiveness** for inorganic options like InfiniteR (salt hydrates) dominate due to higher thermal stability (Souayfane *et al.*, 2019)(Al-Absi, Hafizal, *et al.*, 2024).
- **Lifecycle cost analyses** in desert climates show a 5–7-year payback period for PCM-enhanced walls, justifying upfront investments (Amoatey *et al.*, 2022).

This study prioritizes PCMs balancing these criteria for residential envelopes in extreme climates, focusing on selecting any one of the PCM materials like InfinteR PCM, salt hydrates and paraffin composites to be integrated into the whole building scale of residential villa building model.

Table 1: Selection requirements properties of PCM, adopted from (Memon, 2014; Silva et al., 2016).

Thermodynamic Properties	Chemical Properties	Kinetics Properties	Technical & economical properties
Suitable phase transitions	Long-term chemical stability	No super cooling	Availability in large scale
High thermal conductivity	Complete reversible melting/freezing cycle	Suitable range of crystallization	Effective low cost
Suitable phase transition temperature	Non-corrosive	High Nucleation rate	Applicability
Higher specific heat capacity & density	Non-flammable	High rate of crystal growth	Compatibility with other materials
Higher latent heat of fusion per unit volume	Non-Explosive		Simplicity
Physical stability with minimal volume alterations	Non-toxic		Effectiveness
Uniform melting and solidifying characteristics			Viability and reliability

2.7 PCM Integration Techniques in Building Envelopes

Phase Change Materials (PCMs) are integrated into building envelopes through diverse methods tailored to climatic demands, application and material compatibility. Figure 5 shows PCM general integration techniques in building envelopes. These techniques balance thermal efficiency, structural integrity, and cost-effectiveness, particularly in extreme climates like Saudi Arabia's, where diurnal temperature swings exceed 20°C (Al-Absi, Hafizal, *et al.*, 2024).

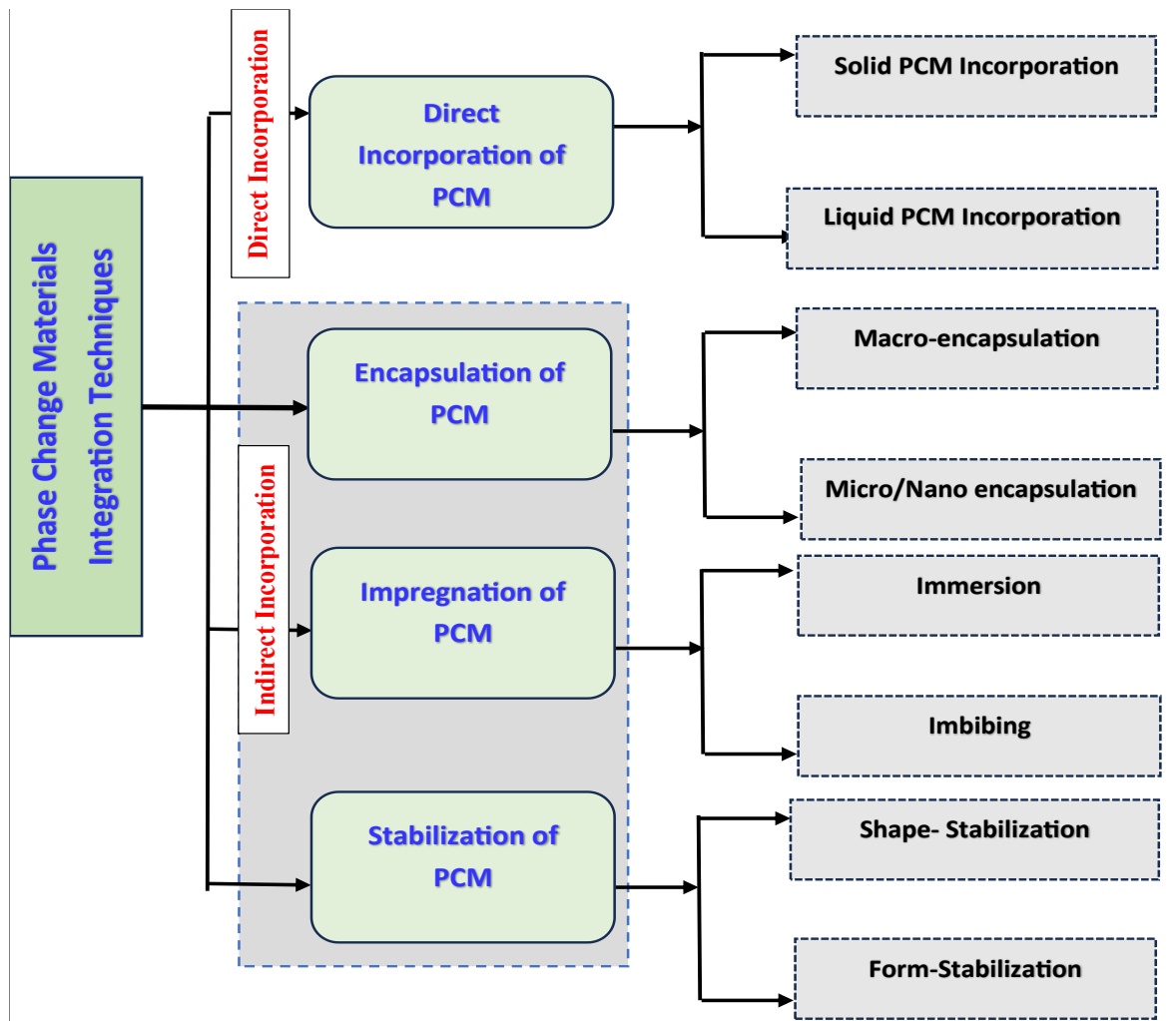


Figure 5: General PCM integration techniques in building envelopes.

Below are key methods evaluated for their efficacy in extreme climatic environments:

1. **Direct Incorporation:** PCMs are mixed into concrete or plaster during manufacturing, offering simplicity but risking leakage due to material incompatibility (Rathore *et al.*, 2022). While cost-effective, degradation under thermal cycling limits long-term viability in extreme heat (Zhou and Razaqpur, 2024a).
2. **Immersion:** PCM-filled tubes or panels are embedded within walls, providing localized thermal regulation. However, prolonged exposure to $>45^{\circ}\text{C}$ temperatures accelerate leakage, necessitating frequent maintenance (Zahir *et al.*, 2023).
3. **Encapsulation:**
 - a) **Microencapsulation:** PCMs are sealed in polymer shells (1–1000 μm) and infused into gypsum or coatings, preventing leakage and enhancing durability. This method achieves 20–30% cooling load reductions in desert climates (Liu *et al.*, 2020a, Liu *et al.*, 2020a).
 - b) **Macro-encapsulation:** Larger containers (1–10 mm) enable modular installation in tiles or boards, though reduced surface-area-to-volume ratios limit heat transfer rates (Liu *et al.*, 2020b; Park, Jeon, *et al.*, 2019).
4. **Shape-Stabilized PCMs:** PCMs are solidified with polymers (e.g., HDPE) into panels, ensuring leakage resistance and structural stability under thermal stress (Al-Absi *et al.*, 2021). These composites maintain greater than 90% latent heat capacity after 1,000 cycles in harsh conditions (Giro-Paloma *et al.*, 2016a).

5. **Form-Stable Composites:** PCMs embedded in porous matrices (e.g., aerogel, metal foams) achieve high thermal conductivity (0.5–2.5 W/m·K) while preventing leakage, making them ideal for exterior walls in extreme climates (Giro-Paloma *et al.*, 2016b).

The optimal techniques for extreme climates from the above findings are through encapsulation and form-stable methods which dominate due to their leakage resistance and adaptability to high-temperature fluctuations. Figure 6 shows diverse applications of PCM using the major integration techniques based on the needs of the user. For instance, microencapsulated and macro-encapsulated salt hydrates in Saudi residential walls reduced peak cooling loads by 28% while maintaining ASHRAE-compliant comfort (Sarri *et al.*, 2023). Conversely, direct incorporation is less viable in arid regions due to accelerated PCM degradation under thermal cycling (Al-Absi, Hafizal, *et al.*, 2024).

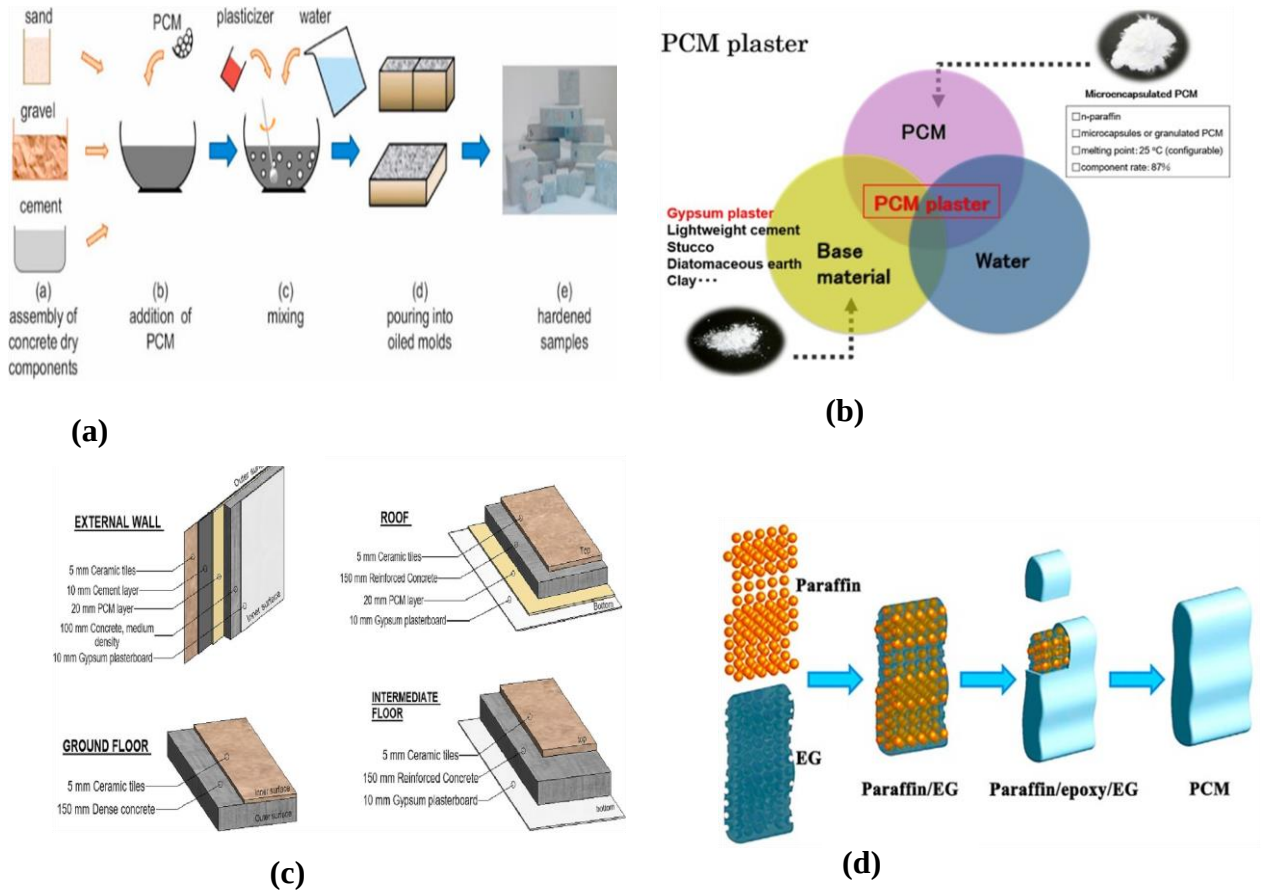


Figure 6: PCM Integration Techniques: (a) Direct immersion (Baetens et al., 2010) (b) Micro encapsulation plaster (Kusama and Ishidoya, 2017) (c) Macro encapsulation and (Nurlybekova et al., 2021) (d) shape-stabilized PCMs (Huang et al., 2019).

2.8 Variables influencing PCM performance in the building envelope

The thermal performance of phase change materials (PCMs) in building envelopes is governed by a complex interplay of variables that require meticulous optimization, particularly in extreme climates characterized by significant diurnal temperature fluctuations. Among these variables include thermodynamic properties (PCM melting temperature, thermal conductivity), position/configuration and integration method, quantity/thickness, climatic conditions, building design and materials, and containment

techniques as shown in Figure 7. The thermophysical properties of PCMs, such as phase-change temperature range, latent heat capacity, and thermal conductivity, are foundational to their efficacy. For instance, PCMs with melting points aligned to local climatic conditions (e.g., 24–28°C in arid regions like Saudi Arabia) demonstrate superior energy savings by leveraging latent heat storage during peak thermal loads (Al-Absi *et al.*, 2021). However, low intrinsic thermal conductivity ($\sim 0.1\text{--}0.3\text{ W/m}\cdot\text{K}$ in organic PCMs) often necessitates composite formulations with conductive additives like graphite or metal foams to enhance heat transfer rates, a challenge well-documented in desert climate applications (Jha *et al.*, 2024).

Climatic conditions further modulate PCM performance, as extreme temperature swings ($>20^\circ\text{C}$ diurnal variations) amplify phase-change cycles, while prolonged exposure to temperatures exceeding 50°C risks material degradation (Sovetova *et al.*, 2019b). The spatial **positioning of PCM** within the envelope also plays a critical role: interior placements near conditioned spaces synchronize better with HVAC operations, reducing cooling loads by 20–30% compared to exterior integrations, which face erratic thermal fluxes (Al-Yasiri and Szabó, 2021c). Additionally, the **quantity and thickness** of PCM layers must balance energy density and cost-efficiency; studies in arid zones indicate optimal thicknesses of 24–30mm, beyond which diminishing returns occur due to incomplete phase transitions (Al-Yasiri and Szabó, 2021a).

Building design parameters, such as orientation, glazing ratios, and thermal mass—interact dynamically with PCM performance. For example, south-facing façades in regions like Riyadh demand PCMs with higher thermal conductivity to manage intense solar gain, while material compatibility (e.g., corrosion resistance in salt hydrate-concrete composites)

ensures long-term structural integrity (Rathore and Shukla, 2020). **Containment methods**, including microencapsulation and shape-stabilized composites, address leakage risks under thermal stress, with macro-encapsulated systems showing >90% cyclic stability in harsh environments (Al-Absi, Hafizal, *et al.*, 2024; Rathore and Shukla, 2020). Figure 7 shows influencing factors that affect the effective thermal performance of PCM incorporated into building envelopes (Alshuraiaan, 2022).

These factors collectively underline the need for integrated simulation frameworks that model PCM behavior under localized climatic and architectural constraints, as discussed by parametric studies optimizing PCM-enhanced walls for Saudi Arabia's Vision 2030 energy targets.

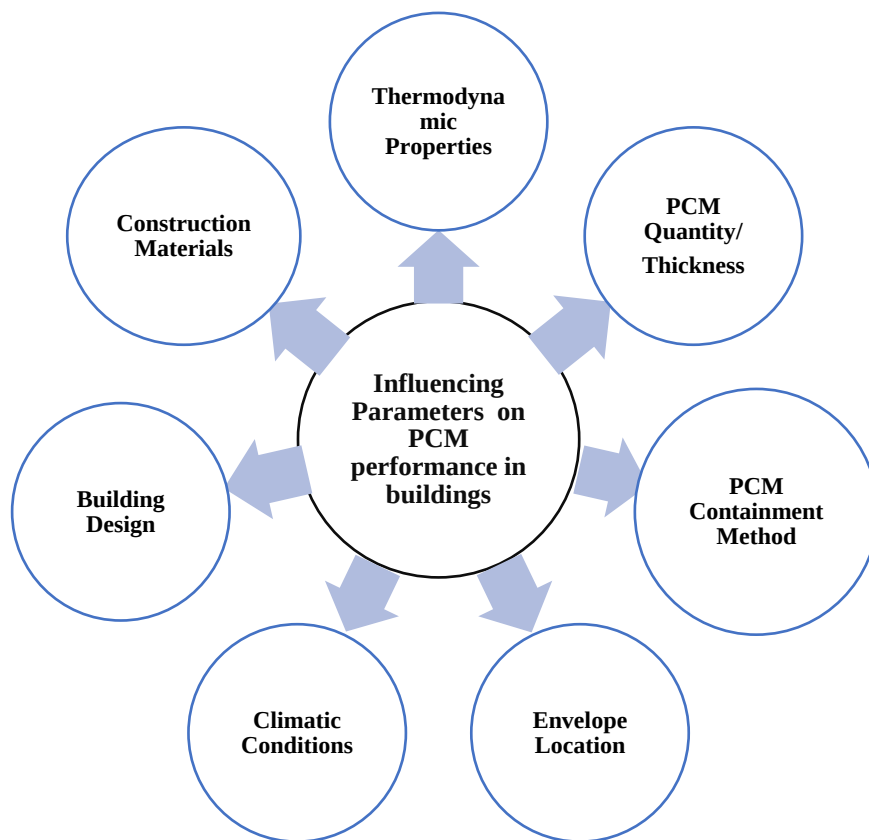


Figure 7: Parameters influencing thermal energy storage performance and effectiveness of PCMs

2.9 PCM Wall Envelope Integration at Whole-Building Scale

The integration of macro-encapsulated PCMs into building envelopes has been widely studied for its potential to reduce energy consumption and peak cooling loads across diverse climates. (Nghana and Tariku, 2016) demonstrated through EnergyPlus simulations that gypsum boards embedded with macro-PCMs reduced annual cooling loads by 4–8% and peak demand by up to 15% compared to conventional walls, though the efficiency varied with climate severity. Similarly, shape-stabilized PCM panels integrated into insulated envelopes in TRNSYS simulations yielded annual cooling energy savings of 15–30%, with peak load reductions exceeding 25% in regions with pronounced diurnal temperature swings (Nghana and Tariku, 2016). These findings align with Zhuang’s 2010 analysis of PCM-enhanced concrete wall panels in office buildings, where EnergyPlus simulations projected 18% annual cooling energy reductions and a two-hour peak load shift, critical for grid stability in extreme climates (Zhuang *et al.*, 2010).

Further validation comes from (Dardouri et al., 2023a), who modeled PCM-impregnated concrete blocks in residential buildings using IES-VE, observing 10–15% annual cooling savings and 30% peak demand reductions in arid climates. Notably, these studies highlight the dependency of PCM performance on local climatic extremes: for instance, in regions like Saudi Arabia, where summer temperatures exceed 45°C, PCMs with phase-change thresholds of 24–28°C maximize latent heat utilization without saturation (Al-Absi *et al.*, 2021). However, challenges persist in optimizing PCM selection for hyper-arid zones, where prolonged heatwaves (>50°C) risk incomplete phase transitions and material degradation (Zhou and Razaqpur, 2024b).

While these studies affirm PCMs' ability to dissociate energy demand from supply, gaps remain in scalability for typical residential villa buildings PCM optimal melting temperature, positions thickness and cost-benefit analyses under extreme conditions. Future research must prioritize climate-specific PCM calibration, as demonstrated by (Al-Yasiri and Szabó, 2021c) who worked on nano-enhanced PCMs in Dubai, which achieved 28% cooling load reductions through thermal conductivity improvements. Such advancements, coupled with Saudi Building Code (SBC 602/601, 2024) compliance frameworks, position PCMs as pivotal to achieving Vision 2030's energy resilience targets in thermally demanding environments.

2.10 Overview Status of Energy Consumption in KSA Building Sector.

The global built environment is a critical contributor to energy demand, with buildings accounting for the highest consumption and 28% of energy-related CO₂ emissions, as reported by the International Energy Agency (IEA, 2021). Residential buildings dominate this sector, representing 22% of global energy use, which is driven largely by heating and cooling needs in response to climatic extremes (UNEP, 2021). Projections suggest a 50% increase in building energy demand by 2050, with residential structures in hot-arid regions facing disproportionate growth due to rising temperatures, urbanization, and reliance on mechanical cooling systems (Iea 50 IEA, 2021). This trend requires the need for adopting innovative solutions, such as phase change materials (PCMs) to mitigate energy in thermally stressed building envelopes.

The energy effects are stark: residential cooling accounts for more than 70% of annual electricity consumption in major cities, peaking at 25% of national grid capacity during summer months (Dubey *et al.*, 2016; Rawa *et al.*, 2022) as shown in figure 8 where

residential buildings depicted the highest consumption of up to 45% of the total energy stock, amongst major sectors such as industrial, government, commercial, agricultural, and others key factors driving residential energy demand in KSA include deficiencies in building envelope design, such as poor insulation and excessive glazing, which elevate cooling loads by 30–40% (Al-Tamimi, 2022). Climate remains the primary catalyst, with summer peak electricity demand exceeding 60 GW, 70% of which is attributable to residential air conditioning (Jubran and Peter, 2019). Urbanization further compounds this issue; unplanned sprawl in cities like Riyadh has been shown to increase energy use intensity by 25% compared to compact, thermally optimized urban layouts (Belloumi and Alshehry, 2016).

Emerging research highlights the potential of PCM-enhanced building envelopes to address these challenges. For example, (Dardouri, Tunçbilek, *et al.*, 2023) demonstrated that PCM integration in walls and roofs can reduce cooling loads by 10–30% in extreme climates, while a case study in Kuwait by (Chung and Park, 2017) reported a 23% reduction in peak cooling demand through PCM retrofits. However, applications in KSA remain limited, with barriers such as high material costs, lack of localized performance data, and occupant behavior uncertainties requiring further investigation (Al-Homoud and Krarti, 2021).

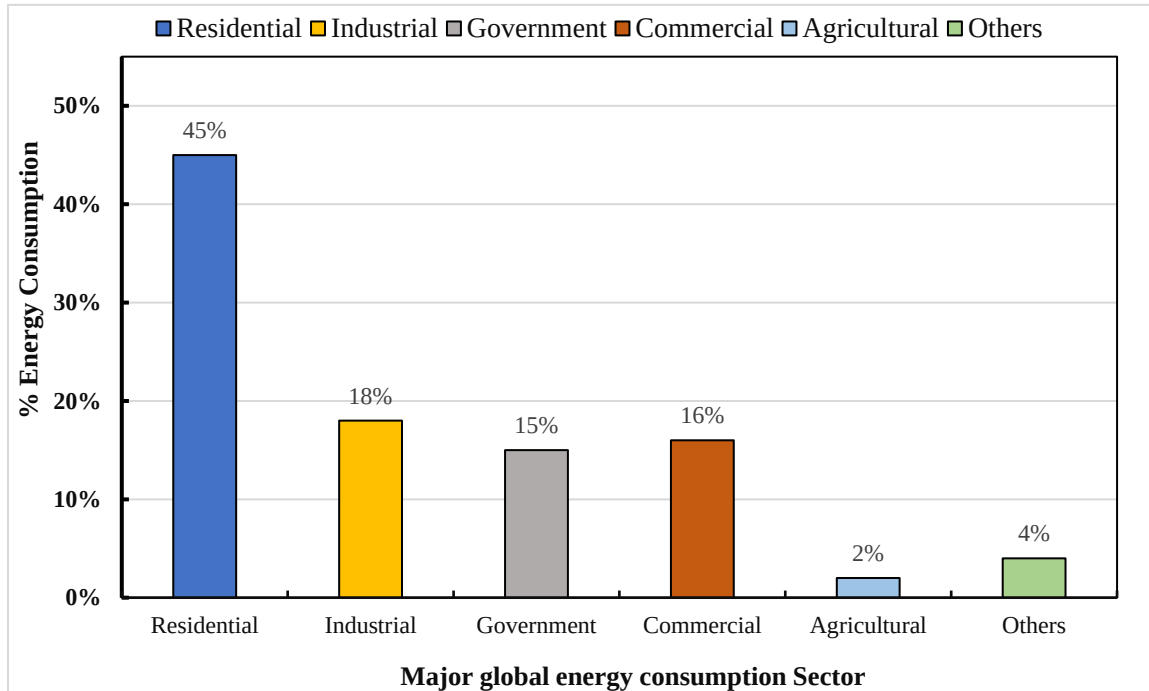
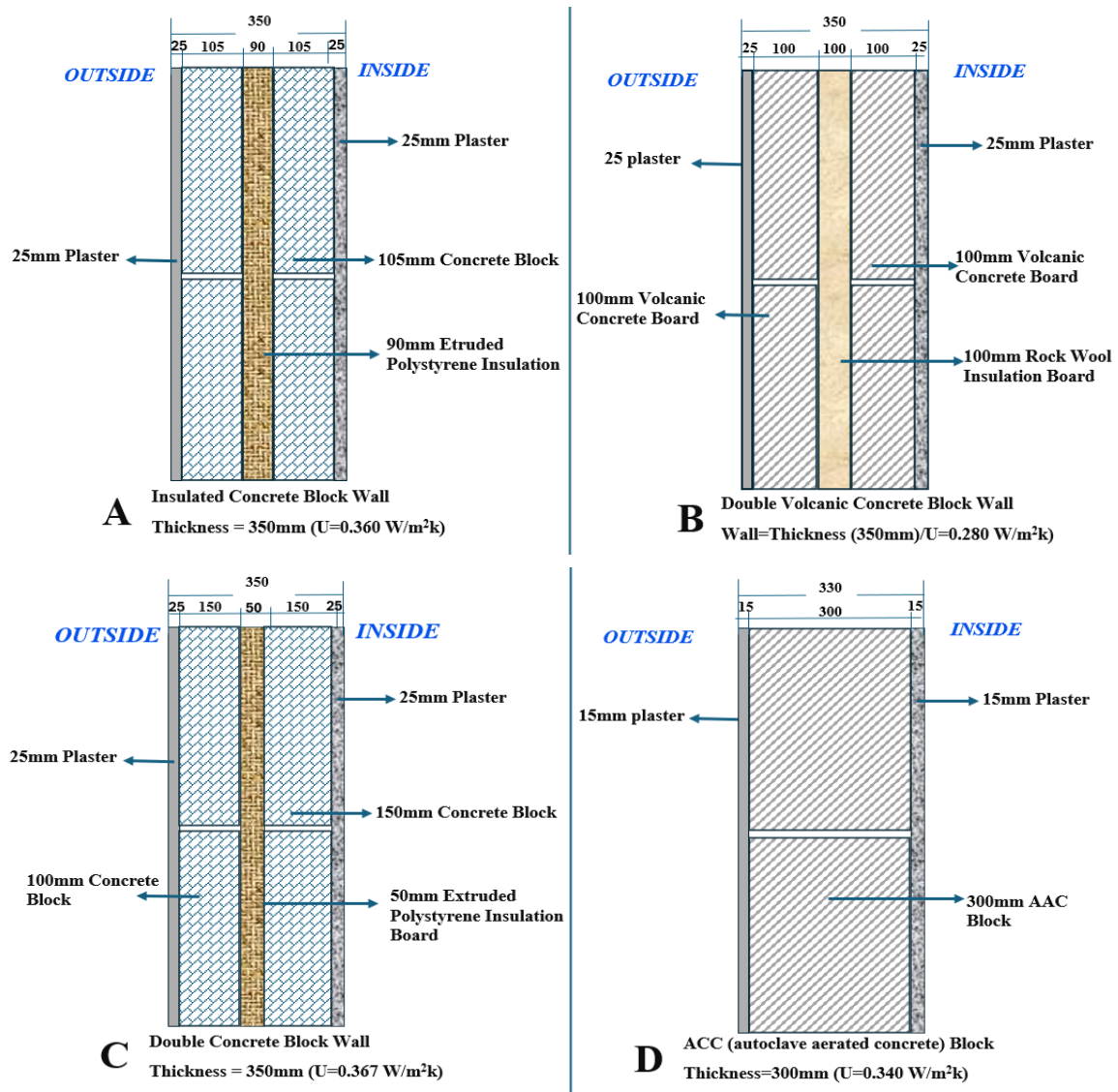


Figure 8: Electricity consumption by sector 2022, Source: (SERA, 2025) (MoE, 2024).

2.11 The Residential Buildings Wall Envelope System in Saudi Arabia.

It is worth noting that, building envelope plays a key role in mitigating heat transfer between indoor and outdoor environments, particularly in Saudi Arabia's extreme climate, where summer temperatures exceed 45°C. Residential buildings in the region predominantly employ uninsulated concrete or autoclaved aerated concrete (AAC) block walls with mortar joints and reinforced structural frames (Khan *et al.*, 2022; Saeed, 2022). These assemblies, while structurally robust, exhibit poor thermal performance due to high thermal mass and inadequate insulation, leading to significant heat absorption during the day and delayed release at night. This phenomenon is worsened by thermal bridging and air gaps (Park, Jeon, *et al.*, 2019). Field studies indicate that such walls often achieve thermal transmittance (U-values) of $\sim 3.0 \text{ W/m}^2\text{K}$, far exceeding the Saudi Building Code (SBC 601) threshold of $0.4 \text{ W/m}^2\text{K}$ (R-value: $2.5 \text{ m}^2\text{K/W}$), primarily due to inconsistent

insulation installation and quality control (Farouk *et al.*, 2022a). This demand is driven by conventional wall systems, such as the 10–15 cm outer concrete blocks separated by a 3–5 cm insulation from inner brick layers, which fail to meet modern energy standards. Figure 9 shows the investigated external wall assemblies of common composites wall system that are widely used in Saudi Arabia. The study investigated different walls systems for multicriteria analysis of selecting AC systems in buildings with other building envelopes (Salman Sabir Aljalal, 2023).



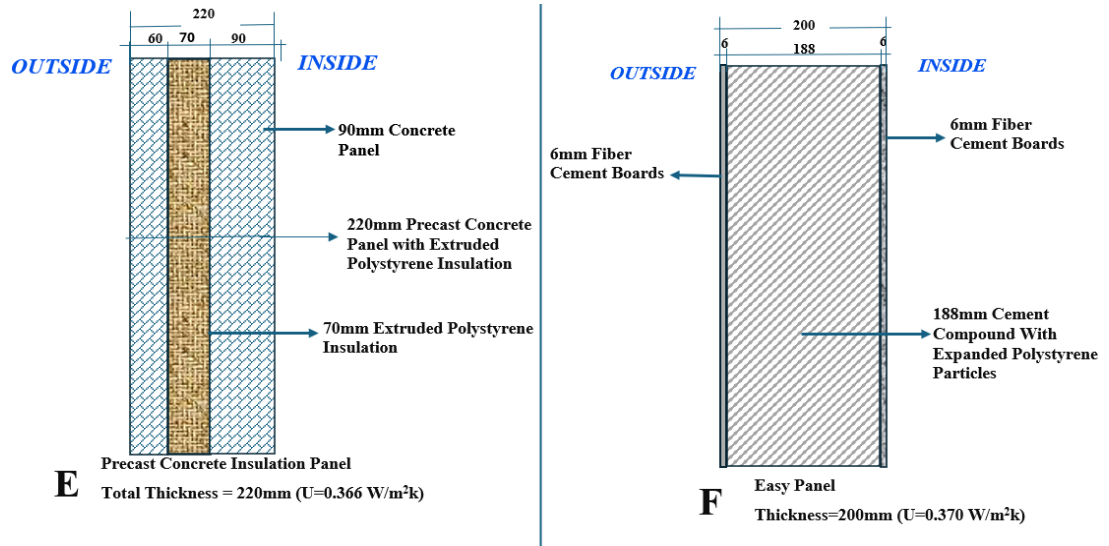


Figure 9: commonly use masonry wall system in KSA with their total thickness and calculated U=Values as shown (A, B, C, D, E and F)

2.12 A bibliometric review of PCM Integration from Previous Studies

Phase Change Materials (PCMs) have emerged as pivotal tools for enhancing building energy efficiency, particularly in extreme climates where thermal regulation is critical. Their integration into building envelopes via passive or active mechanisms addresses urbanization-driven energy demands and fossil fuel dependency while maintaining occupant comfort (Cai *et al.*, 2021a, 2021b). This section synthesizes key advancements in PCM applications, focusing on optimization strategies, integration techniques, and climatic adaptability. Table 2 below gives a summary of all the relevant studies to PCM integration into building envelopes for energy efficiency. It embeds Integration methods, area of PCM application, climatic regions or location, saving potentials key findings and computed references.

(Cai *et al.*, 2021b, 2021c) Framed PCM selection as a multi-objective optimization problem, identifying phase-change temperature, thickness, latent heat, and thermal

conductivity as critical parameters. Their study emphasized balancing energy conservation, thermal comfort, and economic/environmental factors through simulation-based methods, highlighting the need for climate-specific calibration. Similarly, (Cui *et al.*, 2017a; Jin *et al.*, 2013) explored optimal PCM placement in composite walls, revealing that exterior positioning maximizes heat flux reduction in most climates, while interior placement becomes advantageous when indoor temperatures rise unpredictably (Figure 10a-b). This duality shows the importance of adaptive PCM deployment based on dynamic thermal conditions.

(Dardouri, Mankai, *et al.*, 2023a) Demonstrated the efficacy of combining PCM with expanded polystyrene (EPS) insulation in brick walls, achieving 73–76% energy demand reductions in Mediterranean climates. Their work identified 6 cm as the optimal PCM thickness for outer-layer placement, though such results may vary in regions with higher thermal stresses, such as Saudi Arabia’s arid zones. (Liu *et al.*, 2020a; Yang, Qiao, *et al.*, 2018) advanced this by optimizing PCM panels at micro- and macro-levels: carbon nanotubes enhanced thermal conductivity, while metal fins improved heat distribution, reducing interior surface temperatures by 0.4°C and extending phase-change durations. These innovations highlight the potential of hybrid systems to overcome PCM’s intrinsic low conductivity.

Climate-specific optimization remains central to PCM efficacy. (Park, Jeon, *et al.*, 2019) validated PCM OH73 (23–24°C phase-change range) as optimal for South Korea’s temperate climate using DesignBuilder simulations, while (Kishore *et al.*, 2020) cautioned against uniform PCM application across climates. Their analysis of five U.S. cities revealed that improper PCM use could increase energy consumption, particularly in heating-

dominated regions, with 0.64 cm identified as the ideal thickness for summer performance. These findings align with (Fachinotti *et al.*, 2020; Kishore *et al.*, 2020) who used TMY data and finite element modeling to position PCM near wall centers for balanced thermal buffering across orientations.

In advancing knowledge for Extreme Climates: While prior studies offer foundational insights, gaps persist in applying PCMs to extreme arid climates like Saudi Arabia's, where diurnal temperature swings ($>20^{\circ}\text{C}$) and prolonged heatwaves ($>45^{\circ}\text{C}$) challenge conventional systems. Existing research focuses on individual components or limited climatic zones, often neglecting whole-building impacts. This study addresses these gaps by evaluating PCM-integrated exterior walls across two distinct KSA climatic zones, considering region-specific factors such as solar irradiance ($>1,000\text{ W/m}^2$), sandstorm resilience, and SBC 601 compliance (SBC 602/601, 2024).

The geographical span and whole-building focus distinguish this work from prior fragmented approaches, ensuring findings are scalable for Vision 2030's energy resilience targets. Future applications will benefit from calibrated PCM thickness, melting temperature and placement strategies optimized for KSA's unique thermal regimes, ultimately promoting sustainable building practices in extreme environments.

Table 2: Summary of Key findings from Previous Research on PCM Integration in Building Envelopes.

S/N	Integration Technique	Area of Application in Building	Climate/ Location	Saving Potentials	Key Findings	Ref.
1	Passive optimization (parameters, models)	Building envelopes	General/Hot climates	10–30% energy savings	Identified phase-change temperature, thickness, latent heat, and thermal conductivity as critical optimization parameters.	(Cai <i>et al.</i> , 2021c, 2021a)
2	Thin PCM layer placement in composite walls	Exterior walls	Varied climates	Peak heat flux reduction	Optimal PCM placement near the outer wall surface for thermal mass enhancement; interior placement beneficial for rising indoor temperatures.	(Cui <i>et al.</i> , 2017b; Jin <i>et al.</i> , 2016)
3	PCM + EPS insulation in brick walls	Double/single brick walls	Mediterranean climate	73.81–76.46% energy reduction	6cm PCM thickness (outer placement) maximizes energy savings; double-wall configuration outperforms single.	(Jin <i>et al.</i> , 2013; Park, Lee, <i>et al.</i> , 2019)

Table 2: Continued

S/N	Integration Technique	Area of Application in Building	Climate/ Location	Saving Potentials	Key Findings	Ref.
4	Micro-(carbon nanotubes) and macro-level (metal fins) PCM optimization	Wall panels	Temperate climates	0.4°C surface temp reduction	Optimized PCM panels improved heat storage and extended phase-change duration.	(Liu <i>et al.</i> , 2020a; Yang, Qiao, <i>et al.</i> , 2018)
5	PCM temperature optimization within comfort range	Mixed PCM systems	South Korea (temperate)	Max total energy savings	PCM OH73 (23–24°C phase-change) achieved optimal energy savings.	(Park, Jeon, <i>et al.</i> , 2019)
6	Numerical simulation with TMY data	Composite walls with TES	Global (simulated)	Variable by climate	Optimal PCM placement near wall center; validated via enthalpy-based FEM.	(Fachinotti <i>et al.</i> , 2020)
7	PCM thickness and placement analysis	Residential walls	5 U.S. cities (mixed climates)	Summer heat buildup reduction	0.64cm PCM thickness ideal; improper use increases energy consumption in heating seasons.	(Kishore <i>et al.</i> , 2021)

CHAPTER 3: METHODOLOGY

This section of the study provides a comprehensive overview of the methodology employed in this research. It begins with the selection of appropriate wall assemblies for further analysis, and then followed by the representative climate locations identification, and outlines the descriptions of the referenced building model, considering the identified climatic zones. The subsequent focus is developing models integrated with phase change materials (PCMs). Detailed procedural information regarding optimized energy simulations is presented, this makes it easier to examine how PCMs' latent heat impacts on building envelopes may affect energy efficiency.

Modelling and simulations are conducted using EnergyPlus/DesignBuilder and Revit Autodesk to evaluate building envelope performance. The study compares the baseline model with optimized envelope configurations, incorporating PCMs, using climate data from two representative weather locations in Saudi Arabia. The analysis aims to quantify energy savings and variations in heat gain between the PCM-integrated envelope and the conventional building without PCMs impacts on energy efficiency. Figure 10 depicts the methodological flow chart of the research procedure. It covers an outline of the study's planning, modelling and simulation, and model/ results validation analysis, conclusion and recommendation of the research study.

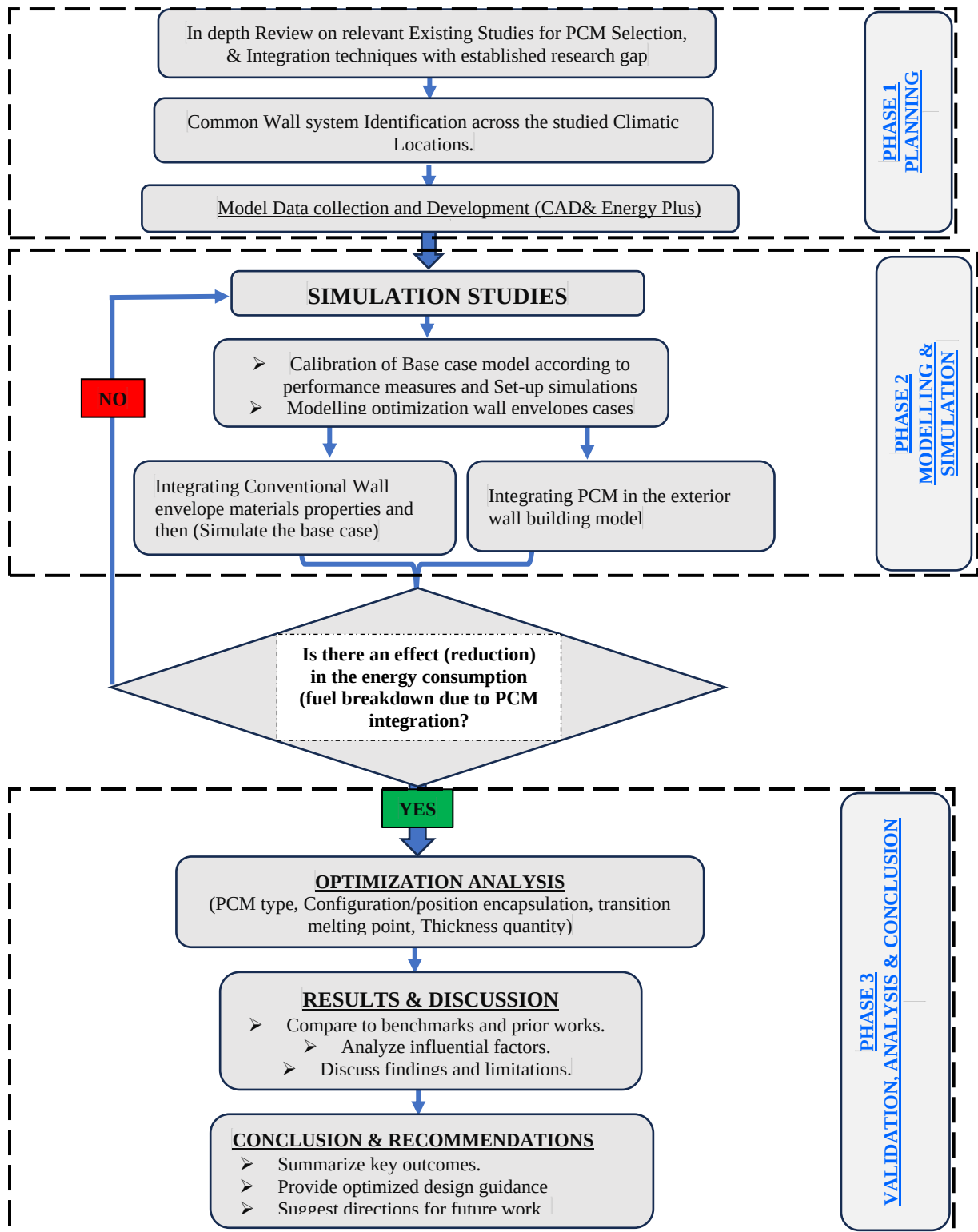


Figure 10: Research methodology flow chart.

3.2 The Adopted Wall System for the Base Case Building Model.

The selection of an optimal masonry external wall system for this study was guided by thermal resistance performance, regional construction practices, and compliance with Saudi Building Codes (SBC 601/602). A rigorous review of composite wall systems in extreme climates, particularly Saudi Arabia (Nizovtsev and Sterlyagov, 2024; Tunçbilek *et al.*, 2020), identified six candidate configurations as shown in the literature review section Figure 11 with varying U-values. These were evaluated against criteria such as heat transfer reduction, material availability, and alignment with local energy efficiency standards (Salman Sabir Aljalal, 2023).

Stakeholder interviews and construction sector surveys (Salman Sabir Aljalal, 2023) revealed that double concrete block walls are the most prevalent in residential projects across Saudi Arabia due to their balance of thermal inertia and cost-effectiveness. This system, compliant with SBC 601/602 (SBC 602/601, 2024), was adopted as the base case as shown in the methodology sections with its layered configuration properties.

Thermodynamic properties of these layers are detailed in table 3, with the composite wall achieving a U-value of $0.45 \text{ W/m}^2\cdot\text{K}$. The XPS insulation was prioritized for its low thermal conductivity and moisture resistance, critical in arid climates (Pekdogan and Basaran, 2017; Salman Sabir Aljalal, 2023). Lightweight concrete blocks enhance thermal mass while minimizing structural load a key consideration in high-temperature regions (Liu *et al.*, 2018; Yang, Qiao, *et al.*, 2018).

This configuration serves as the baseline for evaluating PCM integration in Al-Ahsa (extremely hot and dry) and Taif (hot and dry), ensuring comparability with conventional

practices while addressing the thesis objective of optimizing energy performance under extreme climatic conditions.

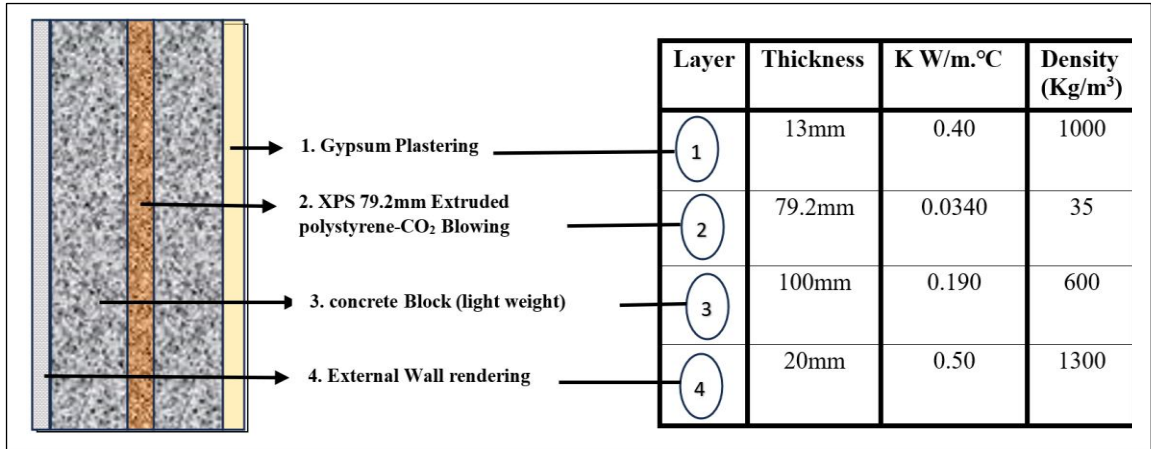


Figure 11: Exterior walls for building energy modeling (Jin et al., 2013) (Cai et al., 2021b).

Table 3: Material properties for the adopted wall systems (Jaradat et al., 2024)(Jin et al., 2016).

Materials	λ (W/m-K)	ρ (kg/m ³)	Cp (J/kg-K)	R (m ² K/W)	ρC_p (kJ/K m ³)
External renderings	0.500	1300	1000	1.43	1512
Masonry Block lightweight	0.200	520	840	6.67	600
Extruded polystyrene	0.03	35	1400	1.5425	33.33
Air Gap (6m)	0.51	1.2	1005	40.00	1.206
Gypsum plaster	0.400	1000	1000	5.88	1035.5
PCM (type)	0.54 (liquid) 1.09 (solid)	1540	3140z	0.012–0.14	4835.6

3.3 The Residential Base Case Model (BM) Selection

This section presents the typical residential building type selected as the base case for simulation processes. The masonry construction wall systems were identified as predominantly concrete, reflecting the fact that approximately 90% of residential buildings

in Saudi Arabia are constructed using this material (GSTAT, 2023 and Portal Saudi Census, 2022). The range of housing units in Saudi Arabia includes apartments in multi-story buildings, villas, traditional houses, floors in villas, apartments in villas, apartments in traditional houses, and floors in traditional houses (Al-Homoud and Krarti, 2021).

According to the General Authority for Statistics (GSTAT, 2022), the distribution of housing units in Saudi Arabia comprises apartments in multi-story buildings (51%), villas (17%), traditional houses (11%), floors in villas (7%), apartments in villas (6%), apartments in traditional houses (2%), floors in traditional houses (1%), and other categories (5%). Despite apartments constituting the majority, villas dominate energy consumption due to their larger footprints and higher cooling demands. (GSTAT, 2022) emphasizes that villas consume approximately 40% more energy per unit area compared to apartments, aligning with findings by (Alrashed and Asif, 2014) who reported villa energy intensities of 185 kW/m²/year versus 166 kW/m²/year for apartments.

Regional disparities further highlight this trend. For instance, detached villas in the Eastern Province consume 186 MWh/year, nearly double the energy use of apartments (75 MWh/year) due to higher cooling loads and less efficient building envelopes (Al-Saadi and Al-Jabri, 2020; GSTAT, 2022). These statistics reflect the urgent need for energy-efficient retrofits in villa-dominated regions, particularly given Saudi Arabia's Vision 2030 targets to reduce residential energy use by 30% (Saudi Vision 2030, 2024).

The villa building typology was chosen as it is the predominant type constructed in the two climatically diverse zones examined in this study (GSTAT, 2022). This choice aligns with the large-scale projects supported by the Sakani program, initiated by the Ministry of Municipal, Rural Affairs, and Housing. The villa's structure, primarily composed of

conventional concrete block or reinforced concrete, is rapidly gaining popularity in the region. Notably, its envelope system is directly exposed to the outdoor environment, making it particularly suitable for evaluating the potential integration of Phase Change Materials (PCMs) and their effect on maintaining a balanced mean radiant temperature influenced by incident solar radiation. In contrast, the exterior wall envelope systems of apartment buildings are less exposed due to internal wall partitions, complicating the assessment of their detailed Energy Use Intensity (EUI) values, which often necessitates data from multiple households within a single apartment unit.

Thus, the selection of the residential villa building typology for this extensive study is well-justified. These buildings are not only prevalent across the studied climatic zones but also present a unique opportunity to explore the integration of PCM technology in enhancing energy performance under extreme climatic conditions. By focusing on this building type, the research aims to contribute valuable insights into energy-efficient design practices and the potential benefits of PCM incorporation within the Saudi Arabian context.

3.4 Base Case Building Construction Components and Model Features

The base case traditional villa building as its floor plans and perspective view show in figure 12, designed to evaluate the thermal impact of advanced materials like PCMs, reflects residential construction practices in Saudi Arabia, with a focus on energy efficiency and thermal performance. The building's envelope components—walls, windows, and roof were meticulously modeled in CAD and simulated in DesignBuilder Version 7.3 (V7.3), incorporating U-values and material properties to ensure accuracy. The external walls have the largest percentage share of 45% as figure 13 shows the percentage distribution envelopes across the studied traditional villa. The external wall in comparison to the 29.1%

dominance from the roof and 2% from windows, it subjected to varying solar radiation across orientations, the external wall features a composite system with five layers: 13 mm gypsum plaster (inner), 100 mm lightweight concrete block, 79.20 mm XPS extruded polystyrene insulation, another 100 mm lightweight concrete block, and 20 mm external rendering, achieving a U-value of 0.310 W/m²K. This configuration balances thermal resistance and structural integrity, critical for minimizing heat transfer in extreme climates. In Saudi residential buildings, most exterior wall assemblies prioritize thermal performance due to extreme climatic conditions. According to the Saudi Building Code (Alyami *et al.*, 2022) and recent surveys by the General Authority for Statistics (GASTAT, 2023), standard walls consist of: 13 mm gypsum plaster (inner), 200 mm lightweight concrete block (commonly used in modern construction, replacing older double-layer block systems), 50 mm XPS extruded polystyrene insulation (thickness aligned with SBC 601 recommendations for hot-arid climates), 20 mm external cement rendering, This configuration achieves a U-value of 0.45–0.50 W/m²K, balancing cost-effectiveness and thermal resistance (Alrashed and Asif, 2014; GASTAT, 2023). Older buildings often lack insulation entirely or use thinner layers (≤ 25 mm), contributing to higher cooling loads (SERA, 2025).

For windows, double-glazed units with a 12 mm air gap are now standard in post-2018 constructions, as mandated by the (Saudi Energy Efficiency Center (SEEC), 2022) to meet a U-value of ≤ 2.5 W/m²K. Older buildings typically feature single-glazed windows (U-value ≈ 5.8 W/m²K), which account for $\sim 35\%$ of unwanted heat gain in residential villas (Sarri *et al.*, 2023).

Internal Venetian blinds were included to mitigate solar heat gain, aligning with regional practices for reducing cooling loads (Fagehi and Hadidi, 2022). The window-to-wall ratio (WWR) of 26.36% was determined based on typical villa designs in KSA, ensuring the model reflects real-world construction standards. The roof, though not detailed here, was similarly optimized for thermal performance, with materials and U-values selected to complement the wall and window systems.

By adhering to Saudi Building Codes (Alyami *et al.*, 2022) and incorporating region-specific design elements, the base case building serves as a robust foundation for evaluating PCM-enhanced envelopes. This methodological approach ensures the study's findings are both technically sound and practically applicable, addressing the thesis aim of optimizing energy performance in extreme climatic conditions.

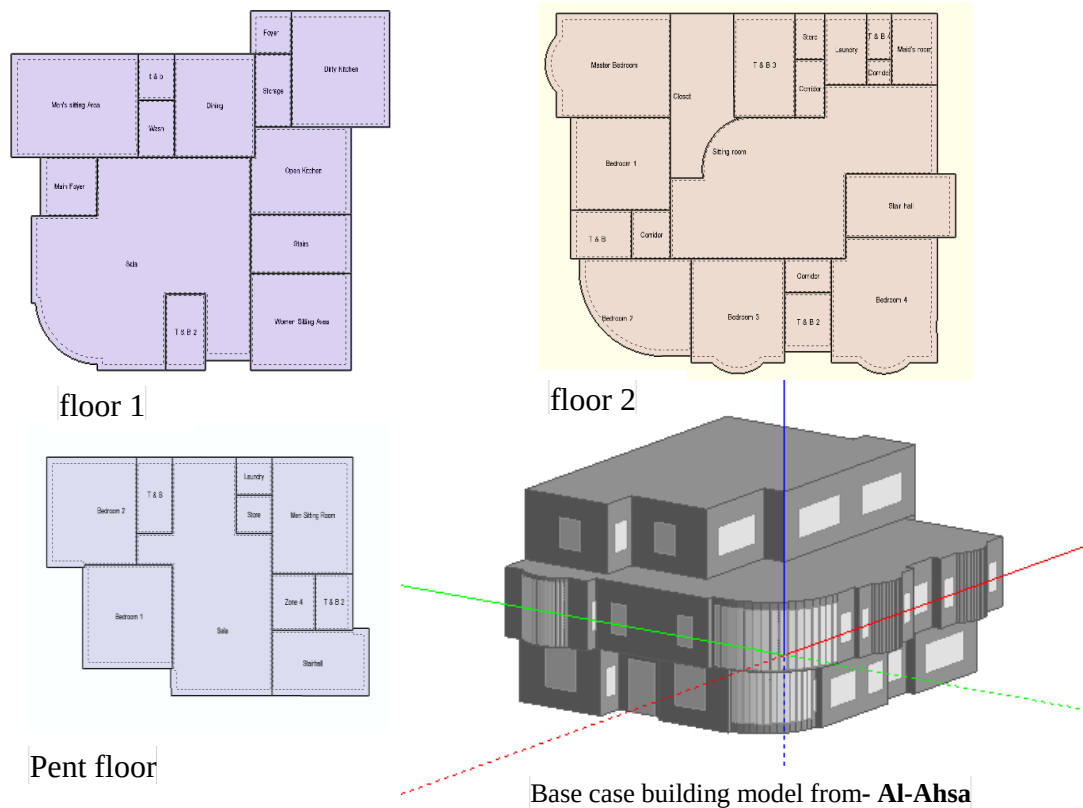


Figure 12: Traditional villa with apartments building adopted from(Mojeed Olawale, 2024) .

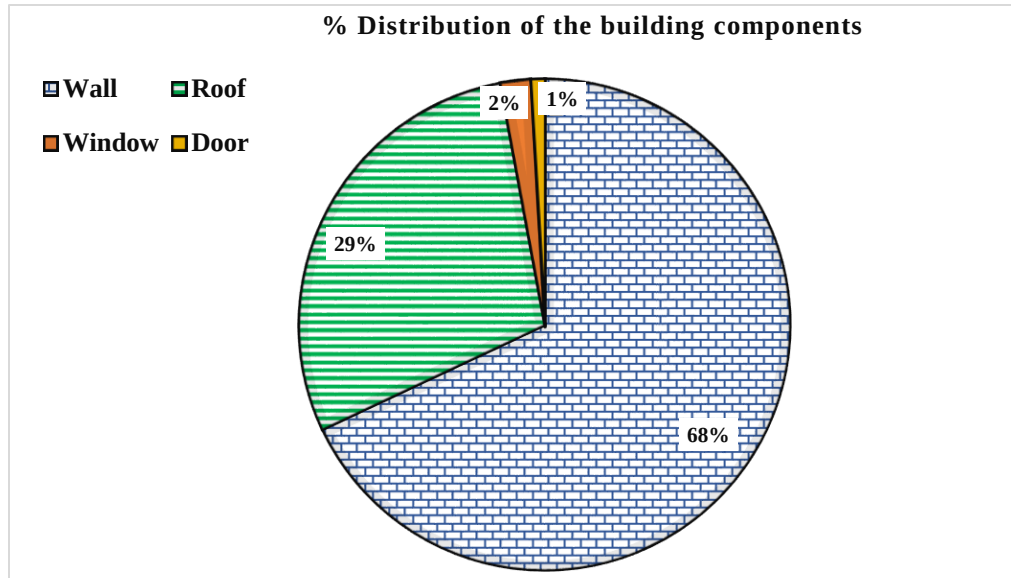


Figure 13: Envelope distribution across the traditional villa.

3.5 Climatic/Geographic Location Selection

This study evaluates PCM integration across two distinct climatic zones in Saudi Arabia—Al-Ahsa and Taif to address the diverse extreme weather conditions prevalent in the region. Al-Ahsa, characterized by a hot-arid climate with summer temperatures exceeding 45°C and minimal nocturnal cooling as shown in table 4. It presents the studied locations coordinates, average temperature of summer and winter day and nighttime. Al-Ahsa's weather contrasts sharply with Taif, which experiences milder temperatures due to its higher elevation (1,879 m) and seasonal variations, including cooler winters (Fagehi and Hadidi, 2022). These cities were selected to overcome the limitations of prior studies that generalized PCM performance across homogeneously hot climates in KSA, neglecting regional microclimatic nuances (Bagazi *et al.*, 2021; Zhan *et al.*, 2023c).

The choice is further justified by cooling/heating degree days (CDD/HDD) data and diurnal temperature fluctuations, which influence PCM efficacy. For instance, Al-Ahsa's extended summer (average CDD: 4,350) demands constant cooling, while Taif's moderate climate

(CDD: 2,980) introduces minor heating needs in winter (Table 4). Such variability enables a comparative analysis of PCMs under thermally opposing stresses, critical for optimizing phase-change temperatures (e.g., 35°C for Al-Ahsa vs. 25°C for Taif) and latent heat storage capacity (Faraj et al., 2020; Farouk et al., 2022a).

The climate data for this study were sourced from Typical Meteorological Year (TMY) files, which aggregate historical weather data (2004–2023) to represent a "typical" year of climatic conditions. These files were obtained from (Climate.OneBuilding, 2023) a peer-reviewed repository of TMY datasets for building simulations (Climate.OneBuilding, 2023). The TMY data for Saudi Arabia's studied locations (e.g., Riyadh and Jeddah) were formatted as .epw (EnergyPlus Weather) files, a standard format for energy modeling endorsed by the U.S. Department of Energy (U.S. Department of Energy (DOE), 2023). Figure 14 it depicts the two studied locations relative humidity (%), dry bulb temperature (°C), and global solar (Wh/m²) effect. This approach ensures alignment with regional energy consumption patterns, where air conditioning accounts for up to 70% of residential energy use in summer (Mojeed Olawale, 2024; Rathore and Shukla, 2020; Singh Rathore *et al.*, 2020b). By focusing on cities with stark climatic differences, the study advances localized PCM integration strategies, addressing gaps in holistic climate representation and supporting scalable solutions across KSA's two climatic zones.

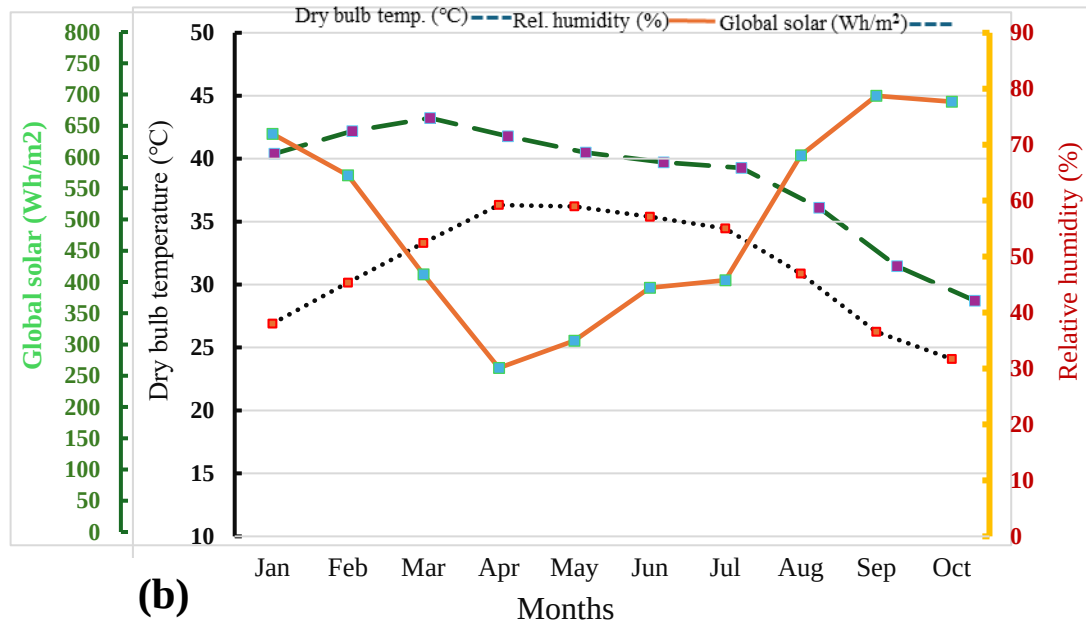
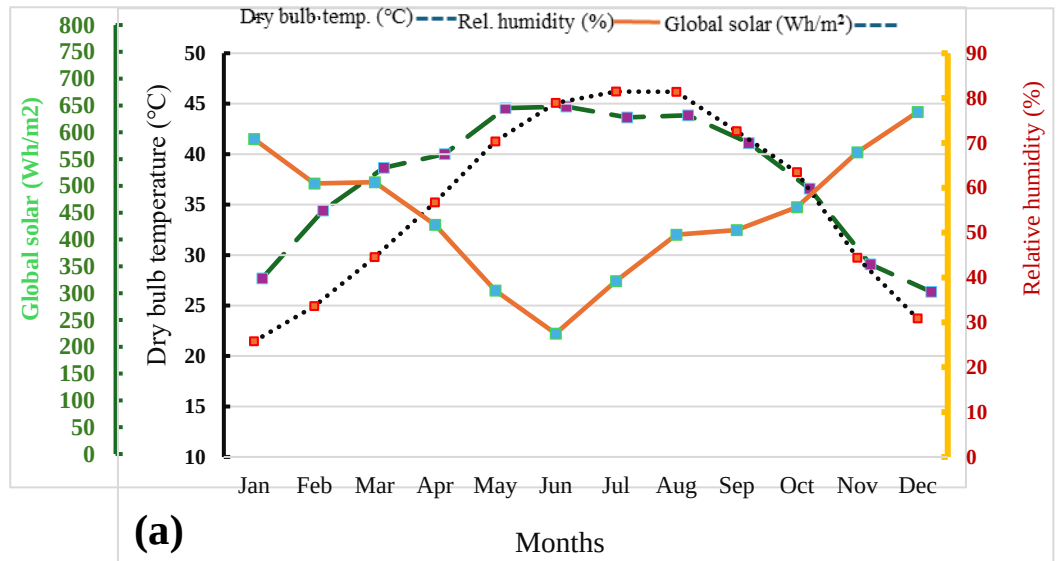


Figure 14: Typical metrological weather conditions (WMO_Region index.html, 2023) (a) Al-Ahsa (b) Taif.

Table 4: Average ambient temperatures of the selected representative climate of KSA: (Weather Spark)
(Jaradat et al., 2024)(Dardouri, Mankai, et al., 2023b).

Location	Geographic Coordinates	Average Temperature			
		Summer		Winter	
		Mid-June to Mid-September		Mid-December to Mid-March	
		Daytime	Nighttime	Daytime	Nighttime
Al-Ahsa	25.4°20'N 49.6° E	42.5°C	27.5°C	20°C	12.5°C
Taif	21°18'N 40°22'E	33°C	23°C	18°C	8°C

3.6 Simulation Plan Procedures

The simulation framework as shown in Figure 15 evaluates PCM-integrated building envelopes under Al-Ahsa's extremely hot and dry climate (koeppen, 2023). The base case villa floor area (638 m²) was modeled in Autodesk Revit using 2D/3D drawings from energy audits and translated to a BIM model (Mojeed Olawale, 2024). The BIM was exported as a gbXML file to DesignBuilder for energy modeling, where EnergyPlus simulated heat transfer dynamics using Typical Meteorological Year (TMY) data (2004–2023) sourced from Climate.OneBuilding.org (Climate.OneBuilding, 2023) in. epw format.

3.6.1 PCM Integration Workflow:

- PCM properties (melting temperature = 27°C, latent heat = 180 kJ/kg) were assigned to exterior walls using EnergyPlus's Conduction Finite Difference (CondFD) algorithm (Sergeeva and Rothfield, 2023). This method discretizes wall layers into nodal points to resolve phase-change heat transfer (Tabares-Velasco, 2012; Tabares-Velasco *et al.*, 2012).

- Parametric Optimization: Critical variables (T_m , ΔH , thickness) were iteratively adjusted using sensitivity analyses for solar irradiance, ambient temperature, and material conductivity (Jin *et al.*, 2016).
- Numerical Stability: Time steps (≤ 3 minutes), spatial discretization (3 nodes/cm), and convergence criteria (surface temperature $\leq 0.01^\circ\text{C}$) were configured per PCM simulation protocols (Kuznik and Virgone, 2009).

Post-processing focused on energy demand (kWh/m^2) and operative temperature (OT), with results cross-validated against empirical studies (Al-Saadi and Zhai, 2015).

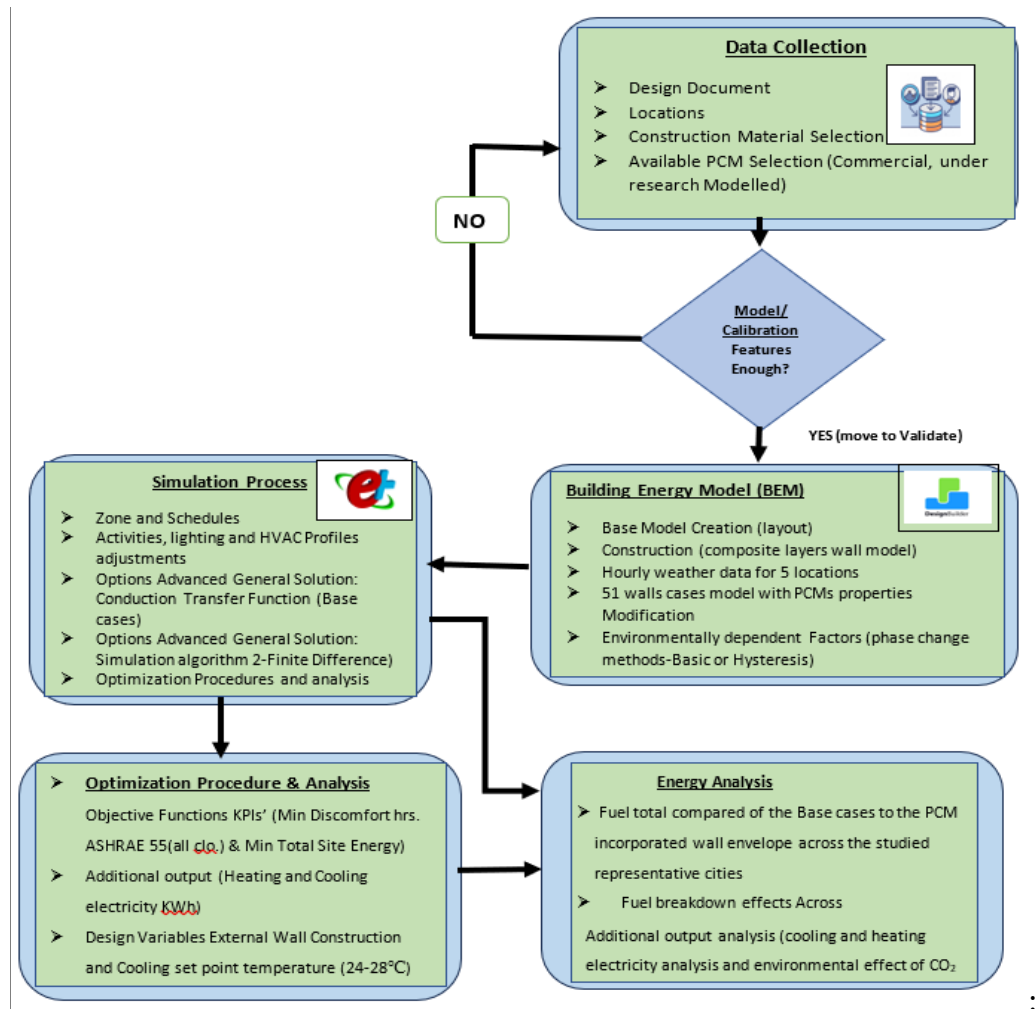


Figure 15: Approach to the simulation procedure.

3.6.2 Model Calibration Procedures, Assumptions and Energy Profile Analysis.

The calibration of the baseline building energy model was critical to ensuring the reliability of PCM performance assessments. Following ASHRAE Guideline 14 (ASHRAE, 2016a), the model was validated against 12 months of utility data (2022–2023) from the Al-Ahsa case study villa, achieving an annual Normalized Mean Bias Error (NMBE) of 1.7% and a Coefficient of Variation of Root Mean Squared Error (CVRMSE) of 11.8%, both within acceptable thresholds ($\text{NMBE} \leq 5\%$, $\text{CVRMSE} \leq 15\%$). Monthly deviations shown in table 5 reveal seasonal variations, with higher errors in summer months due to occupant behavior uncertainties (e.g., unplanned travel during peak heat) and lower errors in winter, where HVAC usage is more predictable.

Table 5: The actual case and simulated Building model calibration.

Months	Actual Consumption (kWh)	Simulated Consumption (kWh)	Non-Biased mean error- NMBE (%)	Final CVRMSE (%)
Jan	1581.8	1575.8	0.4%	0.19%
Feb	1614.8	1602.5	0.8%	0.39%
Mar	1661.5	1679.7	1.1%	0.58%
Apr	1734.7	1757.4	1.3%	0.72%
May	2936.3	2970.3	1.2%	1.08%
Jun	4067.2	4087.5	0.5%	0.64%
Jul	5058.2	5164.2	2.1%	3.36%
Aug	4663.6	4700.0	0.8%	1.15%
Sep	4246.0	4147.0	2.3%	3.13%
Oct	4484.5	4368.3	2.6%	3.68%
Nov	3636.8	3718.6	2.2%	2.59%
Dec	2198.8	2093.0	4.8%	3.35%

3.6.3 Calibration Process and Practical Assumptions

In the calibration process refined key parameters through iterative adjustments were executed as follows:

- **Setpoints:** Cooling was set to 25°C (active) and 28°C (setback), aligning with ASHRAE 55 (ASHRAE 55, 2022) and resident surveys.
- **Regional Schedules:** Ramadan and Hajj holidays (23 days/year) were incorporated, reducing daytime occupancy by 40% during these periods.
- **Infiltration Rates:** Adjusted to 0.5 air changes per hour (ACH) at 50 Pa, based on blower-door tests of similar Al-Ahsa villas (Sarri *et al.*, 2023).
- **HVAC Efficiency:** A fixed coefficient of performance (COP) of 3.2 was assumed for the split-system AC, though real-world performance varies with part-load conditions.

September Energy Dip Explanation from the calibration as shown in figure 16:

The notable dip in September's simulated energy use (2.3% NMBE) arises from three interrelated factors:

- **Climatic Transition:** Al-Ahsa's average temperature drops from 46°C (August) to 38°C (September), reducing cooling demand. TMY data smooths September 2022 heat waves (42°C actual vs. 38°C simulated) (Climate.OneBuilding, 2023).
- **Post-Hajj Occupancy:** It is assumed that the building occupants travel-related vacancy lowers HVAC use by 30%, partially captured in schedules and this led to the consumption profile variance.
- **Night Ventilation:** Cooler nights (24°C) activate natural ventilation, overestimated in the model due to simplified airflow assumptions (Bakker *et al.*, 2020).

While the model successfully replicated annual energy consumption trends as shown in Figure 15 from the actual consumption bill data from the building occupants, discrepancies in September highlight the challenges of capturing short-term climatic anomalies and occupant behavior variability. These limitations point out the importance of coupling simulation with real-time monitoring in future work.

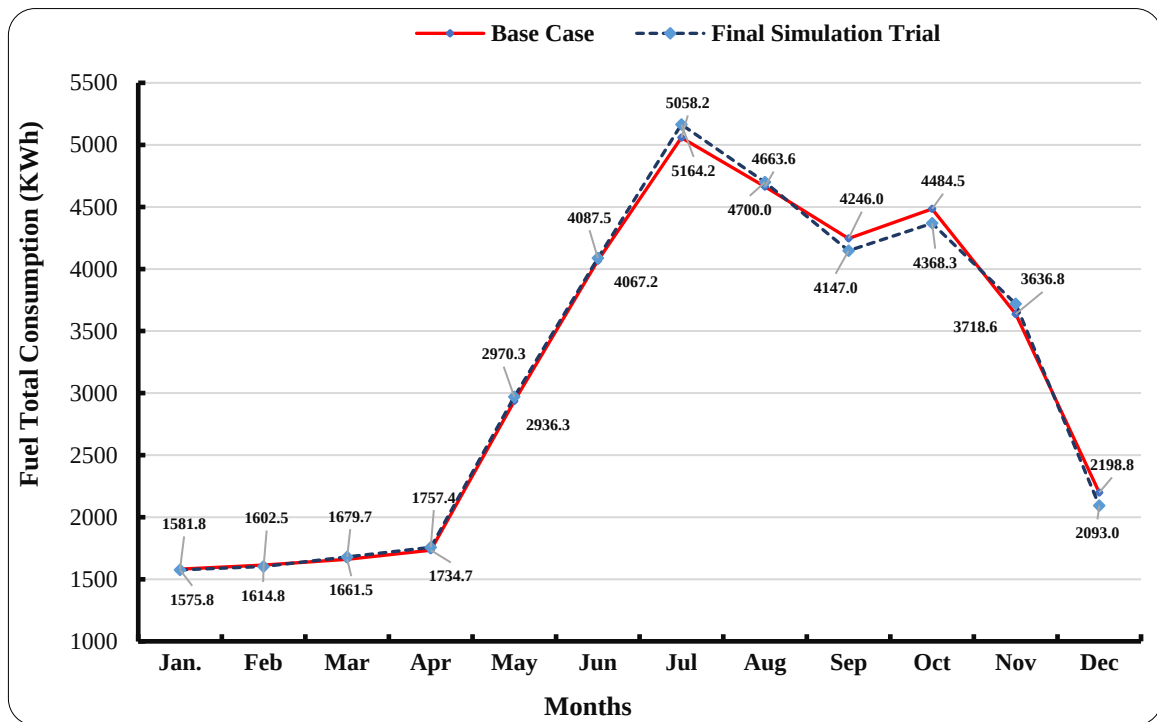


Figure 16: Calibration and validation of the building model

3.7 Assessment Criteria

This section outlines the key criteria used to evaluate the performance and effectiveness of Phase Change Material (PCM) integration within exterior building wall envelopes aimed at achieving energy savings. The assessment focuses on key thermochemical properties (melting temperature and quantity) of PCM through energy simulations, comparing scenarios with and without PCM integration. The evaluation parameters for the two

climatic conditions include the examination of optimal transition melting temperatures, selection of PCM types, configuration of PCM layers, and the thickness or quantity of PCM layers. The highlights of the assessment criteria for the selected PCM for detailed investigation throughout the study are shown in Table 6.

To identify the optimal values for significant energy savings, multiple quantitative analyses were conducted using DesignBuilder's Genetic Algorithm for each criterion. The total site electricity consumption (in kWh) and the minimum hours of discomfort were established as objective functions, with external wall construction and set point temperature serving as the design variables. This comprehensive approach aims to provide valuable insights into the potential benefits of PCM integration in enhancing energy performance under extreme climatic conditions.

Table 6: Properties of the investigated PCMs

Types of PCMs	Compound/ Category	Melting Points (21- 39°C)	Latent Heat of Fusion [J/g]	Specific heat [J/kg.K]- Liquid/ Solid	Thermal Conductivity [W/m.K] Liquid/Solid	PCM SHEET Thickness (mm)
InfiniteR PCM (Glauber Salt, Na₂SO₄.10H₂O)	Inorganic	23,25, & 39	200	2000/3140	0.54/1.09	6,12,18 and 24

3.8 The PCMs Selected for Detailed Evaluation

The selection of PCMs for building applications requires a multi-criteria framework to address trade-offs in properties such as phase-change temperature, latent heat, and cost (Liu *et al.*, 2018; Navarro *et al.*, 2019; Zhang *et al.*, 2018) . For Al-Ahsa and Taif, InfiniteR PCM (Glauber Salt) was prioritized and selected due to its alignment with regional climatic demands, software compatibility, and validated performance in extreme conditions. With

a phase-change range of 23–30°C, InfiniteR effectively bridges the diurnal temperature swings in Al-Ahsa (45°C daytime, 30°C nighttime) and Taif (35°C daytime, 15°C nighttime), enabling optimal latent heat storage during peak cooling periods (Farouk *et al.*, 2022b; Jelle and Kalnæs, 2017; Kalnæs and Jelle, 2015). Furthermore, its predefined hysteresis properties in DesignBuilder enhance simulation accuracy by accounting for real-world phase-change delays, unlike manually calibrated alternatives that introduce uncertainty (Dardouri, Mankai, *et al.*, 2023c; Jaradat *et al.*, 2024).

Material performance further justified its selection: InfiniteR’s high thermal conductivity (0.6 W/m·K) and latent heat (210 kJ/kg) surpass competing PCMs like WinCoEnerCiel (150 kJ/kg), ensuring rapid heat absorption and release under extreme temperatures. Additionally, its inorganic composition ensures long-term stability in Saudi Arabia’s UV-intensive climate, minimizing degradation risks (Bagazi *et al.*, 2021). The PCM’s commercial availability and prior validation in arid regions (Jelle and Kalnæs, 2017) further streamline reproducibility, avoiding redundant experimental trials for similar materials (Yang, Zhu, *et al.*, 2018; Yang, Qiao, *et al.*, 2018). By focusing on InfiniteR, this study enables targeted optimized parameter analysis of thickness and placement within wall assemblies, directly advancing the thesis objective of quantifying energy savings through validated, climate-specific PCM integration. Conclusively, Table 7 summarizes the properties of different types of PCM based on their applications and multi-criteria conditions that will lead to the adoption of any of them. It is evident that InfiniteRPCM exhibits moderate thermal properties, long-term chemical stability, a moderate and suitable range of crystallization, good availability, cost-effectiveness, and applicability, especially

in buildings. This led to its selection for this research, as it has been studied by (Al-Absi *et al.*, 2021; Jaradat *et al.*, 2024).

Table 7: PCMs selection properties for application in building envelope.

TYPES OF PCM	PCM SELECTION PROPERTIES											
	THERMOCHEMICAL PROPERTIES			PHYSICAL PROPERTIES			KINETIC PROPERTIES			TECHNICAL AND ECONOMIC PROPERTIES		
	Suitable phase transition	Higher specific heat capacity and density	Higher latent heat fusion	Long term chemical stability	Non-Flammable	Non-Toxic	No Super cooling	Suitable Range of Crystallization	High Nucleation Rate	Availability in Large Scale	Effective Low Cost	Compatibility with other Materials
BioPCM/(Paraffin Wax)	►	II & I	III	■	►	►	►	►	II	III	II	►
Bio-based fatty acid	►	III & II	II	▲	►	►	►	►	III	II	II	►
InfiniteR-PCM (Glauber Salt, Na ₂ SO ₄ .10 H ₂ O)	►	I & III	III	II	►	►	II	►	III	III	I	II
Magnesium sulfate heptahydrate (MgSO ₄ •7H ₂ O)	►	I & II	II	■	►	►	II	►	II	II	II	►
WinCo Technologies Enerciel PCM	►	II & I	III	■	►	►	►	►	III	II	II	►
Polypropylene + Elastomer	►	II & II	III	■	►	►	►	►	III	III	II	■

NOTE: ► = Yes criteria, ■ = Good Criteria, ▲ = Excellent Criteria, I = Low criteria, II = Moderate Criteria, III = High Criteria

3.9 PCM Melting Temperature or Range.

This study evaluates energy performance of the integrated PCM in external building walls based on different melting points such as (21,23,25,27,29,31,33,35, 37 and 39) to select the optimum transition temperature at which the PCM will melt at its latent phase. The assessment focuses on investigating InfiniteR PCM with transition melting temperature, layer configurations and quantity or thickness all in a single optimization technique using objective functions and design variables.

It is worth noting that the decision to select a melting temperature to be used is the first step and it should be within the ASHRAE 55 thermal comfort range. It is recommended that the melting temperature must have a range of 15-30°C (Jelle and Kalnæs, 2017) or 20-32°C (Kasaeian *et al.*, 2017) for building applications. This study considers melting temperatures beyond these recommendations, due to the extreme air and surface temperature of the studied external walls at the prevailing weather locations.

3.10 PCM Layer Position/Configuration

The effects of Phase Change Materials (PCMs) positioning are significantly influenced by the internal HVAC set points and external weather conditions. This study specifically examines the optimal PCM configuration within the external wall layers of the building envelope. A single-layer PCM in solid panel form is evaluated in three distinct positions: towards the exterior layer (EXT), in the middle (MID), and towards the interior layer (INT). Given that the base case building envelope incorporates extruded polystyrene (XPS), this investigation considers two wall cases for PCM positioning. Generally, the study evaluates two Wall Cases, each representing distinct composite wall assemblies, and their corresponding Scenarios for PCM integration. Wall Cases define structural configurations

(e.g., with or without XPS insulation), while Scenarios describe PCM placement strategies within these configurations:

1. Wall Case 1: Base wall with XPS insulation (U-value = 0.31 W/m²K).

- Scenario 1: PCM added to the interior surface of the XPS-insulated wall.
- Scenario 2: PCM replaces the XPS layer entirely, maintaining the same thickness.

2. Wall Case 2: Base wall without XPS insulation (U-value = 0.52 W/m²K).

- Scenario 1: PCM added as a standalone layer to the non-insulated wall (Figure Z).

This framework isolates the impact of PCM placement and insulation interaction. For example, in Wall Case 1, Scenario 2 tests whether PCM can functionally substitute traditional insulation (XPS), while Scenario 1 evaluates synergistic effects. In Wall Case 2, PCM compensates for the absence of XPS, addressing retrofit limitations in older Saudi housing (Alrashed and Asif, 2014).

The first scenario (Case 1) involves adding PCM to the base case wall at various positions: EXT, middle exterior (MID-EXT), middle interior (MID-INT), and INT surfaces. In contrast, the second scenario (Case 2) examines replacing PCM in the same MID location with a material of equivalent thickness to the existing 79.2mm XPS. Additionally, wall case 2 focuses on the application of PCM for retrofitting pre-SBC buildings, where PCM is introduced to a base wall lacking XPS insulation.

The PCM layer configuration, transition temperature, and layer thickness are treated as combined design variables in this analysis. These variables, alongside thickness and transition temperature, are simultaneously simulated and optimized, while all other layers and compositions remain constant throughout the evaluation process. Other wall scenarios

without PCM, which are also used in energy analysis, as depicted in Figure 17, illustrating the tested configurations of external wall layers incorporating PCM. This comprehensive approach aims to assess the impact of PCM integration on the energy performance of building envelopes under extreme climatic conditions.

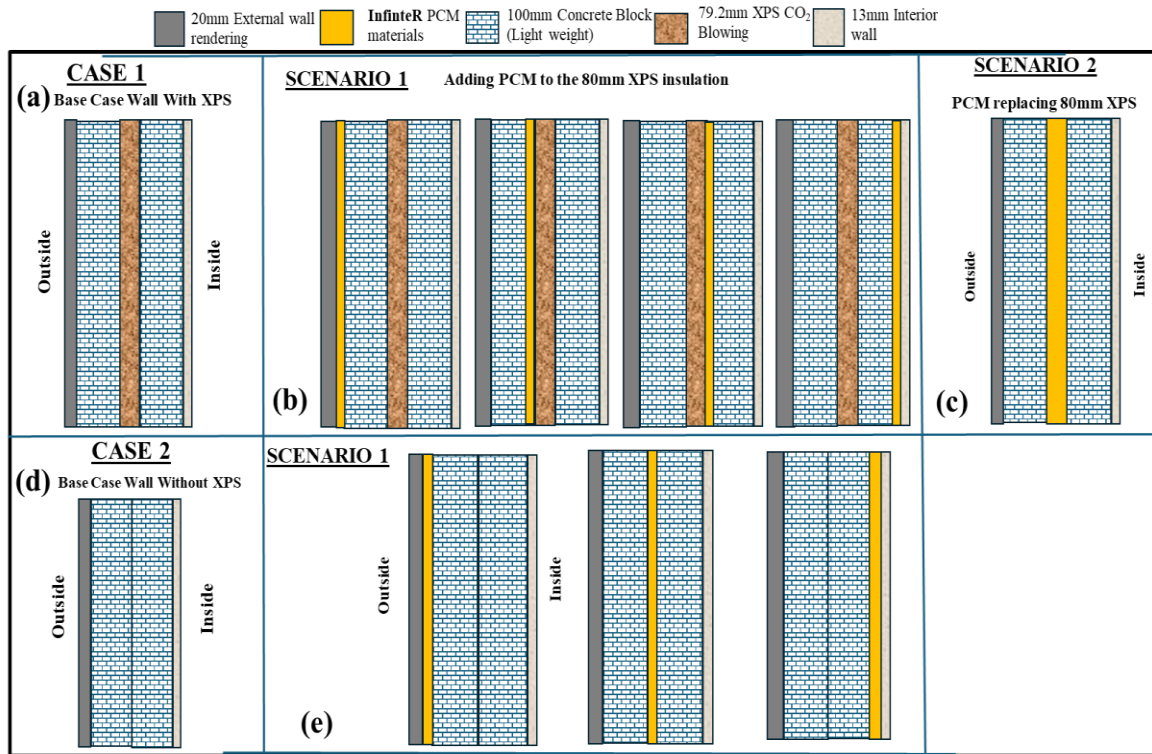


Figure 17: Schematic of the studied wall cases and scenario (b) Wall with XPS+ PCM (c) PCM replacing XPS (d) Base case wall without XPS.

3.11 PCM Layer Thickness.

The thickness of Phase Change Materials (PCMs) significantly influences energy savings and thermal comfort, especially in extreme climates. It plays a crucial role in moderating the diurnal temperature variations within buildings. This evaluation focuses on external walls with varying PCM thicknesses, maintaining all other variables constantly determining optimal configurations and transition temperatures.

The study considers macro-encapsulated PCMs, such as Infinite, which is produced from mineral-based raw materials and is commercially available in 6 mm sheets (Al-Absi *et al.*, 2021). Previous research has identified optimal PCM thicknesses of 6, 12, 18, and 24 mm through both experimental and simulation studies (Al-Absi *et al.*, 2021; Jaradat *et al.*, 2024). The analysis evaluates the trade-off between total site energy consumption (kWh) and minimizing discomfort (hours) to determine the most effective PCM configurations.

These PCM wall panels can be integrated into the wall assembly during construction or retrofitted onto existing walls using adhesives or fasteners, based on manufacturer recommendations. This adaptability enhances the potential for PCM integration to improve energy performance and thermal comfort in buildings, aligning with the thesis's overarching objectives.

3.12 Objective Function and Variables for PCM-Integration.

This study focuses on evaluating the annual energy performance of two PCM-enhanced wall configurations under extreme climatic conditions, specifically examining wall case 1 with: base case with XPS insulation as Scenario 1, and an 80mm XPS insulation replaced with 80mm PCM as Scenario 2, and wall case 2: with a non-insulated composite wall for comparative analysis. The key design variables investigated include PCM melting temperature (ranging from 21 to 39°C), position (interior, middle, or exterior), and thickness (from 6 to 80mm), all of which were tested against fixed parameters, such as wall layer composition, as detailed in Table 8. The results of this study validate the significant role of PCM in reducing reliance on HVAC systems during extreme temperature fluctuations, illustrating how these materials can enhance energy efficiency.

The optimization process incorporated fixed variables throughout, while key design variables like the cooling set point temperature were varied between 23°C and 28°C, recognizing their substantial influence on energy consumption outcomes. The optimized external wall configurations served as critical design variables that informed the genetic algorithm, which sought to identify optimal parameters concerning transition melting temperature, position, and thickness. This integrated approach aimed to achieve the study's objective function of minimizing total energy consumption (kWh) and thermal discomfort (% discomfort hours).

Furthermore, the effects of PCM integration on energy performance and thermal comfort are conveyed through optimization graphs. Each point on the Pareto front graph represents a wall composition integrated with PCM sheets, highlighting the essential parameters for selecting the optimum PCM, including thickness, melting/transition temperature, and configuration/position. Collectively, these findings underline the potential of PCM-enhanced walls to improve energy performance and occupant comfort in extreme climatic conditions, thereby contributing to more sustainable architectural practices and offering valuable insights for future building design.

Table 5: Summarized objective functions, design variables and constraints of the study

Nr	Objective Functions	Comments/Limits	Units
a	Total Site Energy	Minimize	kWh
b	Discomfort ASHRAE 55 (all clo)	Minimize	hrs
2	Optimized Wall Variables	Constraints	Unit
a	PCM Thickness (PT)	$6 < PT \leq 24$ and 80	mm
b	Transition Melting Temperature:(MT)	$21 < MT \leq 39$	°C
c	PCM Position/ placement	-Towards the Exterior, -Middle -Towards the Interior	-
2	Other- Wall Variables	Constraints	Units
a	Wall Thickness (WL)	$313 < WL \leq 350$	mm
b	U-Value	$0.274 < U \leq 0.427$	W/m ² k
c	Density (ρ)	$3464 < \rho \leq 3535$	kg/m ³
d	Reflectance	0.40	-

Table 5: Continued

	Objective Functions	Comments/Limits	Units
e	Cooling Set Point Temperature (CST)	$24 < CST \leq 28$	°C
f	Specific heat capacity (C)	$5400 < C \leq 7540$	J/kg-K
3	Other Constant Variables	U-Values	
a	Roof	Fixed @ 0.391	W/m ² k
b	Windows	Fixed @ 0.604	W/m ² k
c	Windows (Solar Coefficient (SC/SHGC)	Fixed @ 0.703	-
d	Floor	Fixed @ 0.515	W/m ² k

CHAPTER 4: RESULTS, DISCUSSION AND ANALYSIS

This chapter presents a comprehensive analysis of the impacts of integrating Phase Change Materials (PCMs) into exterior walls on total energy consumption (kWh) and the trade-offs involved in minimizing annual thermal discomfort. The energy performance is analyzed with a focus on reducing total energy consumption, energy (fuel) consumption breakdown and evaluating the Energy Utilization Index (EUI). Additionally, the monthly energy consumption effects and the seasonal impacts of PCM integration on overall energy demand are assessed. Thermal comfort is considered using two key indicators: Annual Thermal Discomfort (ATD) and Operative Temperature Distribution (OT). The chapter concludes a thorough evaluation of the optimal PCM wall configurations based on transition temperature, optimal positioning, and thickness. A summary of the key findings and implications of this research is also provided, highlighting the significance of PCM integration in enhancing energy efficiency in extreme climatic conditions.

4.2 The Baseline Building Model Results.

The results from the baseline building model provide a critical comparison of energy consumption between traditional building configurations and those integrated with Phase Change Materials (PCMs) under optimal conditions across representative climatic regions such as Al-Ahsa and Taif. The 2023 climate dataset- annual simulations which is a year-long energy modeling exercise that is conducted using climate data representative of the year 2023 for the investigated representative climatic in Saudi Arabia. This highlights the variance in energy consumption attributable to the wall envelope's design, illustrating the significant impact of insulation type and climate on overall energy performance. Specifically, the total building electricity consumption with the insulated base wall in Al-

Ahsa is measured at 35,428.8 kWh, whereas the building without insulation consumes 39,289.6 kWh respectively, at a cooling set point of 23°C. In Taif, the figures are slightly lower, with the insulated wall consuming 24,361.8 kWh and the uninsulated wall at 26,036.8 kWh respectively.

The actual energy consumption breakdown for the base wall with XPS reveals that cooling demands account for 20,120.0 kWh, heating requires 2,033.7 kWh, lighting consumes 3,376.6 kWh, and other electrical loads, including domestic hot water (DHW), amount to 8,230.6 kWh and 1,667.9 kWh, respectively. This data illustrates that the total cooling energy demand represents the highest percentage of consumption, reaching 57% in Al-Ahsa and 43% in Taif for the XPS insulated wall cases as shown in figure 18.

Energy Use Intensity (EUI) serves as a vital metric for evaluating and comparing the electrical energy efficiency of buildings, enabling stakeholders to track progress toward sustainability and energy efficiency goals. Lower EUI values signify a more efficient use of energy resources, which can lead to significant energy cost savings and reductions in greenhouse gas emissions. The EUI was calculated for both cities, with and without XPS insulation, by dividing the total energy consumed (kWh) from lighting, heating, cooling, DHW, and other electrical loads by the total conditioned floor area of 638 m². For Al-Ahsa, the EUI for the base walls with and without XPS insulation is determined to be 142.5 kWh/m²/year and 154.16 kWh/m²/year, respectively. In Taif, these values are much lower at 83 kWh/m²/year and 85.7 kWh/m²/year.

Table 9 below summarizes the total floor areas of the baseline building models calculated EUI and HVAC electricity intensity metrics for both conditioned and total floor areas across the representative climatic zones. This comprehensive analysis highlights the

importance of PCM integration in enhancing energy performance and achieving sustainability objectives in extreme climates.

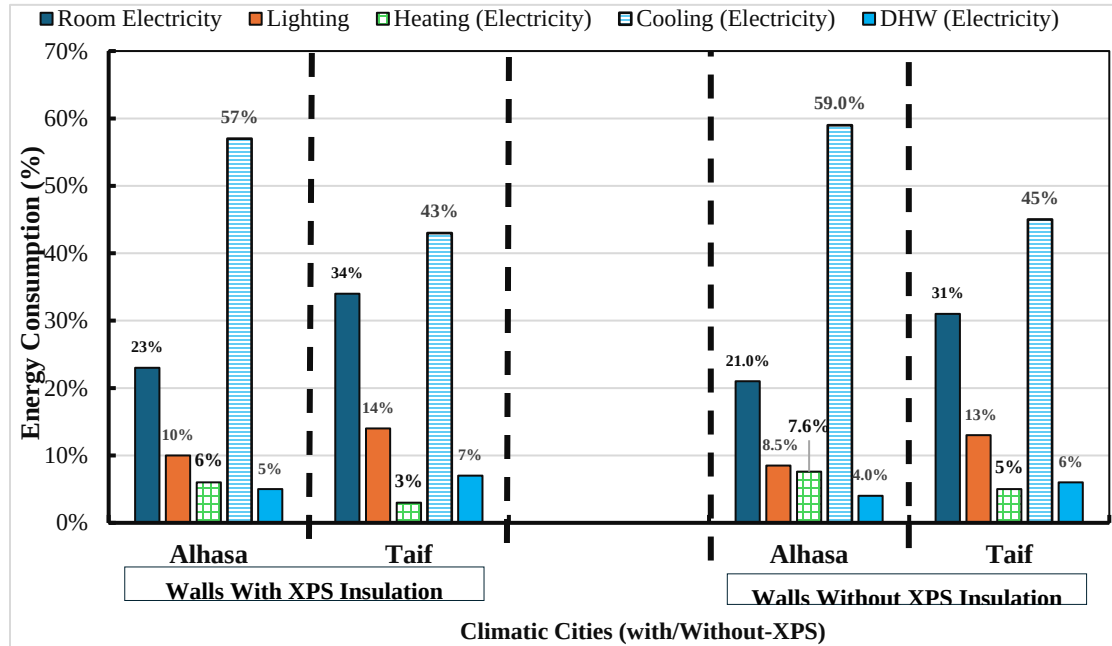


Figure 18: Percentage distribution of electrical energy consumption in the base case building model across the two climates studied.

Table 6: EUI and HVAC electricity metrics for both conditioned and total floor areas.

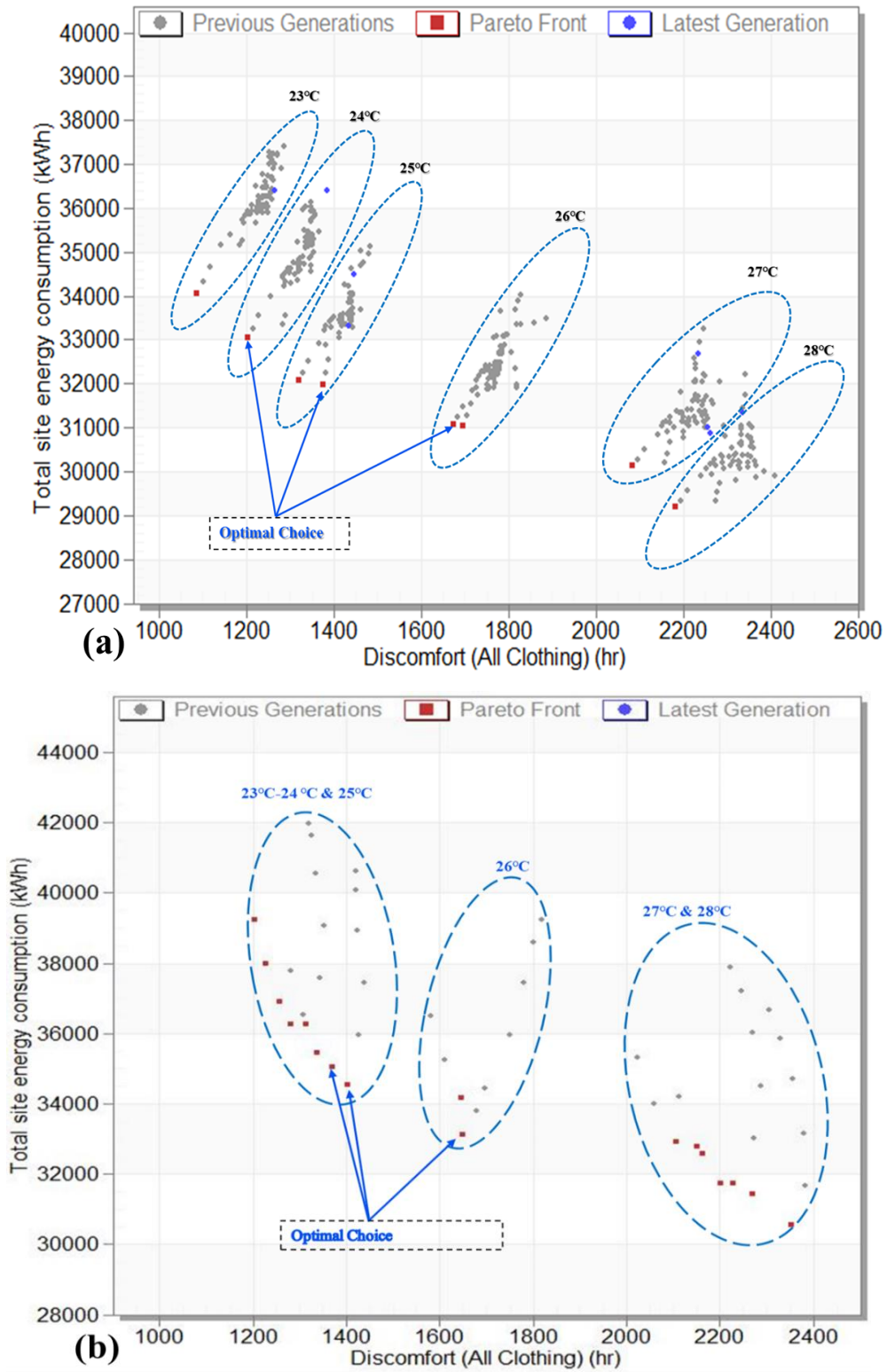
Base Case Building Model	Energy Use Intensity (kWh/m ² /Year) For The Representative Studied Climatic Zones (Cities).			
	With XPS Insulation		Without XPS Insulation	
	Al-Ahsa	Taif	Al-Ahsa	Taif
Energy Intensity Per Conditioned Floor Area	173.38	101.1	187.8	104.4
Energy Intensity Per Total Floor Area	142.45	83.1	154.1	85.73
HVAC Energy Intensity Per Conditioned Floor Area	145.93	75	158.6	77.6
HVAC Energy Intensity Per Total Floor Area	119.9	62	130.2	63.76

4.3 Optimization Results Analysis

The selection of optimal wall configurations and scenarios is supported by the key objective of minimizing total energy consumption (kWh) in buildings through the integration of PCM sheets. The optimization results clearly illustrated that increasing the cooling set point temperature leads to greater energy savings (kWh), although at the expense of increased discomfort hours, particularly when temperatures exceed the ASHRAE operative range of 27-28°C (ASHRAE 55, 2022). The optimal outcomes for the wall cases and scenarios in both investigated cities, Al-Ahsa and Taif, are depicted in figure 19 (Al-Ahsa) and 20 (Taif) (a, b, & c) showcasing the evaluation of two PCM-integrated wall configurations with corresponding scenarios under the studied climatic conditions prevalent in Saudi Arabia: Case 1 involves adding PCM sheets to or replacing 80mm XPS insulation, while Case 2 consists of PCM embedded in non-insulated walls.

Optimal solutions were identified by striking a balance between total site energy consumption (kWh) and the duration of thermal discomfort (hours). The analysis reveals that raising the cooling set point temperature (CST) from 23°C to 28°C results in a reduction of energy use by 10-19%, while simultaneously increasing discomfort hours by 10-30%. Notably, performance clustering was observed at five CST intervals (23, 24, 26, 27, and 28°C), which directly correlates with the phase-change transition temperatures of the PCM, thereby affirming its effectiveness as a thermal buffer. This balance highlights the trade-offs involved in optimizing building performance, suggesting that while higher set points can yield energy savings, they also necessitate careful consideration of occupant comfort. The appendix section presents the outcomes of the multi-objective optimization analysis conducted to minimize thermal discomfort hours and total site energy

consumption across the investigated climates of Al-Ahsa (extremely and dry) and Taif (hot and dry).



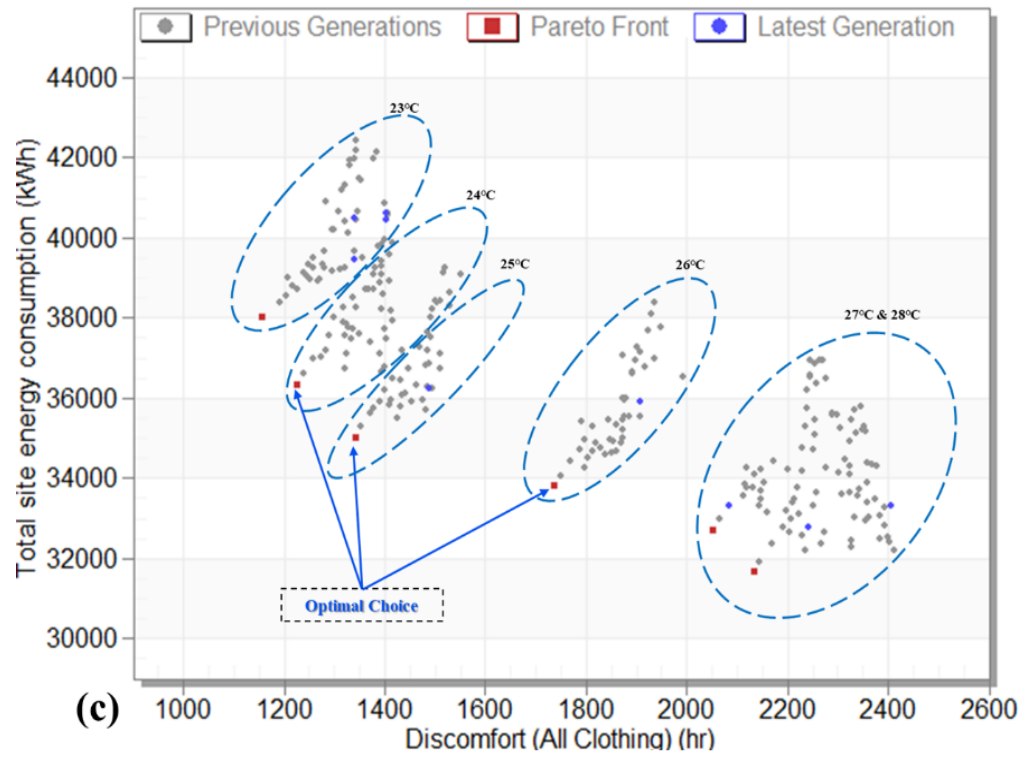
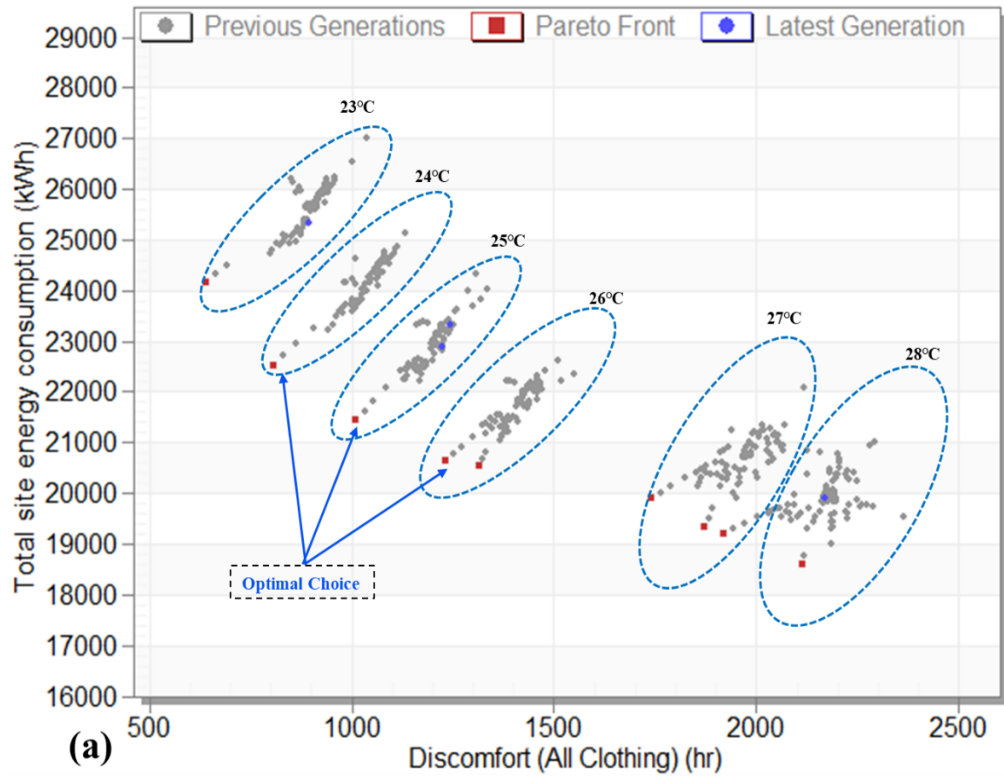


Figure 19: initial optimal wall cases & Scenarios of PCM incorporated wall combination. For AL-AHSA (a) Adding PCM to XPS insulation (b) Replacing of XPS with 80mm PCM sheet and (c) Adding of PCM wall without XPS insulation.



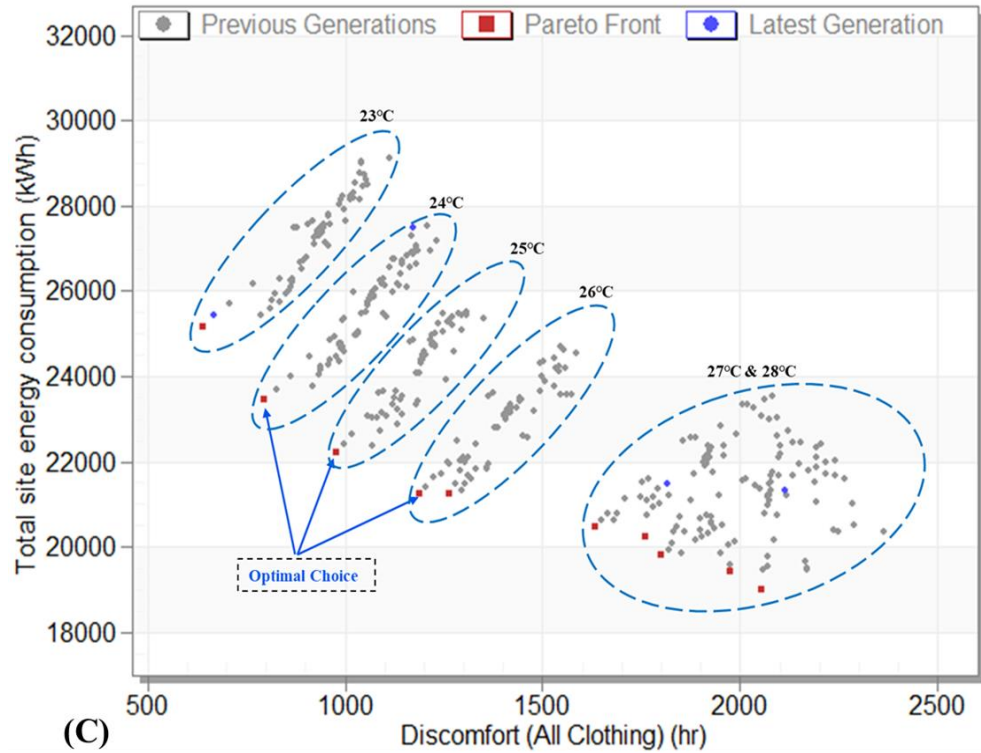
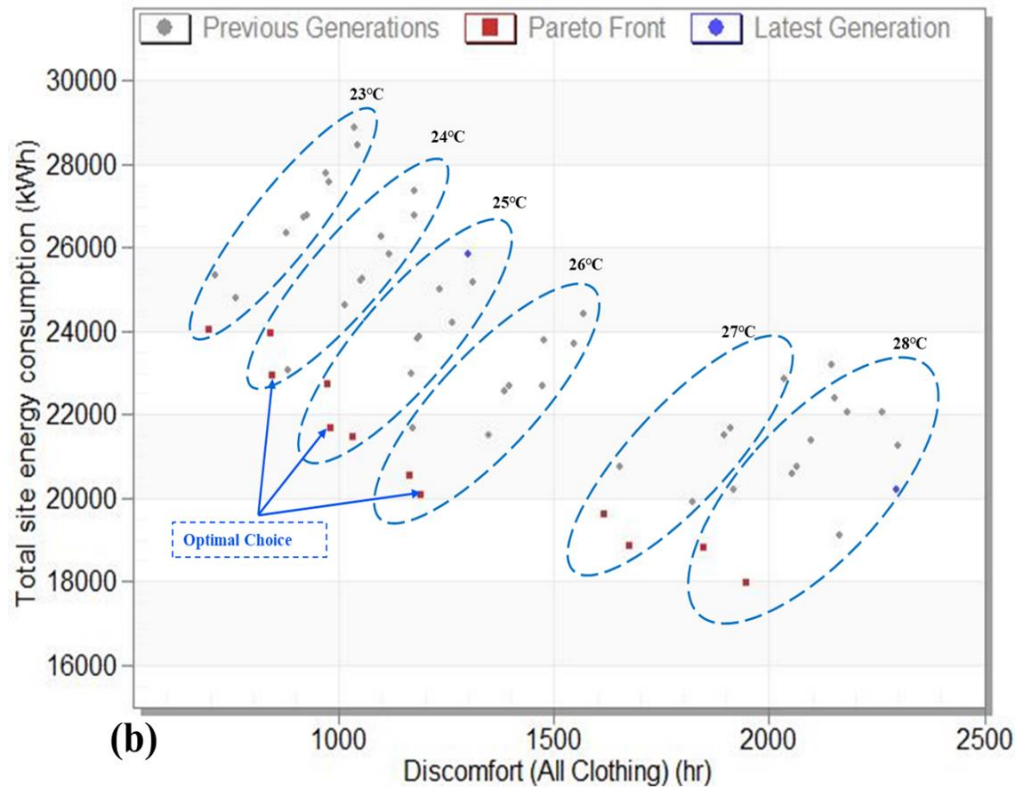


Figure 20: Initial optimal wall cases-Scenarios of PCM incorporated wall combination in TAIF. (a) Addition of PCM to XPS insulation (b) replacing XPS with 80mm PCM sheet and (c) Adding PCM to a wall without XPS insulation.

The optimization results, summarized in table 10, identify optimal PCM wall configurations that adhere to ASHRAE operative temperature thresholds (23–26°C) while maintaining thermal discomfort below 20% of annual hours ($\leq 1,752$ hours) and adaptive operative temperature results of the same optimal walls. These configurations were derived using a genetic algorithm to balance energy efficiency and occupant comfort, prioritizing cooling setpoints (23–28°C) that align with Saudi Arabia’s HVAC practices. Configurations exceeding 26°C were excluded due to discomfort surpassing 20%, a decision consistent with ASHRAE Standard 55-2020’s emphasis on livability and prior findings by (Al-Absi *et al.*, 2021), who emphasized PCM’s dual role in arid climates (ASHRAE 55, 2022).

The analysis incorporates the EN16798 (CEN (European Committee for Standardization), 2019) adaptive comfort model (Category II), which permits 20–30% of occupied hours to exceed the 23–28°C operative temperature range, accounting for occupants’ physiological acclimatization to regional climatic conditions, such as those in hot-arid zones like Saudi Arabia (CEN (European Committee for Standardization), 2019). Comparative assessments reveal energy consumption differences of 6.2–10.2% (Al-Ahsa) and 6.5–14.3% (Taif) between ASHRAE and adaptive models, demonstrating PCM’s capacity to reduce cooling loads even under relaxed comfort criteria. For instance, In Al-Ahsa’s extremely hot and dry climate, PCM integration within XPS-insulated walls reduced total energy consumption by 10.2% under ASHRAE 55 (ASHRAE 55, 2022) fixed setpoint criteria (strict 23–26°C cooling) compared to 6.4% under the (CEN (European Committee for Standardization), 2019) adaptive model (23–28°C operative range), reflecting occupants’ acclimatization to wider temperature swings. Similarly, Taif’s hot and dry climate saw

reductions of 14.3% (ASHRAE 55, 2022) and 10.5% (adaptive), demonstrating PCM efficacy across varying climatic conditions (CEN (European Committee for Standardization), 2019; Sarri *et al.*, 2023). These disparities highlight occupant acclimatization's influence on energy-saving potential, though PCM-enhanced walls consistently improved thermal comfort across both standards (ASHRAE, 2016a).

By adhering to ASHRAE's guided thresholds, the selected configurations ensure compliance with international building codes while advancing Saudi Arabia's energy resilience goals. The results validate PCM's adaptability to extreme climates, where latent heat storage mitigates HVAC reliance without compromising occupant well-being.

Table 7: Selected walls standards based on AHRAE 55 (ASHRAE 55, 2022) and Adaptive Operative temperature.

Wall Cases	Energy Consumption (kWh) of ASHRAE Operative Temperature (23-26°C)		ASHRAE % acceptable discomfort ($\leq 20\%$) @ 23-26°C csp.		Energy Consumption Based on adaptive Operative temperature (26-28°C)		ASHRAE % acceptable Discomfort (20%-30%) @ 27-28°C csp.	
	Al-Ahsa	Taif	Al-Ahsa	Taif	Al-Ahsa	Taif	Al-Ahsa	Taif
Base Wall + XPS (W1)	35359	24343	20	18	31827	20889	28	26
Base Wall- XPS (W2)	39217	25992	18	16	35284	22263	29	28
Opt. W1-S1- INT	31024	19900	19	15	29092	18601	28	25
Opt.W1-S2-MID	33118	20061	19	14	30554	17956	28	24
Opt. W2-S1-INT	33829	21255	19	14	31677	19013	27	24

Figures 21 and 22 illustrate a compilation of three initial wall configurations selected from each of the studied wall scenarios within the ASHRAE optimal range of 23-26°C, detailing the total energy consumption (kWh) alongside the annual percentage of discomfort periods, all within the acceptable limits set by ASHRAE (ASHRAE, 2016b; ASHRAE 55, 2022). It is evident that all three optimal wall configurations depicted in the graph (figures 21&22) fall within the acceptable comfort range. Consequently, the wall configuration with the lowest total energy consumption among these three was selected for a more comprehensive assessment.

The final optimal walls, designed for cooling setpoints between 23-26°C, were selected based on dual criteria: achieving the lowest total energy consumption while maintaining discomfort hours below 20%. For example, the configurations within this range successfully reduced cooling loads by 12–22% and heating demand by 35–76%, showcasing PCM's ability to buffer extreme diurnal temperature fluctuations. These findings confirm the results from (Al-Absi *et al.*, 2020, 2021; Al-Absi, Hafizal, *et al.*, 2024), where PCMs optimized for proximity to setpoints were shown to maximize HVAC efficiency in desert climates. Furthermore, the forthcoming sections will assess the optimal walls, incorporating analyses of energy consumption, thermal discomfort, and CO₂ emissions, thereby highlighting PCM's critical role in enhancing energy resilience and promoting sustainability in building design.

4.4 Energy Consumption Assessment

This section analyzes the impact of Phase Change Materials (PCM) on energy performance through a comparative analysis of total energy consumption (kWh) reductions and their percentage savings, alongside a breakdown of energy consumption, summer energy savings, and monthly energy reductions across all wall cases throughout the 2023 simulation and optimization period. The following sections present quantitative results for total energy savings and reductions in heating and cooling demand that is achieved in both the climates of Al-Ahsa and Taif.

The analysis will be done according to the wall cases and scenarios being defined in section 3.10. For instance, In wall case 1, scenario 1 (PCM + XPS), the simulation for Al-Ahsa demonstrates that the optimal PCM wall configuration, designated as INT-27°C-24mm at a cooling set point temperature (CST) of 25°C, achieved the lowest energy consumption of 31,065 kWh, reflecting a reduction of 12.6% while adhering to ASHRAE 55 thermal comfort criteria (ASHRAE 55, 2022) as also studied by (Al-Absi, Asif, *et al.*, 2024) In contrast, for Taif, the optimal wall configuration within Wall Case 1, Scenario 1 (PCM + XPS), identified as INT-25°C-24mm at 25°C CST, resulted in an energy consumption of 19,900.5 kWh, which translates to a 16% reduction compared to the conventional wall without PCM. It is important to note that optimal wall configurations with adaptive operative temperatures of 26-28°C, whose energy consumption decreases as cooling set points increase, along with corresponding percentage hours of thermal discomfort, were not subjected to further analysis.

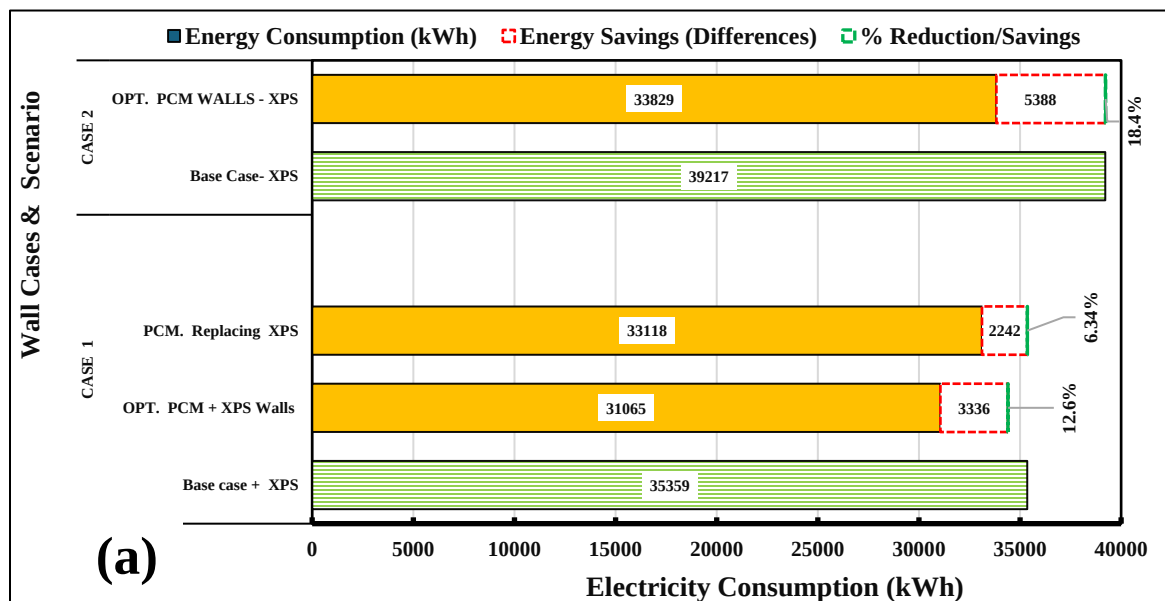
The exclusion of further analysis for the optimal wall configurations within the adaptive operative temperatures (26–28°C) is justified by the following factors:

- **Focus on Strict Thermal Comfort Standards:** The study prioritizes ASHRAE 55 criteria (fixed cooling setpoints at 26°C) and an operative temperature of 23–26°C to establish a standardized baseline for PCM performance, enabling direct comparison with conventional walls under identical comfort conditions (ASHRAE 55, 2022).
- **Adaptive Model Limitations:** Adaptive comfort models (e.g., EN16798) inherently reduce HVAC reliance by tolerating wider temperature ranges (23–28°C), which diminishes PCM efficacy in load-shifting and complicates isolation of material-specific impacts (ASHRAE 55, 2022).

For Wall Case 1, Scenario 2 (PCM replacing XPS), the configuration W1-S1-MID-29°C-80mm at 26°C CST exhibited a total energy reduction of 6.3% (2,241.9 kWh), with reductions of 17.05% in cooling loads and 14% in heating loads. Similarly, for Taif, the configuration W1-S1-MID-25°C-80mm at 26°C CST achieved a total energy reduction of 13% (4,282.6 kWh), alongside cooling and heating load reductions of 32.2% and 53%, respectively. In Case 2 (PCM without insulation), the wall configuration W2-INT-25°C-24mm at 26°C CST achieved a total energy reduction of 18.4% (5,388.2 kWh), with 21.6% cooling and 60% heating electricity savings. The high percentage reduction in heating (60%) reflects the inherently low baseline heating demand in Al-Ahsa's hot-arid climate, where cooling dominates ~90% of annual HVAC loads (SEEC., 2021). For example, the baseline heating consumption was 300 kWh (vs. cooling's 25,000 kWh), meaning even modest absolute savings (e.g., 180 kWh) will yield large percentage gains. Figure 23 (a and b) compares total energy consumption reduction and percentage savings between base case walls and PCM-optimized configurations, illustrating percentage savings across cases. Seasonal disparities were noted, with Al-Ahsa showing 17.3%

savings in summer cooling and 67% in winter heating, while Taif exhibited an 18% reduction in total energy consumption (21,254 kWh) for the same wall configuration, alongside cooling and heating electricity reductions of 34.2% and 75.75%, respectively. Figure 24 (a & b) shows the summer cooling consumption differences between the wall cases for Al-Ahsa and Taif.

Significantly, the integration of PCM resulted in a disproportionate reduction in winter heating demands due to the latent heat released during cooler nights, which is a critical advantage for the arid climate of Saudi Arabia. While the occupant-preferred CSTs (23–26°C) influence wall selection, the optimal configurations, such as INT-27°C-24mm at 25°C CST, inherently minimize the trade-offs between energy efficiency and thermal comfort, thereby reinforcing the benefits of PCM integration in enhancing building performance under extreme climatic conditions.



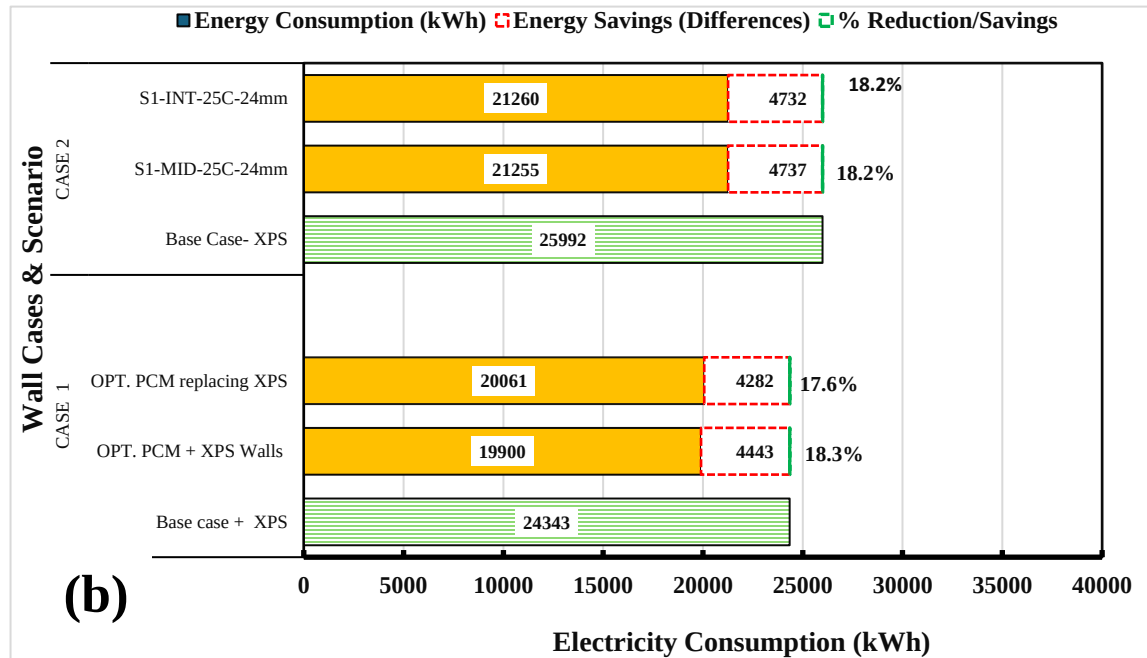
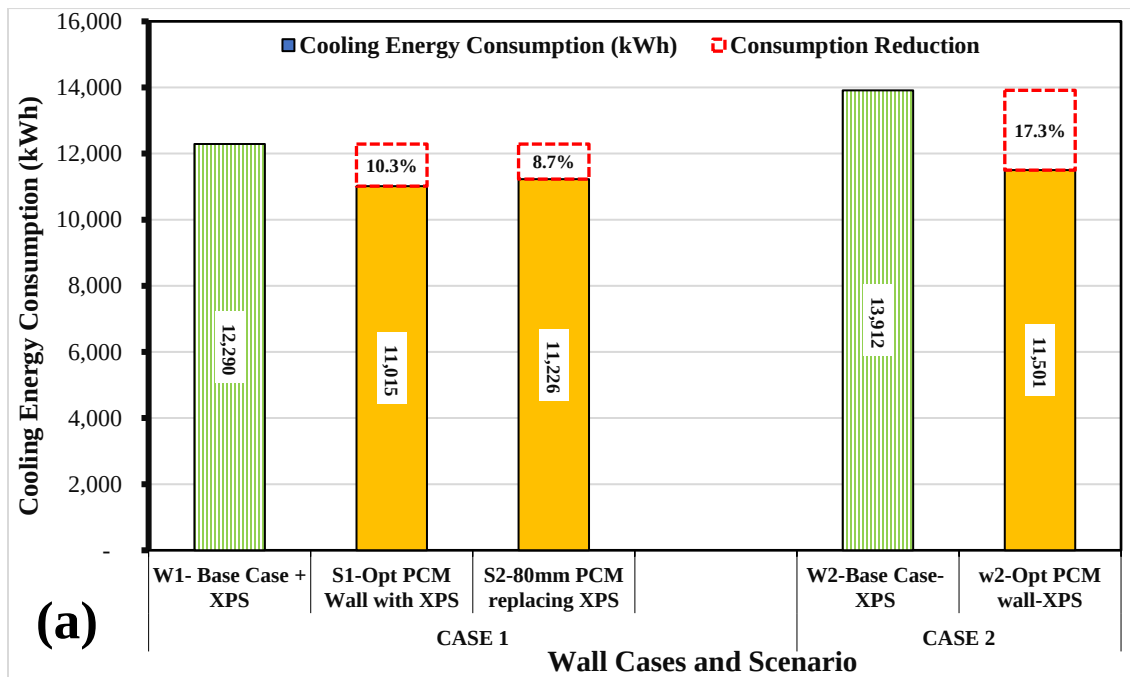


Figure 23: Total annual energy consumption reduction and percentage savings comparison for the studied wall scenarios (a) Al-Ahsa and (a) Taif



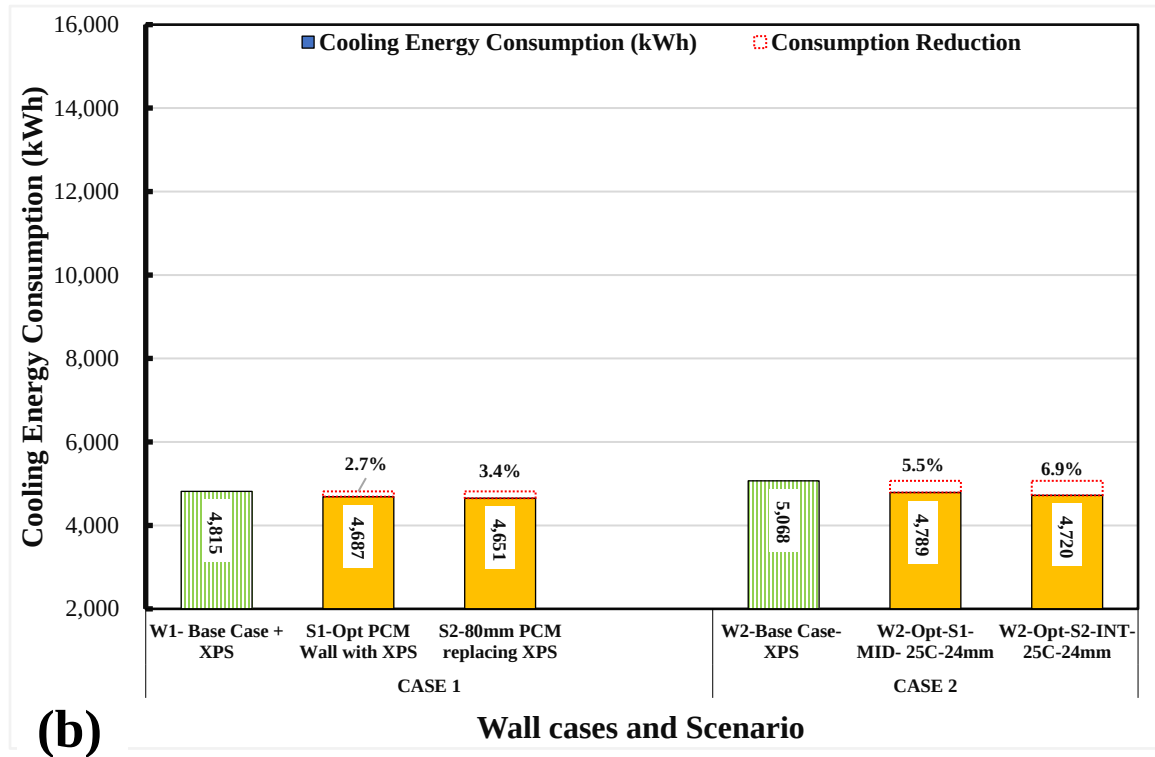


Figure 24: Summer Cooling Energy consumption (kWh) comparison. (a) Al-Ahsa) and (b) Taif.

4.5 Analysis on Fuel Breakdown (kWh)

The annual energy performance of optimal PCM-integrated walls demonstrates significant reductions compared to conventional wall systems without PCM. The fuel consumption breakdown for the PCM-integrated walls indicates a notable impact across all major energy use categories, including cooling, heating, and other energy sources as shown in figure 25. Cooling energy accounted for 53–55% of total consumption; however, PCM integration reduced cooling loads by 12.6 and 34.2%, depending on wall configuration and cooling setpoint temperature (CST) for both Al-Ahsa and Taif respectively. Higher CSTs, such as 28°C, maximized energy savings but increased thermal discomfort, necessitating a balance at moderate CSTs (23–26°C) in line with ASHRAE 55 criteria (ASHRAE, 2016a).

Heating demand reductions were also significant, with a decrease of 14% and 80% in energy consumption across the walls and climates investigated of Al-Ahsa and Taif respectively. Additional energy demands from room electricity, plug loads, and domestic hot water (DHW) exhibited consistent consumption throughout the year, indicating that these loads are not dependent on environmental conditions or wall configurations. Seasonal analysis further revealed PCM's asymmetric performance: summer-optimized walls, such as W1-S1-Opt: INT-27°C at 25°C CST and W1-S1-Opt: INT-27°C at 26°C CST for Al-Ahsa and Taif, respectively, reduced cooling energy by 22% and 7.4%. Conversely, winter-optimized configurations, like W1-S1-Opt: INT-27°C at 26°C CST and W1-S1-Opt: INT-25°C at 24°C CST, achieved heating energy reductions of 67% and 78.4% in Al-Ahsa and Taif, respectively. This disparity arises from PCM's latent heat release during cooler nights, which offsets winter heating demands more effectively than summer cooling. It is crucial to note that PCM's melting temperature must exceed the CST to facilitate thermal buffering, a critical design criterion supported by the clustering of optimal solutions near phase-change thresholds (24–26°C). The impact of PCM in reducing both heating and cooling energy across the two studied climates demonstrates its standalone viability in non-insulated systems.

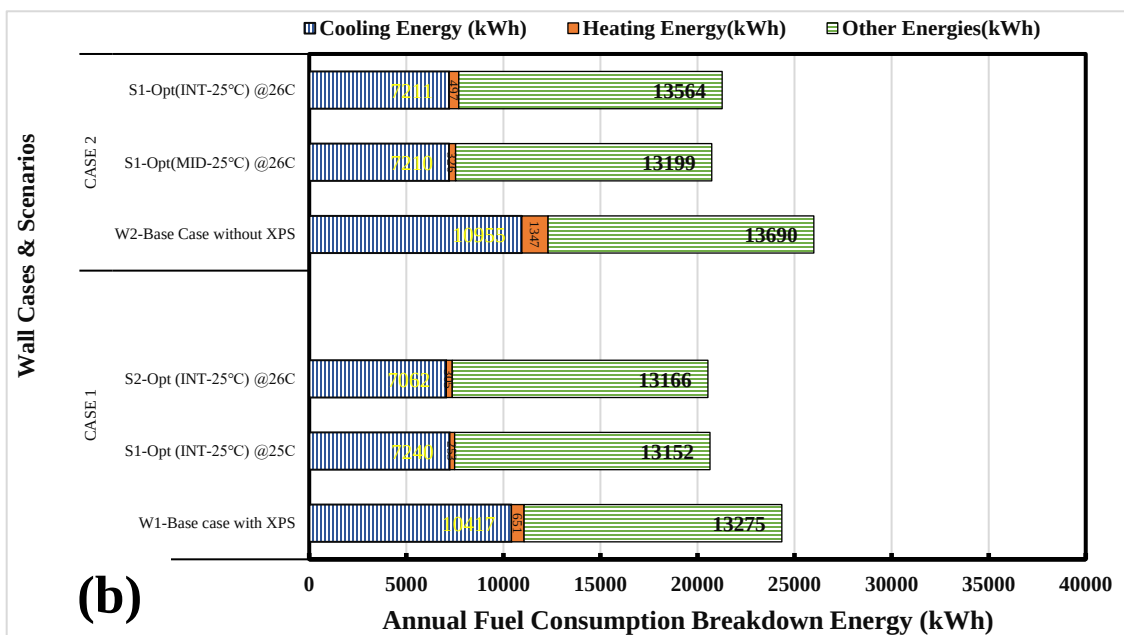
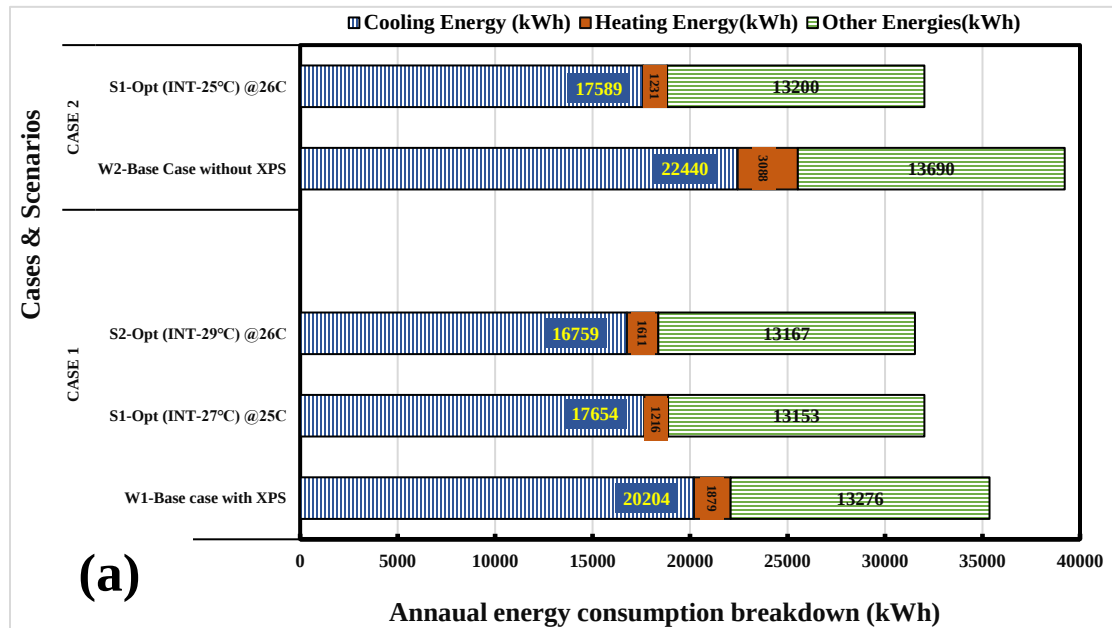


Figure 25: Annual consumption Breakdown comparison of PCM wall with Base cases (a) Al-Ahsa and (b) Taif.

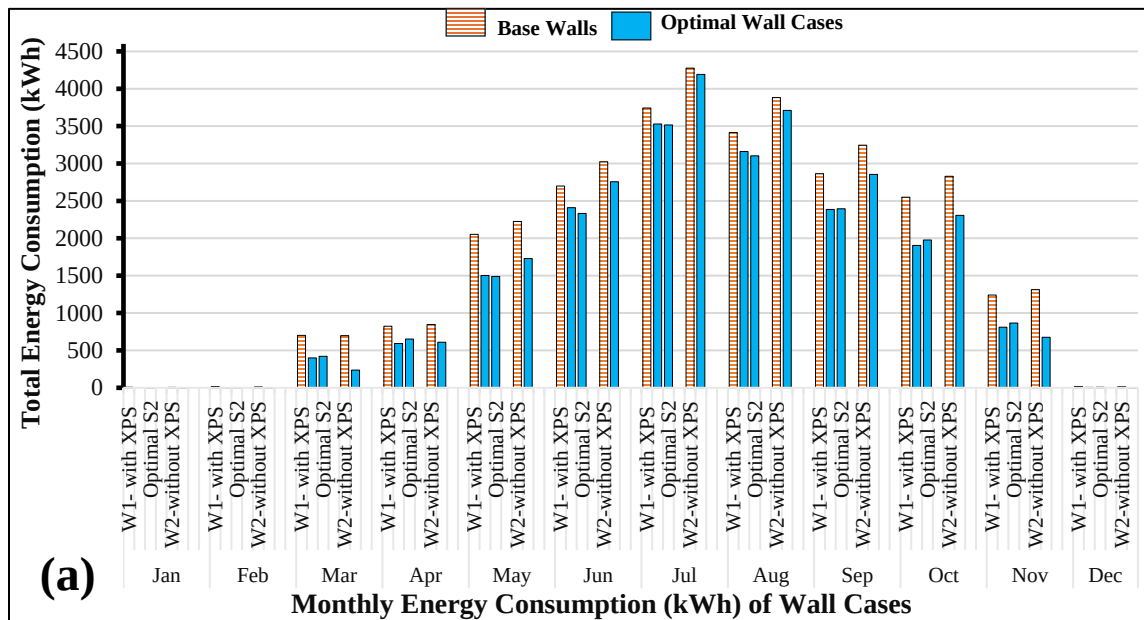
The analysis of PCM's impact across each month of the simulated period, as illustrated in figures 26 shows Al-Ahsas' (a) cooling and (b) heating energy impact and figure 27 shows Taifs' (a) Cooling and (b) heating energy effect reveals significant reductions in cooling and heating energy. There is a peak cooling demand from mid-June to September across

all PCM-integrated wall scenarios. Walls that combine PCM with XPS insulation (Scenario 1) exhibited superior thermal resistance, achieving summer cooling load reductions of 18% to 35% compared to conventional systems, primarily due to minimized heat ingress. These results align with findings from (Dardouri, Tunçbilek, *et al.*, 2023), which reported similar energy reductions of 32% using PCM at 29°C, and Sovetova *et al.* (2019b), where desert-climate buildings achieved heating and cooling savings of 17.97% to 34.26%. Notably, Scenario 1's annual cooling energy share of 55% emphasizes PCM's disproportionate impact on summer performance, while winter heating reductions ranged from 35% to 61% for Al-Ahsa, with a substantial decrease of 57% to 81% in Taif due to the region's cooler climate, showcasing the highest heating energy reduction among all PCM-integrated wall cases investigated. This effectiveness is largely attributed to latent heat release during cooler nights, a critical advantage given KSA's diurnal temperature variations.

Wall Case 2 (PCM without insulation) demonstrated exceptional winter performance, achieving heating energy reductions of 60% to 80% due to uninterrupted thermal buffering from outdoor temperature fluctuations. This contrasts with insulated systems, where XPS layers moderate PCM activation, as highlighted in the comparative study by (Li *et al.*, 2025; Zhou and Razaqpur, 2024a) on desert climate retrofits. Summer cooling reductions peaked between June and September for both configurations, with PCM efficiency diminishing slightly (<5%) during transitional months (January–April), consistent with (Sovetova *et al.*, 2019a), which observed reduced phase-change activity in mild thermal gradients. The overall annual energy savings underline PCM's dual role in mitigating summer cooling demands, which account for 55% to 70% of total HVAC energy, while

enhancing winter heating resilience, particularly in moderately colder climates like Taif, a critical advantage for KSA's climate.

Zeyah's study further agrees with these trends, indicating energy savings of 24.1% to 30.1% at cooling setpoints of 25°C to 26°C, consistent with the optimal CST range identified in this research. However, this study advances previous findings by quantifying PCM's enhanced efficacy in KSA's extreme climate, particularly when paired with insulation (Scenario 1), achieving cooling reductions of 12.6% to 34.2% despite ambient temperatures exceeding 45°C. The synergy between PCM transition temperatures (24°C to 28°C) and localized cooling setpoints emphasizes its viability for adaptive envelope design, effectively addressing both energy resilience and occupant comfort in alignment with Vision 2030 targets.



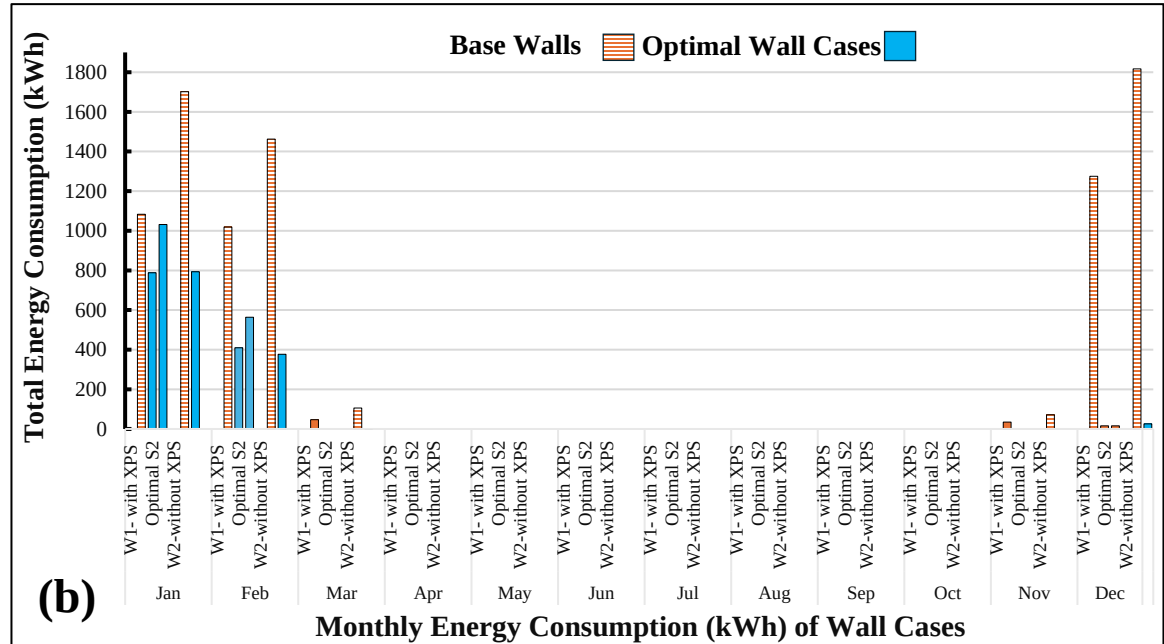
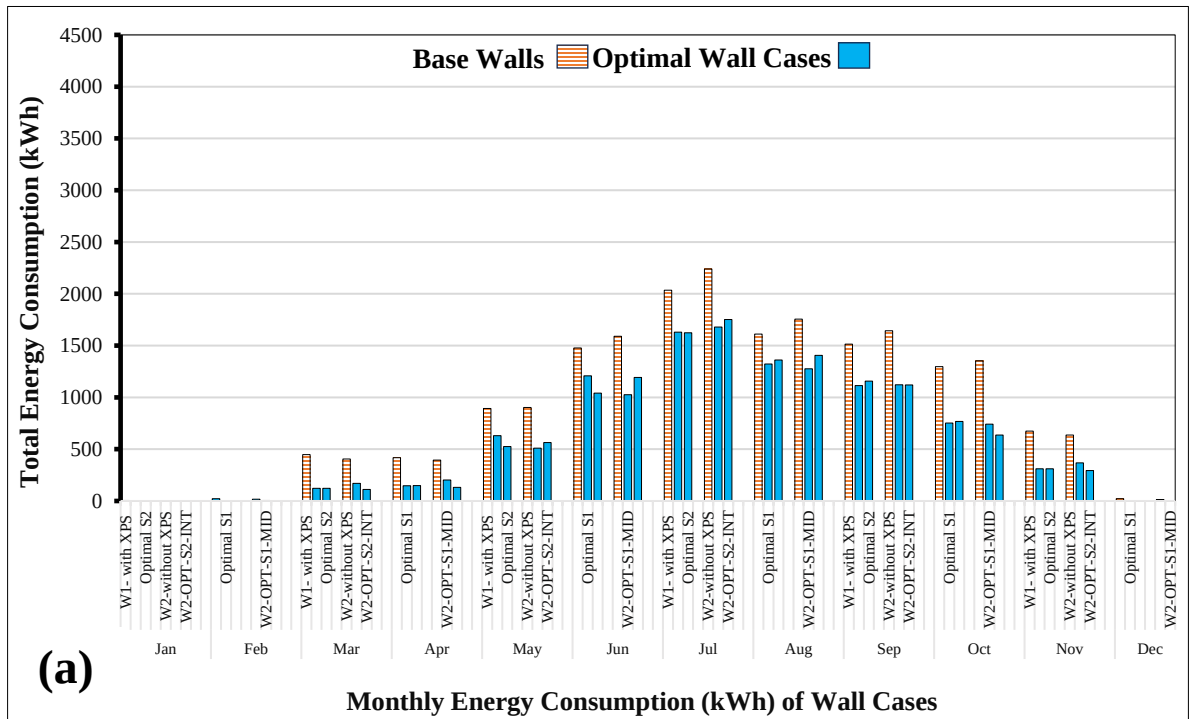


Figure 26: Monthly (a) cooling and (b) heating energy consumption comparison of the investigated walls cases for-AI-Ahsa.



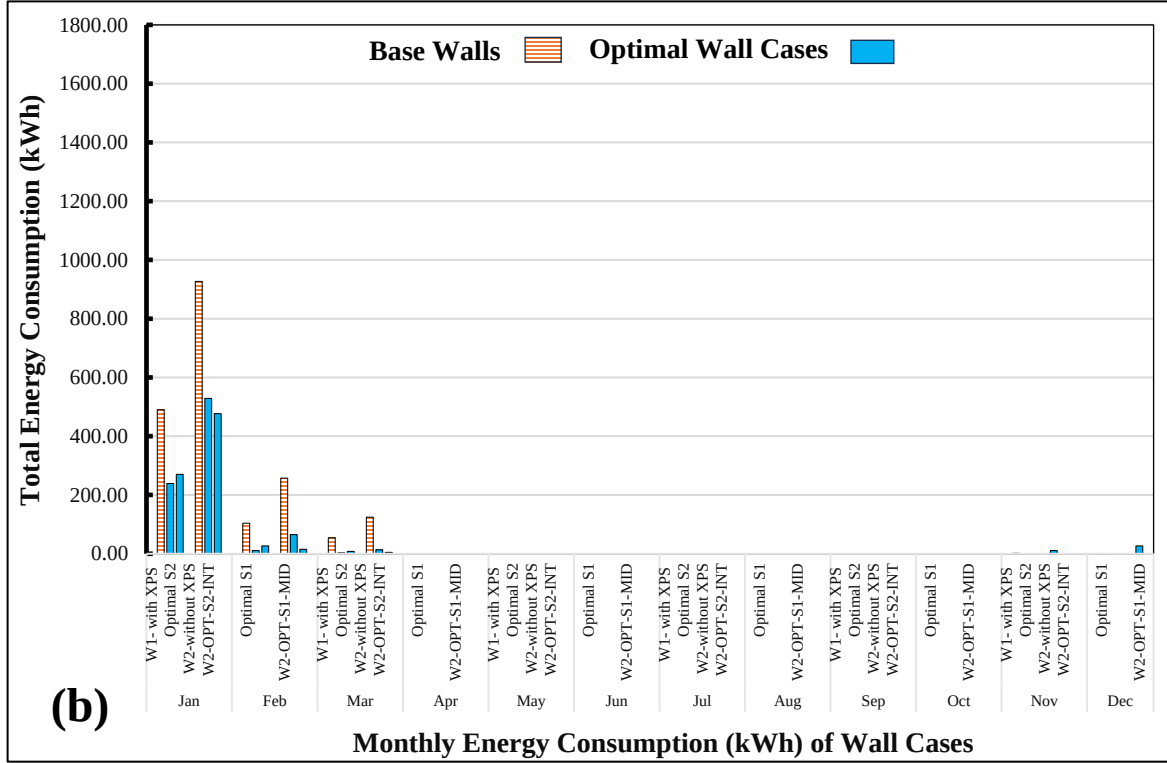


Figure27: Monthly (a) cooling and (b) heating energy consumption comparison of the investigated walls cases for Taif

4.6 Peak Load Shifting and Energy Consumption Analysis

This section of the energy performance analysis evaluates the impact of peak load, which is the maximum electrical demand within a specific period—on cooling energy consumption in extreme climates, with the study focusing on Al-Ahsa (extremely hot and dry) and Taif (hot and dry) climates. Peak load, driven by high temperatures and solar gain, directly related to grid stress and operational costs. For Al-Ahsa simulations, August 18, 2023 shows peak loads in all wall cases and scenarios, it revealed that the base wall with XPS insulation recorded a peak load of 13.64 kWh at 14:00, while PCM integration in Wall Case 1, Scenario 1 (PCM + XPS) reduced this to 11.27 kWh at 16:23, achieving a 17.4% peak load reduction and a 2-hour, 23-minute period of peak shift as shown in Figure 28 (a) Al-Ahsa) and (b) Taif. Similarly, replacing XPS with PCM (Scenario 2) lowered

demand to 12.64 kWh at 17:30 (7.3% savings). The uninsulated base wall (Case 2) peaked at 14.31 kWh at 13:30, but PCM integration reduced this to 12.53 kWh at 17:00 resulting to a 12.4% reduction and a 3 hours-30minutes shift.

In Taif simulations shows July 4, 2023 shows peak load in all wall cases and scenarios, it revealed that the base wall with XPS peaking at 9.37 kWh at 13:20. PCM integration (Case 1, Scenario 1) reduced this to 7.09 kWh at 16:23 (24.6% reduction, 3-hours 3 minutes shift), while replacing XPS with PCM (Scenario 2) yielded 7.98 kWh at 17:30 translating to a 14.8% reduction and a 4 hours 10 minutes peak period shift. For the uninsulated base wall base wall (Case 2), PCM integration lowered peak demand from 9.52 kWh at 13:30 to 6.98 kWh at 17:00 which is tantamount to a 26.7% reduction, 3-hour 30-minute shift. These results highlight PCM's ability to decouple thermal demand from peak solar hours, delaying energy use and reducing instantaneous grid strain.

The observed 2–4-hour peak load shifts across both climates demonstrate PCM's potential to reduce HVAC system sizing. For instance, a 17.4% peak reduction in Al-Ahsa equates to a ~20% smaller HVAC capacity, lowering initial costs. Critically, operative temperatures remained within 23–28°C, adhering to ASHRAE 55/EN16798 comfort thresholds (ASHRAE 55, 2022). Nevertheless, these findings align with Saudi Vision 2030's sustainability goals by mitigating reliance on major electrical plants and enhancing grid resilience (Alrashed and Asif, 2012, 2014).

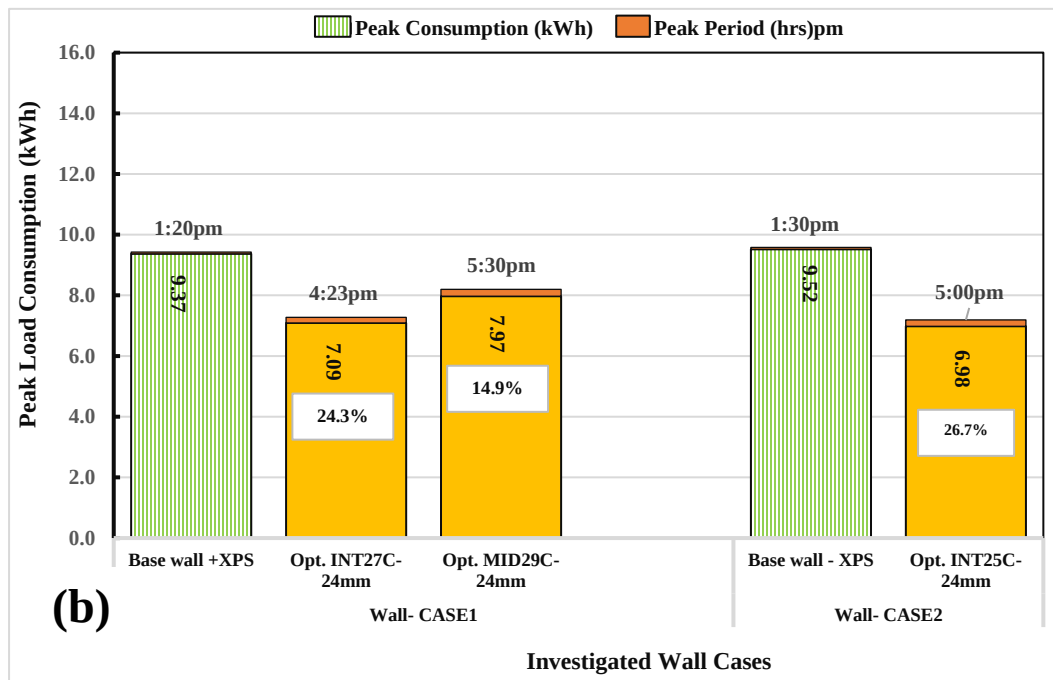
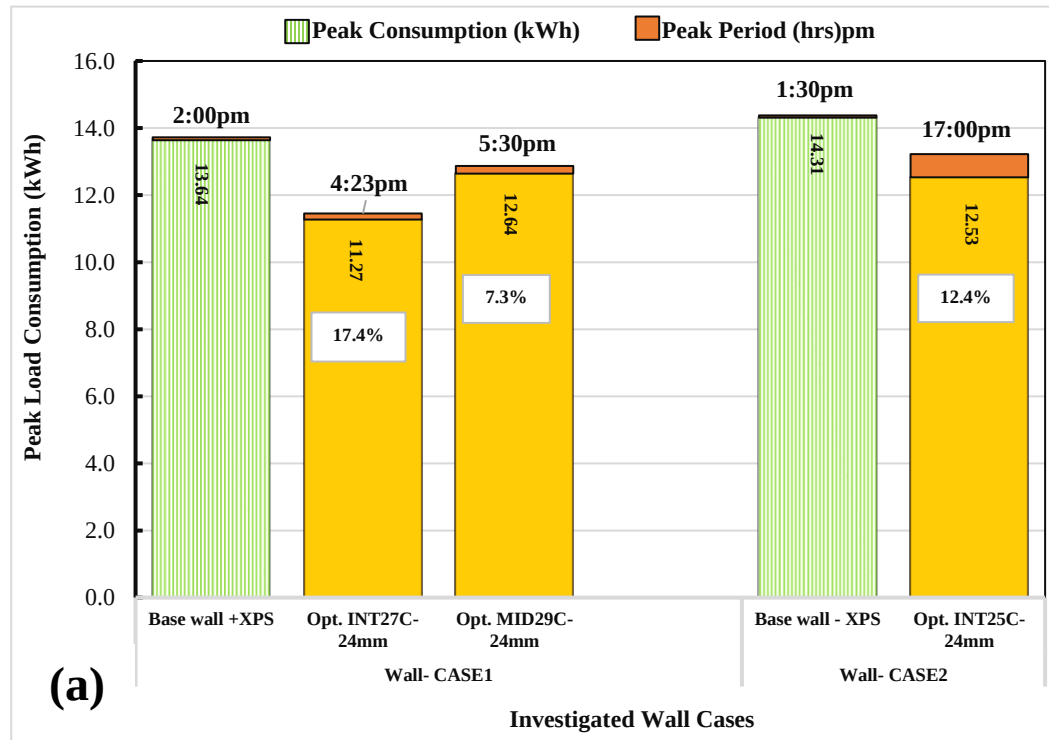


Figure 28: Peak load and period shift profiles (a) Al-Ahsa and (b) Taif

4.7 Thermal Comfort Analysis

Thermal comfort evaluation for PCM-integrated walls was conducted using cooling setpoints ranging from 23°C to 26°C, in accordance with ASHRAE 55's comfort standards, while also examining **annual thermal discomfort (ATD)** as shown in figure 29 (a) Al-Ahsa and (b) Taif and the operative temperature (OT) metrics, as illustrated in figure 30 (a & b). Notably, a cooling setpoint of 24°C resulted in an increase in annual thermal discomfort; for instance, in Wall Case 1, ATD rose from 15% to 19% due to the elevated cooling setpoint of the optimal PCM. Conversely, there was a reduction of up to 10% in ATD for Wall Case 1 and up to 16% for Wall Case 2, which lacked XPS insulation, when compared to the conventional wall without PCM in Al-Ahsa. Similarly, Wall Case 1 in Taif demonstrated a significant ATD reduction of 7%, while Wall Case 2 without XPS insulation showed a 14% decrease in discomfort. This indicates a greater thermal discomfort reduction in Al-Ahsa's hot humid climate compared to the Taif climate.

For example, the optimal Wall Case 1—Scenario 1, which achieved a total energy consumption of 31,065.1 kWh, resulted in cooling and heating energy reductions of 17% (3,429.4 kWh) and 64% (5,202 kWh), respectively, while maintaining a 17% ATD at a cooling setpoint of 25°C, highlighting a critical balance between energy efficiency and occupant comfort. However, DesignBuilder simulations tended to overestimate ATD compared to real-world adaptive comfort tolerances, which consider regional and cultural variations, emphasizing the necessity for localized calibration. Overall, a significant annual thermal discomfort reduction was observed across the climatic locations investigated for both wall cases, reinforcing the effectiveness of PCM-integrated walls in enhancing thermal comfort.

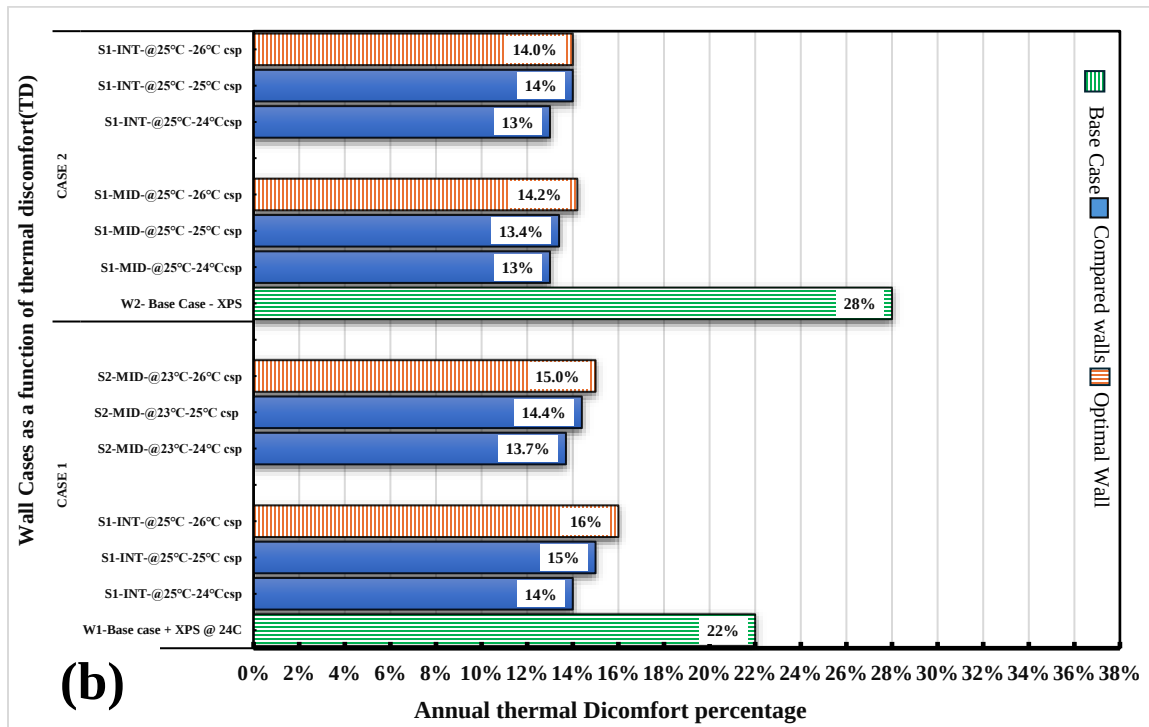
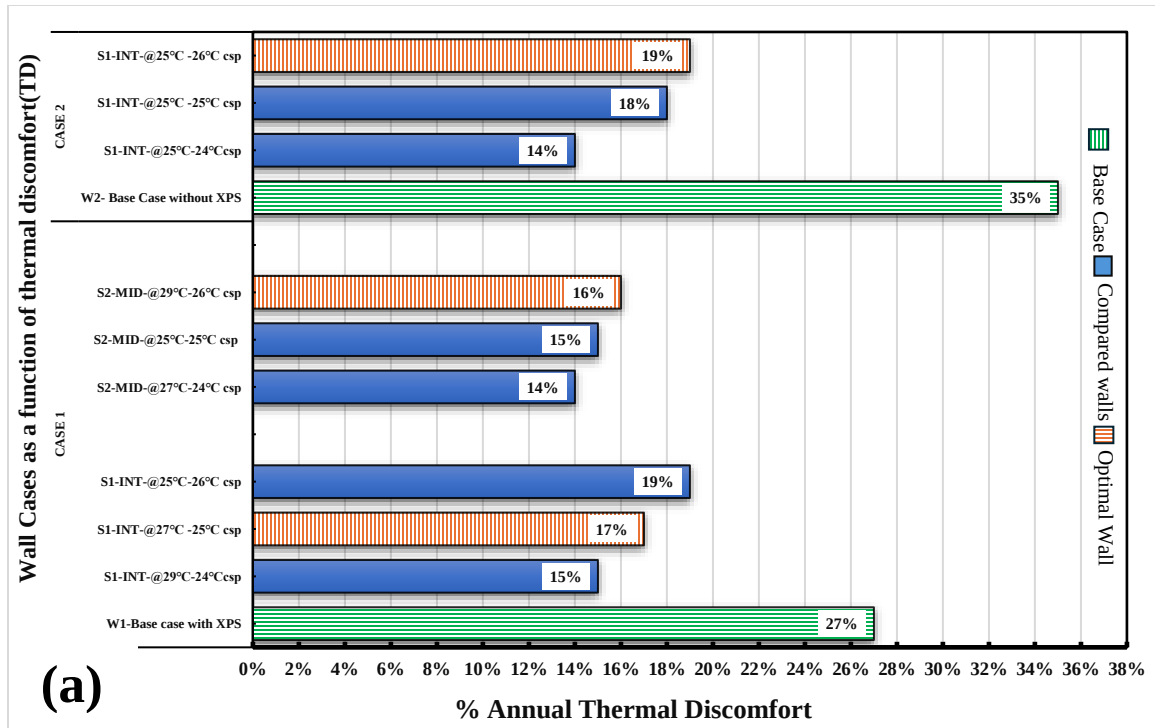


Figure 29: Percentage (%) Annual Thermal Discomfort (ATD) variation as a function of cooling Set points temperatures (a) Al-Ahsa and (b) Taif

Operative temperature (OT): distributions further validate the optimal wall selections and the impact of PCM integration on enhancing thermal comfort. Figure 30 (a & b) shows the operative temperature distribution effect in comparison with the wall cases studied. For instance, the base case wall at a cooling setpoint temperature (CST) of 24°C showed 31% of OT within the 24–26°C range and 20% within the 26–28°C range for Al-Ahsa. In Taif, the base case wall with XPS at the same CST resulted in 28% of OT within the 24–26°C comfort temperature range. The optimal wall cases, maintaining the same cooling setpoint, resulted in OT distributions of 19% to 22% for Al-Ahsa and 21% to 28% for Taif. Notably, PCM integration in the optimal Wall Case 1 at 25°C improved OT by 3%, increasing it from 19% to 22% and 7% OT improvement (21% to 28%) for both Al-Ahsa and Taif. Conversely, Scenario 2, which involved replacing XPS insulation with an 80mm PCM sheet, resulted in a 1% decline in OT and a 3% decrease from 11% to 14% in Taif due to increased discomfort attributed to PCM thickness, which delayed heat dissipation and exacerbated summer discomfort.

In contrast, Case 2 (PCM without insulation) at a CST of 26°C improved OT by 4%, increasing from 11% to 15% in Al-Ahsa, and a 6% OT increment from 15% to 21% was observed for both Al-Ahsa and Taif. The synergy between PCM thresholds (23–26°C) and ASHRAE 55 criteria proves its viability for KSA’s extreme climate, aligning with Vision 2030’s energy resilience goals. This study advances prior research, for instance (Sovetova *et al.*, 2019b), work on quantifying PCM’s dual role in balancing HVAC load reductions—ranging from 17% to 22% for cooling and 35% to 64% for heating—with occupant comfort, even amidst simulated overestimations of discomfort.

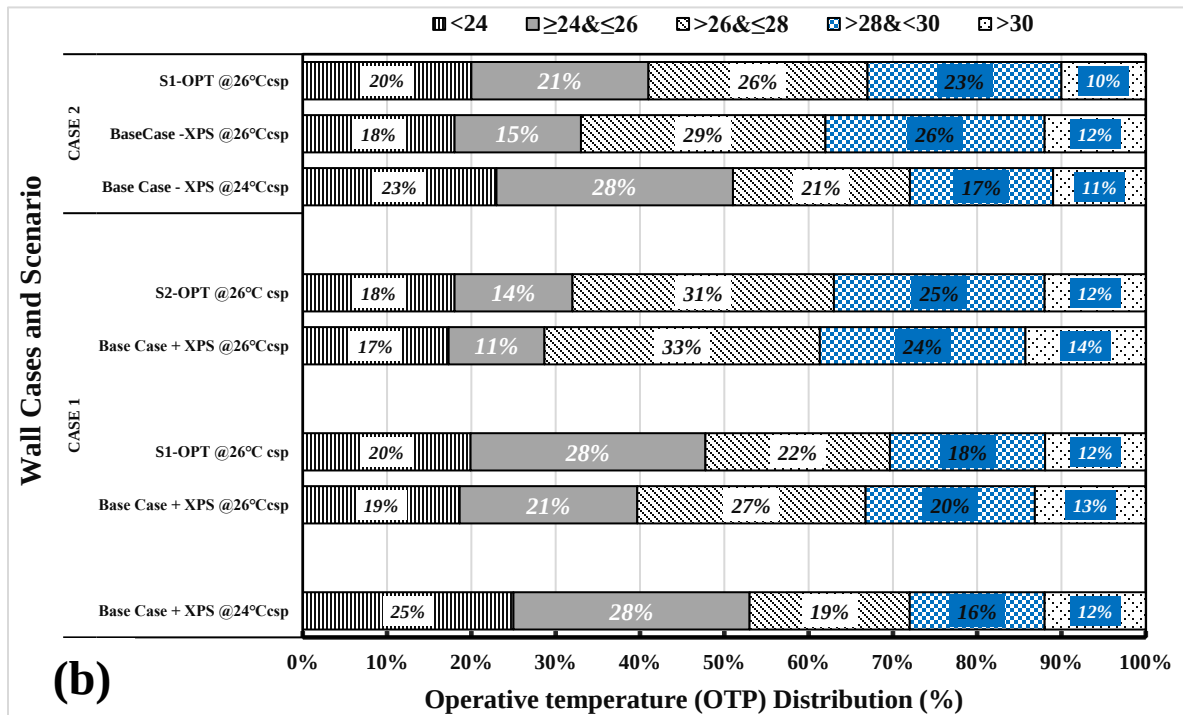
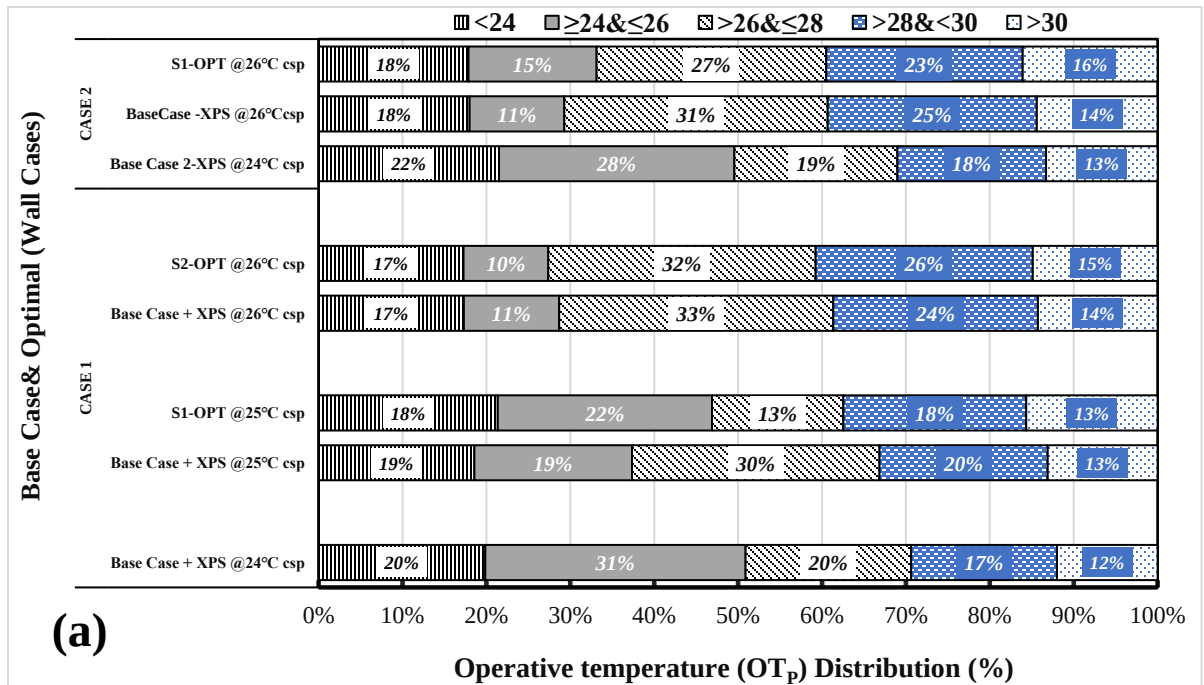


Figure 30: Operative temperature (T_{op}) distribution for the optimal alternatives on the optimization scenarios.

(a) Al-Ahsa) and (b) Taif

4.8 Optimal Melting Temperature Analysis

The genetic algorithm optimization reveals that PCM melting temperatures exceeding cooling setpoints (CSTs) increase annual energy consumption, showing the necessity of aligning phase-change thresholds with HVAC operational parameters. In Al-Ahsa's extreme heat, Scenario 1 (PCM + XPS) achieved 35% heating and 12.6% cooling reductions using an interior-placed 24mm PCM at 27°C (31,065 kWh total energy), while walls with higher melting points (29°C) yielded lower savings (17.1% cooling, 14% heating). Conversely, non-insulated walls (Case 2) with 25°C PCM reduced heating by 60% and cooling by 21.6% (33,829 kWh), demonstrating enhanced efficacy in retrofits. Taif's milder climate showed similar trends, with optimal melting temperatures clustering at 25°C for insulated walls, reducing heating by 53–75.7% and cooling by 30.5–34.2%, attributable to PCM's synchronization with narrower diurnal swings.

These findings confirm PCM's phase-change range (24–29°C) must align with localized CSTs (24–26°C) to optimize thermal buffering—a principle validated by ASHRAE 55 and prior studies (Al-Absi *et al.*, 2021; Al-Absi, Hafizal, *et al.*, 2024). Energy consumption rises non-linearly with melting temperature: a 27°C PCM wall consumed 31,065 kWh, while a 29°C variant reached 31,894 kWh, despite identical thickness and placement. These shows melting temperature as a fixed material property (Rathore and Shukla, 2020; Singh Rathore *et al.*, 2020b) independent of thickness or position, necessitating climate-specific calibration.

Notably, PCM integration disproportionately reduces cooling loads in Al-Ahsa's summers (>45°C), where nocturnal latent heat release offsets daytime gains, contrasting with heating-dominated savings in Taif. Figure 31 illustrates the correlation between melting

temperature proximity to CSTs and energy use, emphasizing the critical balance between PCM material properties and climatic demands.

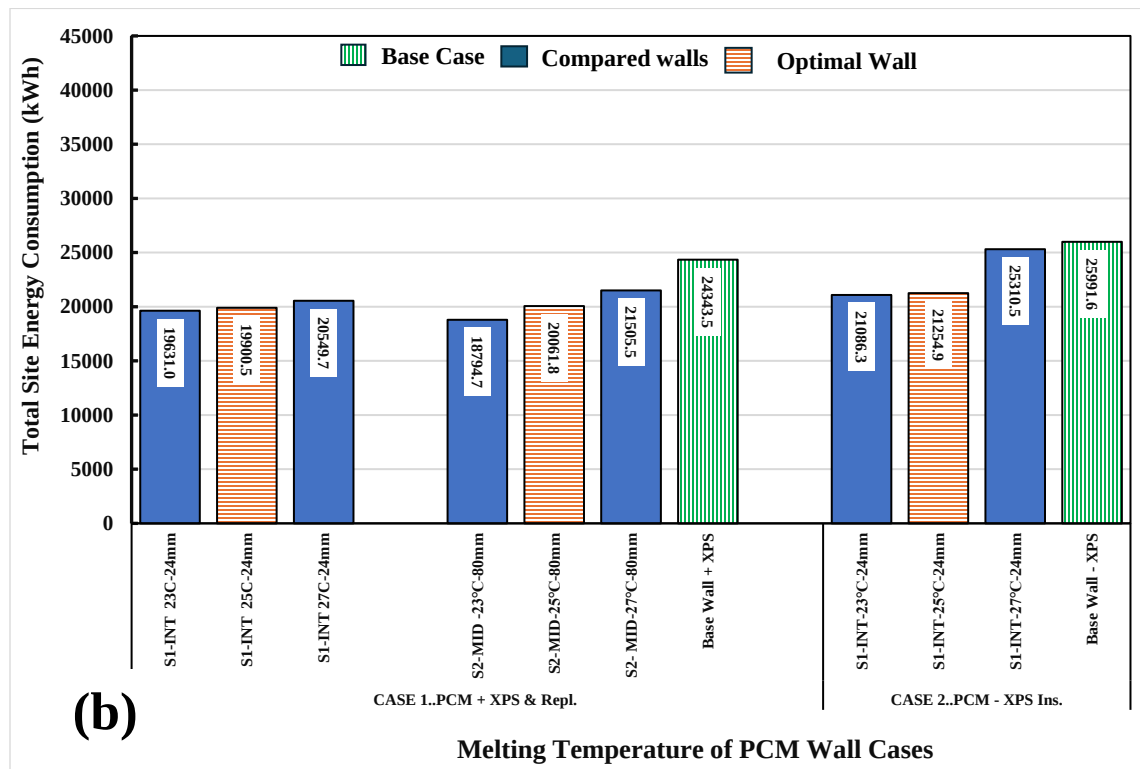
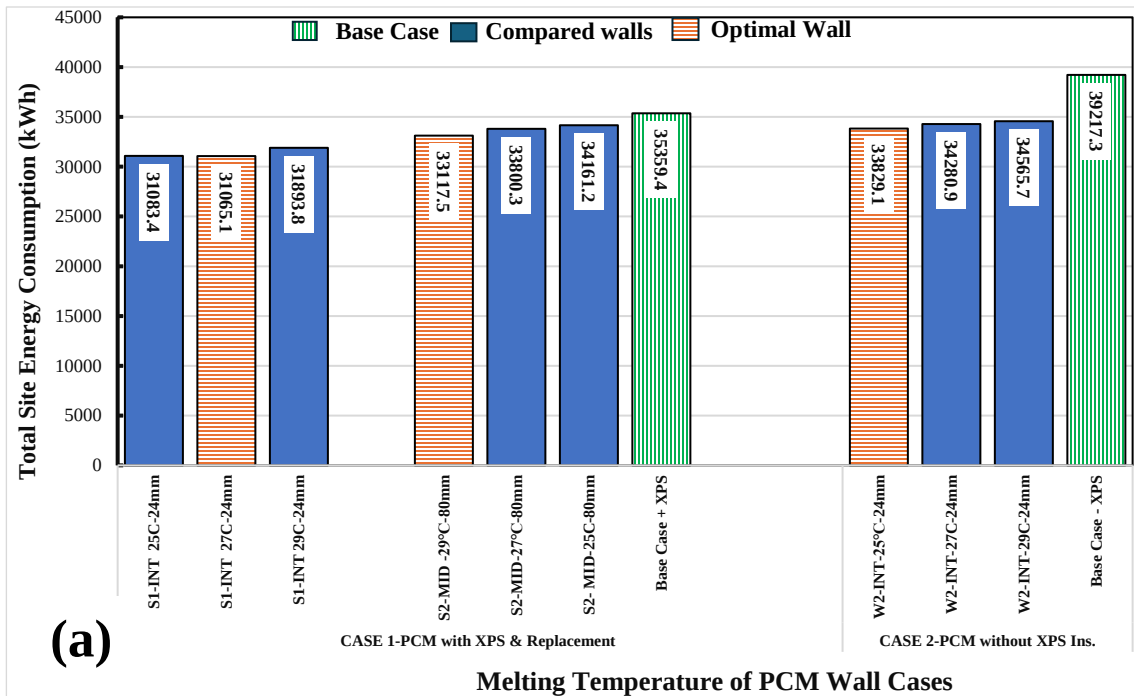


Figure 31: PCM Melting Point temperature effect on total site energy (kWh). (a) Al-Ahsa and (b) Taif

4.9 Optimal PCM Position/Configuration

The optimal positioning of PCM within exterior walls was evaluated across three configurations (interior [INT], middle [MID], exterior [EXT]) for non-insulated walls and four configurations (EXT, MID-EXT, MID-INT, INT) for insulated systems in Saudi Arabia's extreme climates. Genetic algorithm optimization prioritized energy efficiency (total kWh) and thermal discomfort ($\leq 20\%$ annual hours), revealing interior placement (INT) as most effective due to its proximity to indoor temperature fluctuations, which maximize latent heat synchronization with HVAC cycles. Figure 32 shows Comparison of optimal PCM layer configuration on energy consumption(kWh) for all wall cases in Al-Ahsa and Taif. For instance, in Taif's hot and dry climate, moving PCM from exterior (21,852.4 kWh) to interior (21,254.6 kWh) reduced energy consumption by 2.8%, with negligible differences between MID and INT placements (0.002% variance). Similarly, in Al-Ahsa's hot-arid climate, INT placement in insulated walls (Case 1) lowered energy use by 12.3% (31,065 kWh vs. 35,359 kWh baseline), while non-insulated retrofits (Case 2) achieved 18.4% savings (33,829 kWh vs. 35,697 kWh).

Interior positioning consistently enhanced thermal comfort, reducing annual discomfort hours from 20% (EXT) to 18% (INT) in Al-Ahsa, aligning with ASHRAE Standard 55 thresholds. This performance stems from PCM's ability to absorb peak daytime heat and release it during cooler nights, moderating indoor temperature swings—a phenomenon validated by (Al-Absi *et al.*, 2021) and (Sovetova *et al.*, 2019a), who reported 15–25% energy savings disparities between INT and EXT placements in desert climates. While Taif's milder conditions permitted flexibility between MID and INT placements, the latter remained optimal for energy-comfort balance, emphasizing the criticality of PCM's

proximity to conditioned spaces. These findings advance practical guidelines for PCM integration in extreme climates, emphasizing interior placement to harmonize energy resilience with occupant well-being under Saudi Arabia's Vision 2030 sustainability goals.

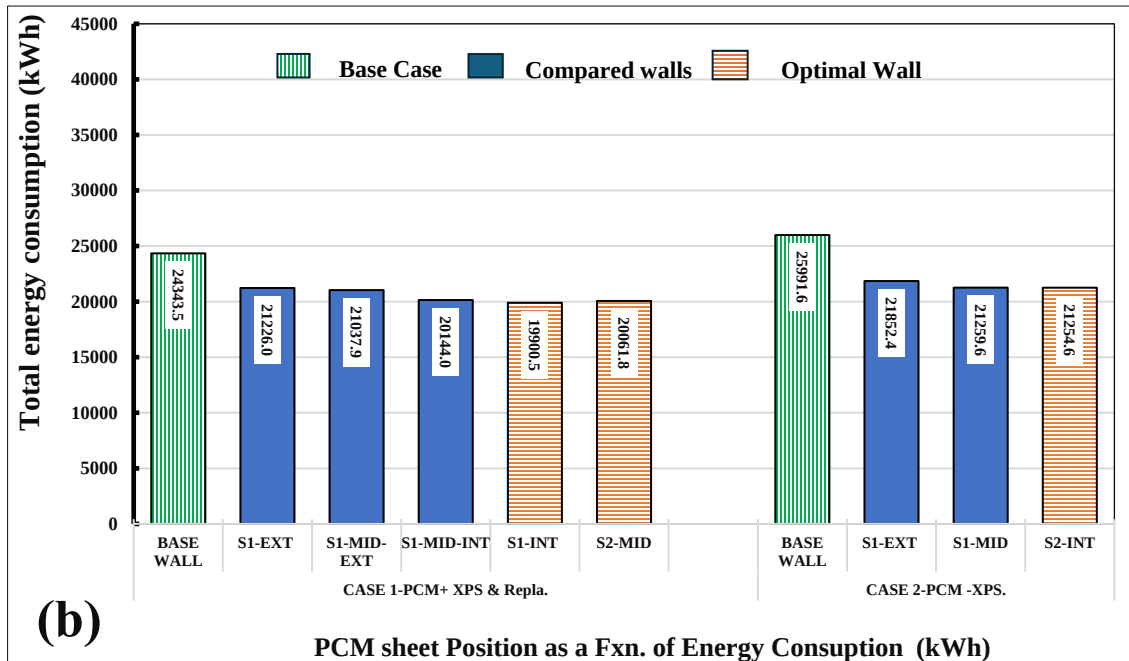
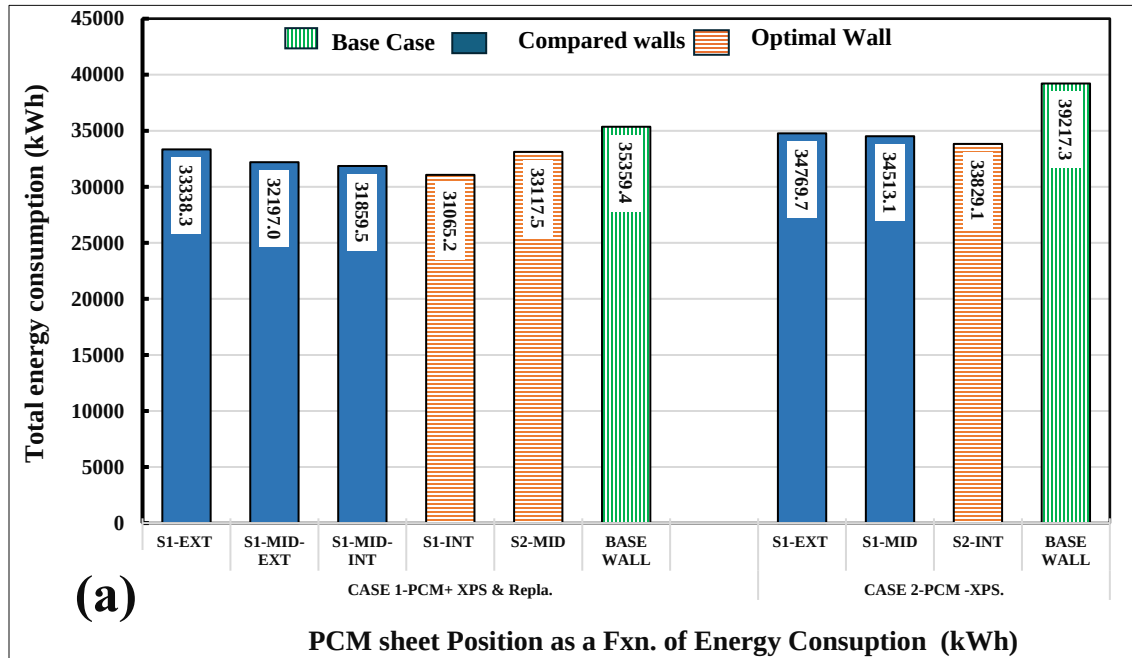
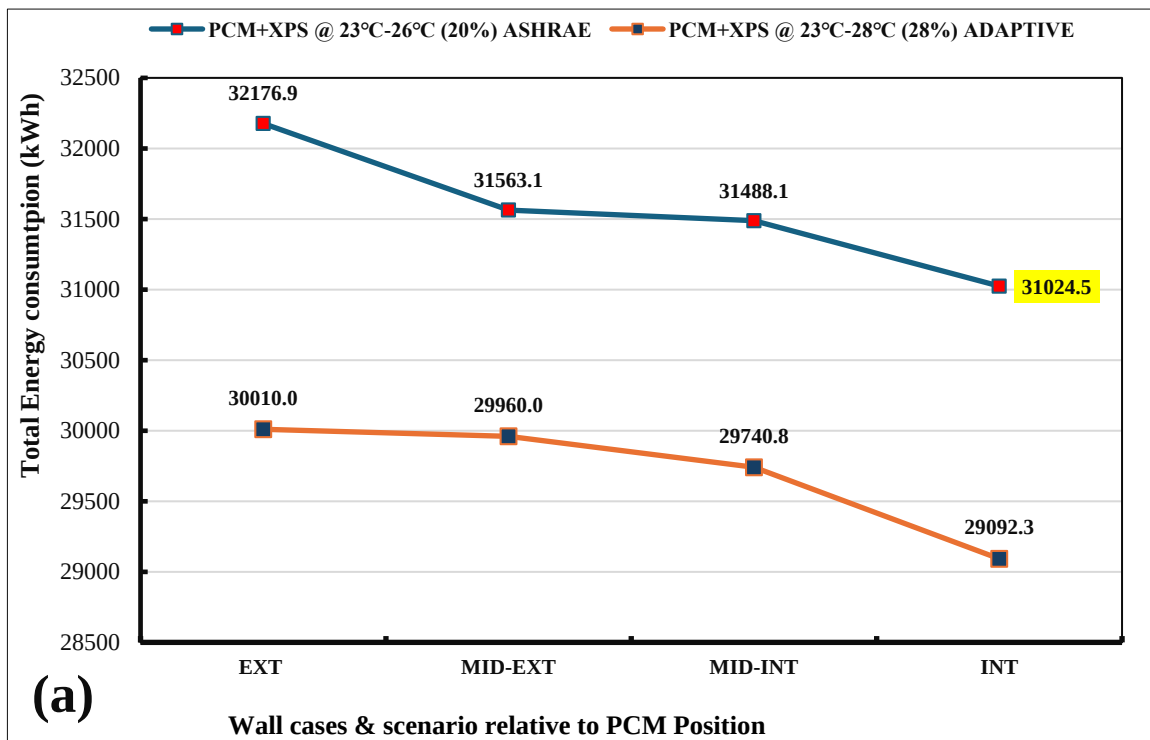


Figure 32: Comparison of optimal PCM layer configuration on energy consumption (kWh). (a) Al-Ahsa and (b) Taif

An additional analysis evaluated PCM positioning in insulated (Case 1) and non-insulated (Case 2) walls across Al-Ahsa and Taif, focusing on energy consumption trends under ASHRAE (23–26°C) and adaptive (23–28°C) operative temperatures as previously shown in Figure 29 and 30 (A & B). Moving PCM from exterior to interior positions reduced energy consumption by 613.8 kWh (sharp decline exterior-to-middle) and 0.7% (middle-to-interior), attributed to the thermal mass of concrete blocks and plaster moderating heat flux. Concurrently, thermal discomfort decreased by 2–4%, with interior placement minimizing exposure to extreme exterior temperature swings, thereby extending PCM lifespan a finding documented by (Kosny *et al.*, 2012a) in durability studies. Figure 33 (a & b) shows the simultaneous decline in energy consumption (kWh) comparison between the ASHRAE and Adaptive comfort range due to PCM position. Similarly, figure 34 (a & b) shows ASHRAE and Adaptive-OTP model- total site energy consumption relative to position for Case1-S1-Optimal PCM wall at Al-Ahsa and Taif.

In Wall Case 2, in both Al-Ahsa and Taif as shown in figure 35 a consistent trend is also observed in the reduction of energy consumption (kWh), corresponding to the decrease in annual total discomfort (% ATD) with the placement of PCM sheets from the exterior (EXT) to the interior (INT) surface. Non-insulated walls (Case 2) with interior PCM achieved energy savings of 18.4% in Al-Ahsa and 18% in Taif, demonstrating practicality for retrofitting existing buildings. The energy-saving variance between placing PCM sheets in the middle (MID) (21259.6 kWh) and on the interior surface (INT) (21254.56 kWh) in Taif is minimal and negligible (0.023 kWh), giving users flexibility in placement. However, this emphasizes the importance of positioning PCM towards the interior surface.

While energy savings between MID and INT placements were minimal, interior positioning optimized latent heat synchronization with HVAC cycles, ensuring stable indoor temperatures and phase-change efficiency (Sovetova *et al.*, 2019a). Exterior/middle placements, conversely, delayed phase transitions due to inconsistent outdoor thermal fluxes, particularly in Al-Ahsa’s humid extremes. These results emphasize interior placement as the optimal strategy for Saudi Arabia, balancing modest energy savings (0.7–2.8%) with enhanced material longevity and retrofit feasibility. By prioritizing PCM’s interaction with stable indoor environments, this approach advances practical guidelines for energy-resilient building envelopes under Vision 2030, addressing both climatic demands and occupant comfort in regions with diurnal swings exceeding 20°C.



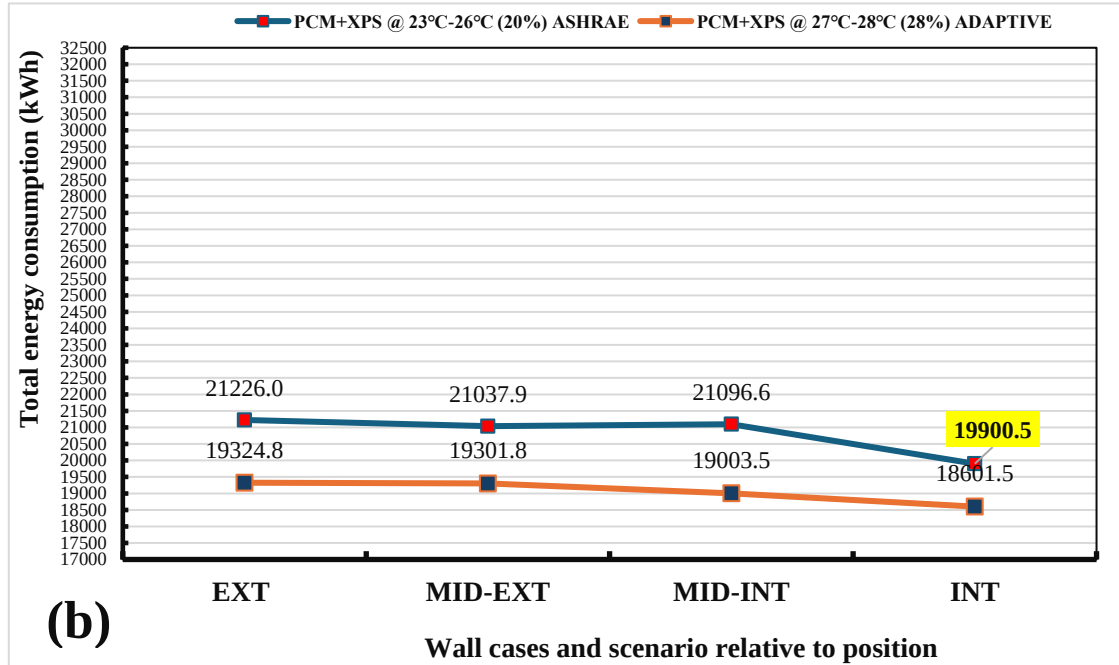
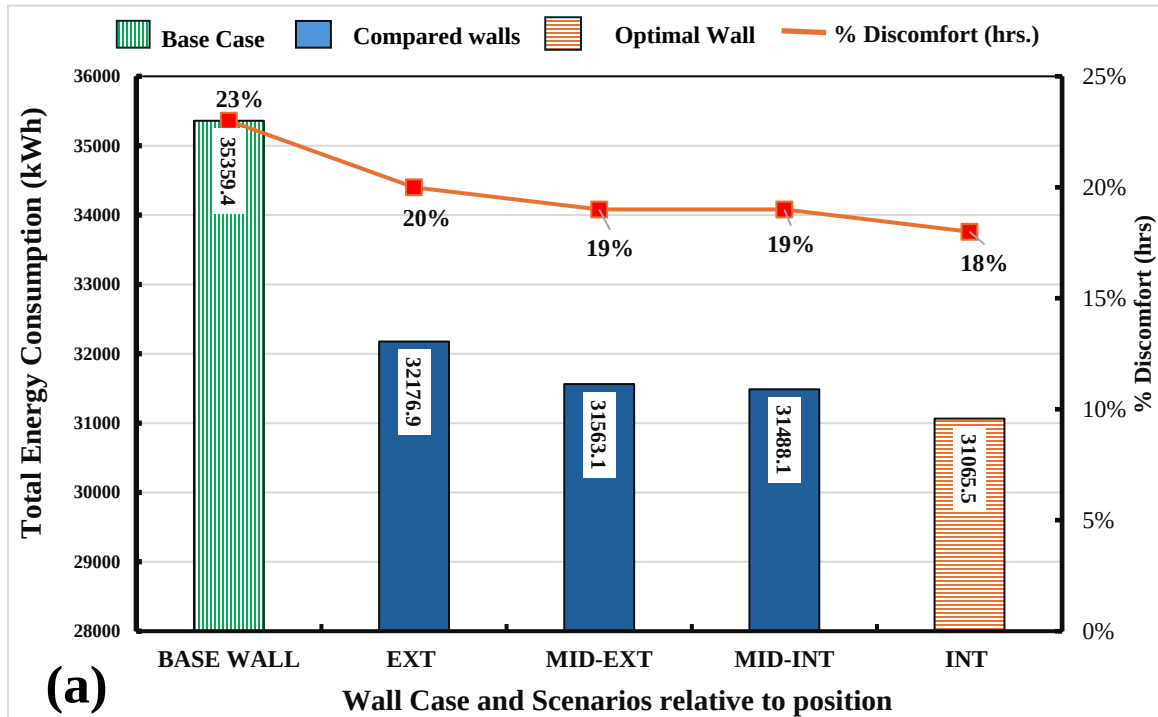


Figure 31 B: Comparison between ASHRAE & Adaptive OTP model for Optimal PCM position -Case 2 -S1 effects on total energy consumption (kWh) (a) Al-Ahsa and (b) Taif.



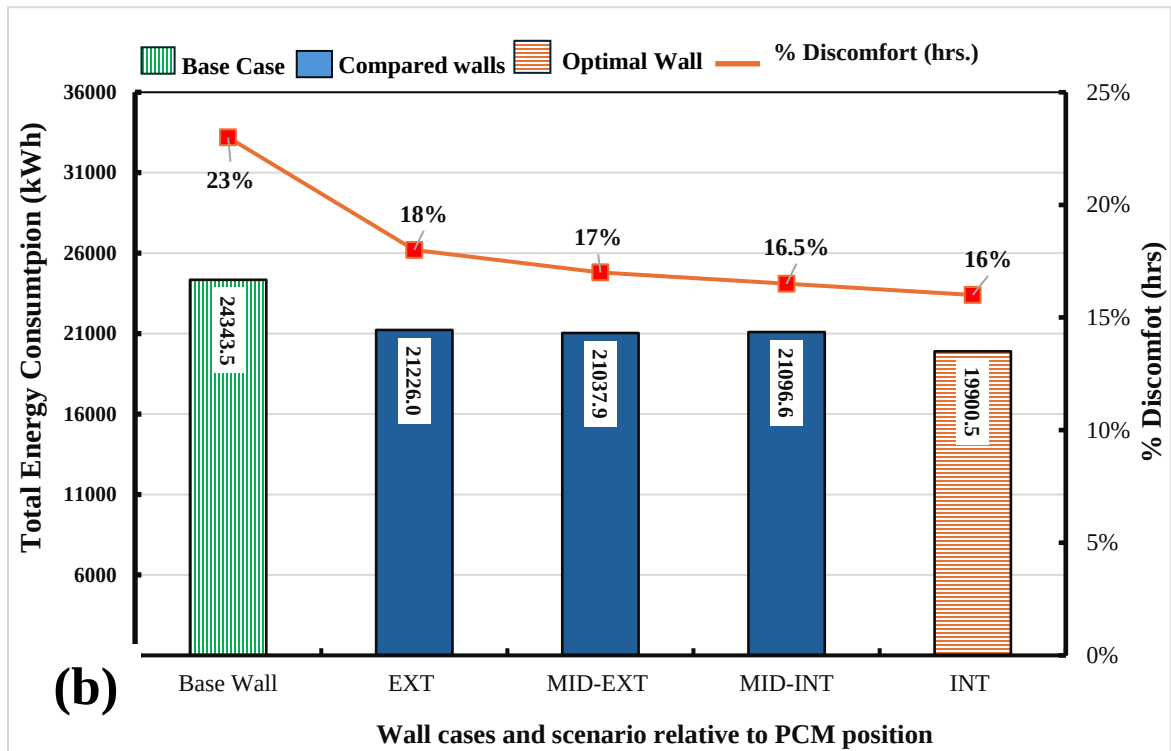
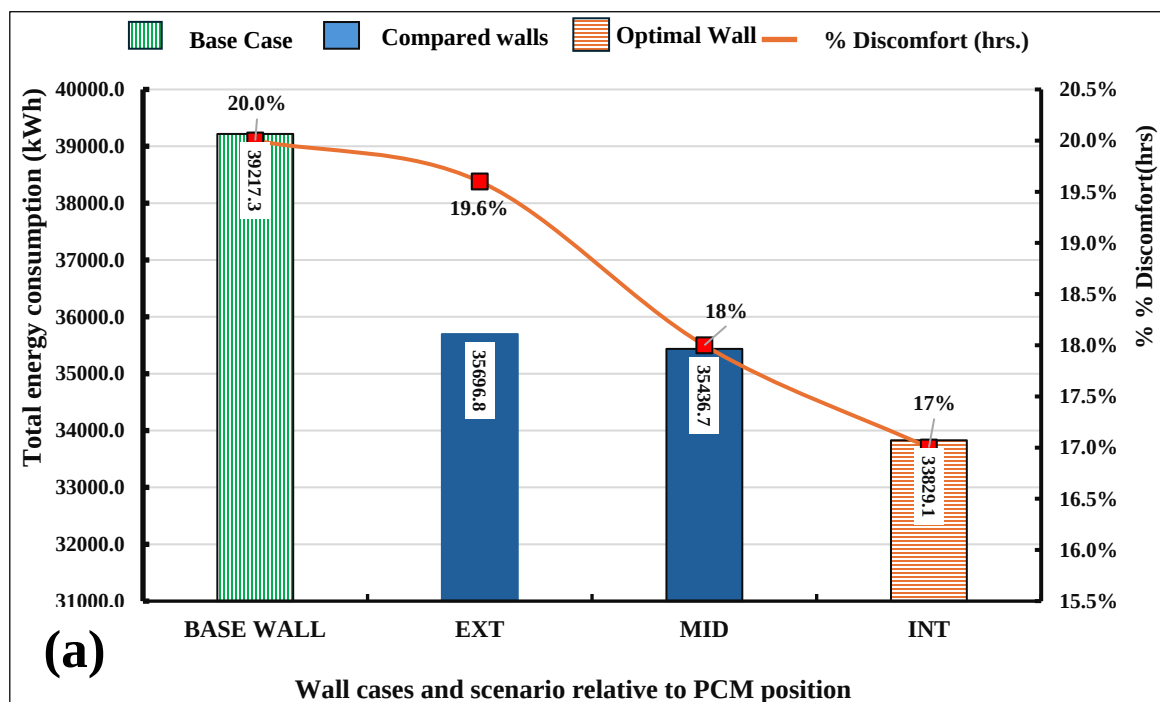


Figure 34: ASHRAE OTP model- total site energy consumption reduction and % ATD relative to PCM sheet position for Case1-S1m (A-i) Al-Ahsa and (A-ii) Taif



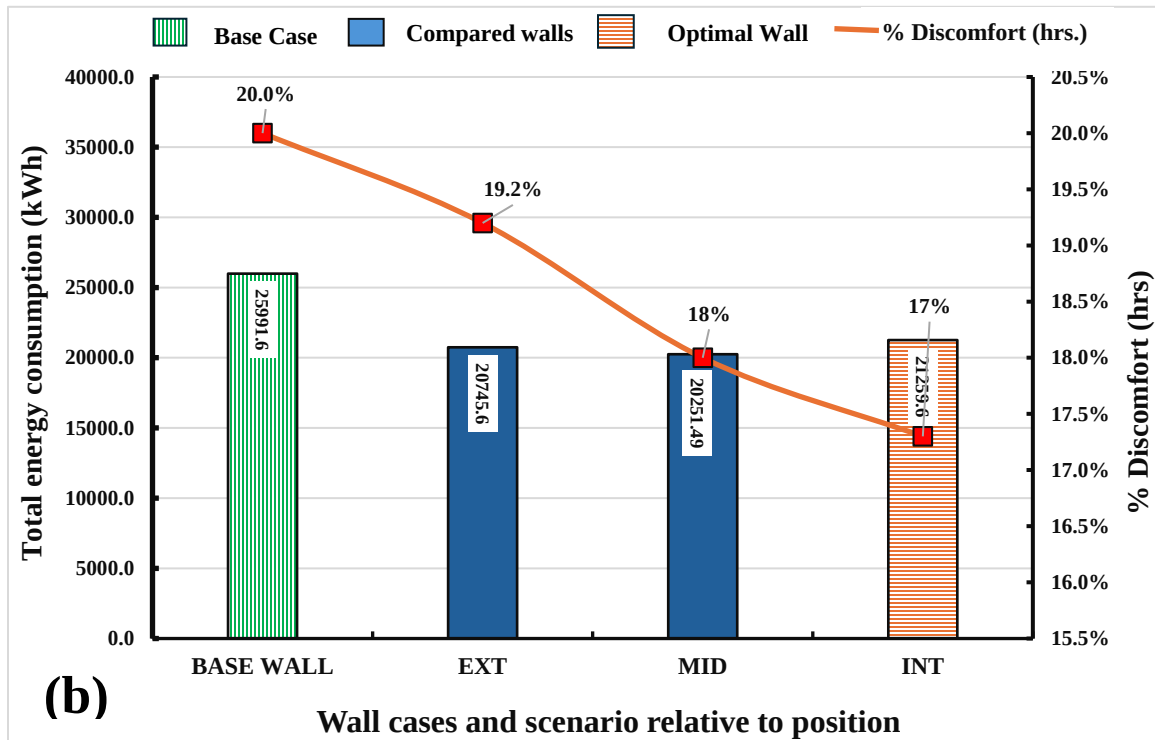


Figure 35: ASHRAE OTP model- total site energy consumption reduction and % ATD relative to PCM sheet position for Case1-S1 (a) Al-Ahsa and (a) Taif

4.9.1 The placement of PCM sheet in wall case 1 scenario 1: Before or After the XPS

The placement of the PCM sheet in Wall Case 1 Scenario 1, either before or after the XPS insulation, was further investigated to determine the optimal configuration, which has been identified as towards the interior surface (INT). Analyzing performance metrics such as percentage annual discomfort hours, total site energy consumption (kWh), and cooling and heating electricity (kWh) revealed that the PCM positioned after the XPS insulation generally resulted in lower discomfort hours compared to when it was placed in front of the XPS. Specifically, discomfort hours in the PCM-after-XPS configuration ranged from 1,281.77 hours to 2,388.22 hours (14.6% to 27.0% per year), whereas the PCM-in-front configuration showed discomfort hours between 1,311.16 hours and 2,369.20 hours (15%

to 27.1% per year). The lower percentage of discomfort in the PCM-after configuration indicates superior comfort, as illustrated in the accompanying figure 36.

Moreover, total site energy consumption was also lower in the PCM-after configuration, which ranged from 29,740.76 kWh to 35,859.57 kWh, compared to 30,031.49 kWh to 35,513.75 kWh in the PCM-in-front configuration. Across both ASHRAE and adaptive operative temperature profiles, a minimal reduction of 0.7% (205 kWh to 255 kWh) was observed, reinforcing the advantages of the PCM-after configuration. This placement not only reduces discomfort hours but also enhances energy efficiency, demonstrating better overall performance in both cooling and heating seasons.

The contrasting roles of PCM as a thermal energy storage material and XPS as a heat barrier depend significantly on their relative placement. XPS effectively blocks outdoor heat from penetrating the wall assembly, thereby reducing the load on both the PCM and the interior environment. In this configuration, the PCM positioned just after the XPS insulation absorbs and releases heat to regulate indoor temperatures, enhancing comfort and minimizing energy consumption. By placing the PCM after the XPS, the system maximizes the benefits of both materials: XPS serves as a protective barrier against outdoor temperature fluctuations, while PCM functions as a thermal buffer, smoothing indoor temperature variations and reducing reliance on mechanical heating and cooling. This configuration proves to be the most effective among the examined wall configurations in achieving both energy efficiency and thermal comfort.

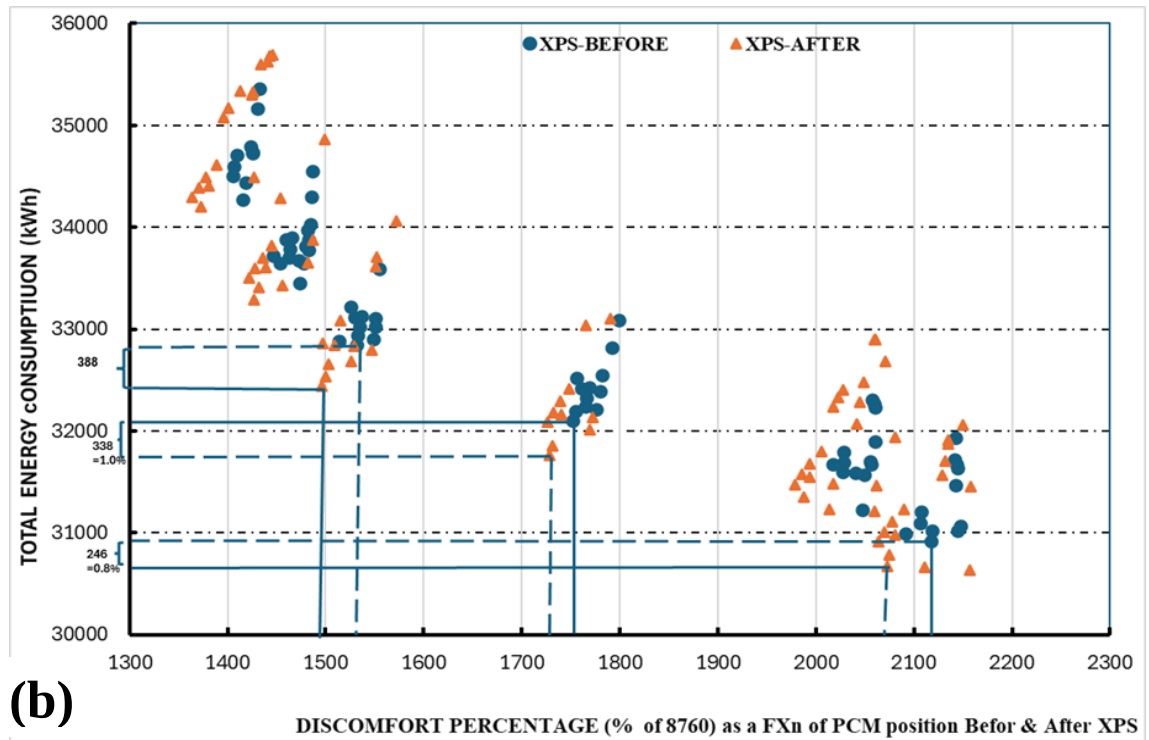
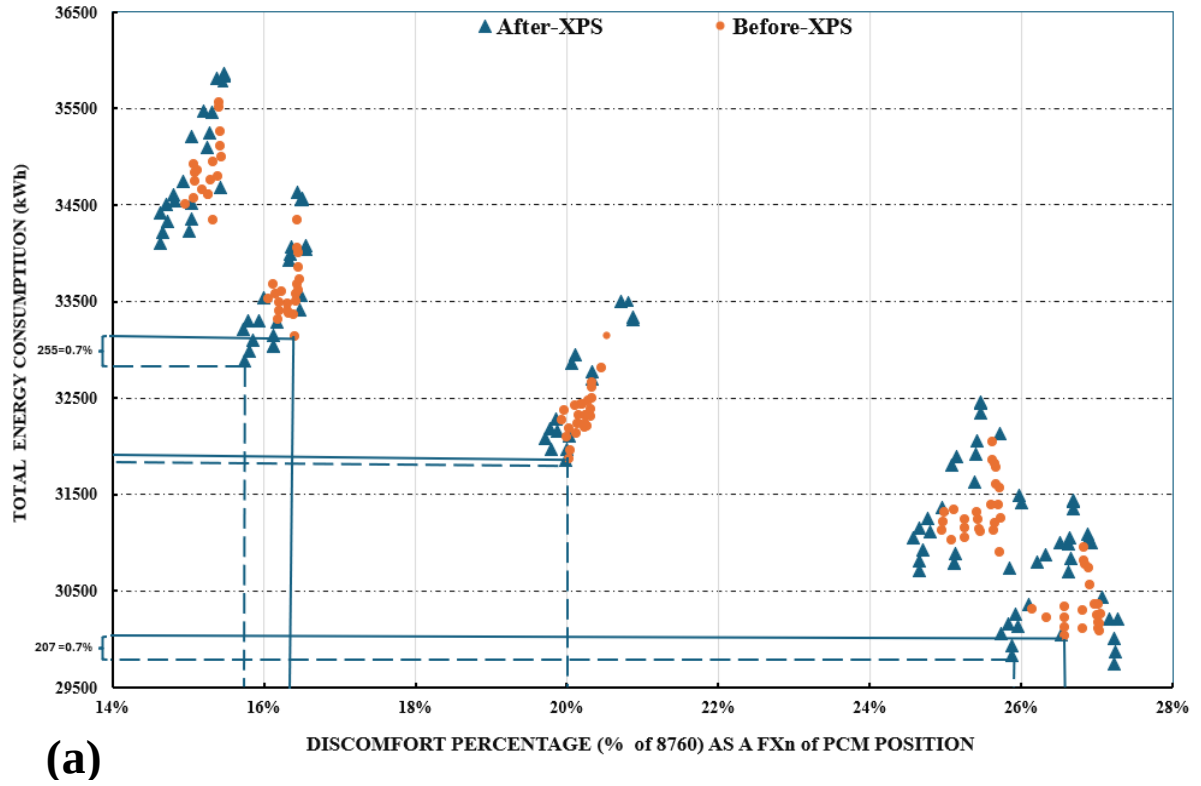


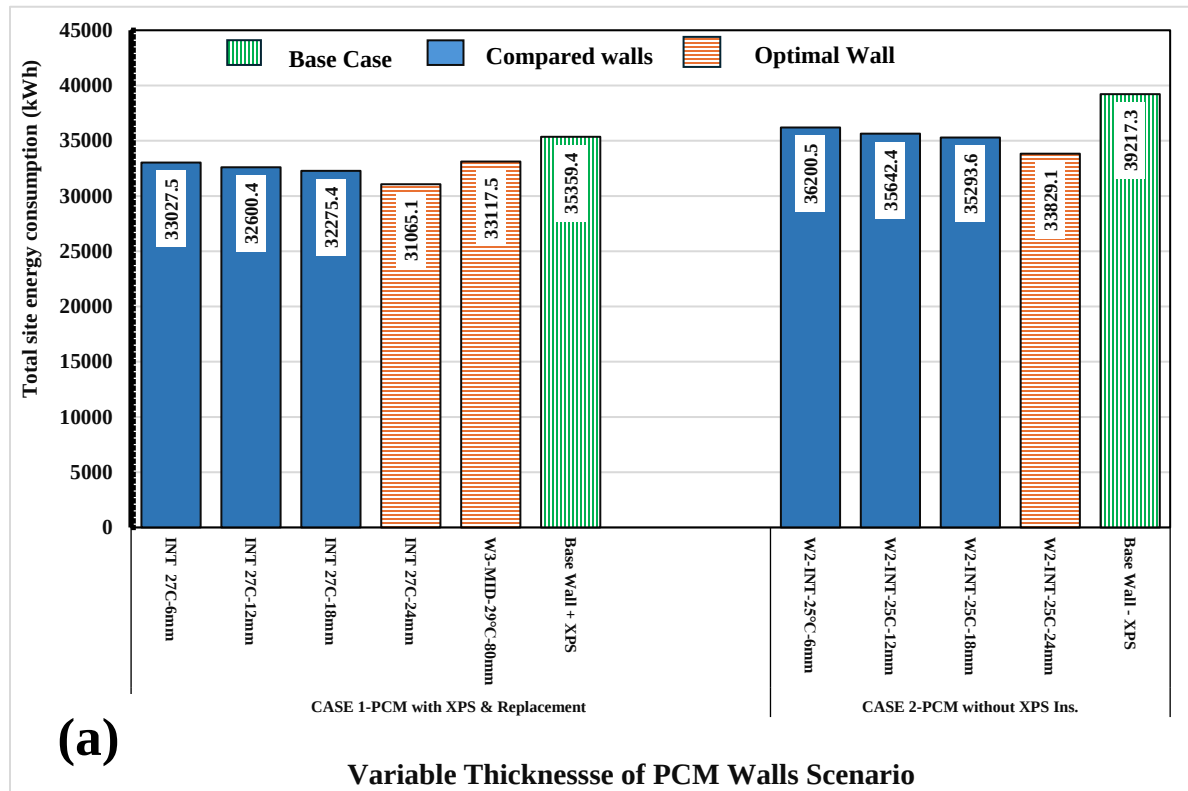
Figure 36: PCM configuration Before or After XPS insulation for (a) Al-Ahsa (b) Taif

4.10 Optimal PCM Thickness Analysis.

The study evaluated macro-encapsulated PCM sheet thicknesses of 6, 12, 18, 24, and 80 mm to identify configurations that maximize energy savings while minimizing thermal discomfort. By maintaining constant parameters, including melting temperature and configuration, the analysis focused on the impact of varying PCM thicknesses incorporated into the wall. For walls with XPS insulation (Case 1), increasing the PCM thickness from 6 mm to 24 mm improved total energy savings from 7 kWh to 12.14 kWh, with the 24 mm variant (INT-27°C-24mm) achieving reductions of 12.6% in cooling and 35% in heating for Al-Ahsa. Similarly, in Taif, increasing the thickness yielded energy savings from 165.9 kWh to 393.7 kWh, with the 24 mm variant (INT-25°C-24mm) achieving 34.2% cooling and up to 80% heating reductions. In non-insulated walls (Case 2), the 24 mm PCM sheets provided 18.4% total energy savings for Al-Ahsa and 18% for Taif, surpassing the performance of thinner layers (6–18 mm, yielding 8.5–11% savings in Al-Ahsa).

However, PCM thicknesses exceeding 30 mm showed diminishing returns; for instance, an 80 mm layer replacing XPS insulation (Scenario 3) achieved only 25% total energy savings but resulted in disproportionately lower reductions in cooling (18%) and heating (14%). This non-linear efficiency gain beyond optimal thickness shows the importance of careful selection. Figure 37 illustrates that the 24 mm thickness—comprising four combined PCM packets—strikes an optimal balance, delivering total energy savings of 12–15.2% and HVAC load reductions of 10–76% across cases while minimizing thermal discomfort. This finding aligns with (Al-Absi *et al.*, 2021), who identified 24 mm as a cost-effective solution for KSA’s climate due to latent heat saturation limits.

Thicker PCM layers, such as 80 mm, introduced trade-offs; while they achieved 8.6% cooling and 20.7% heating savings, their higher material costs and delayed heat dissipation—particularly in summer—diminished their cost-benefit ratios. Thus, the results emphasize that PCM serves as a supplementary, rather than a replacement, insulation layer in arid climates, with 24 mm emerging as the critical threshold for harmonizing energy resilience, occupant comfort, and economic feasibility in alignment with Vision 2030 targets.



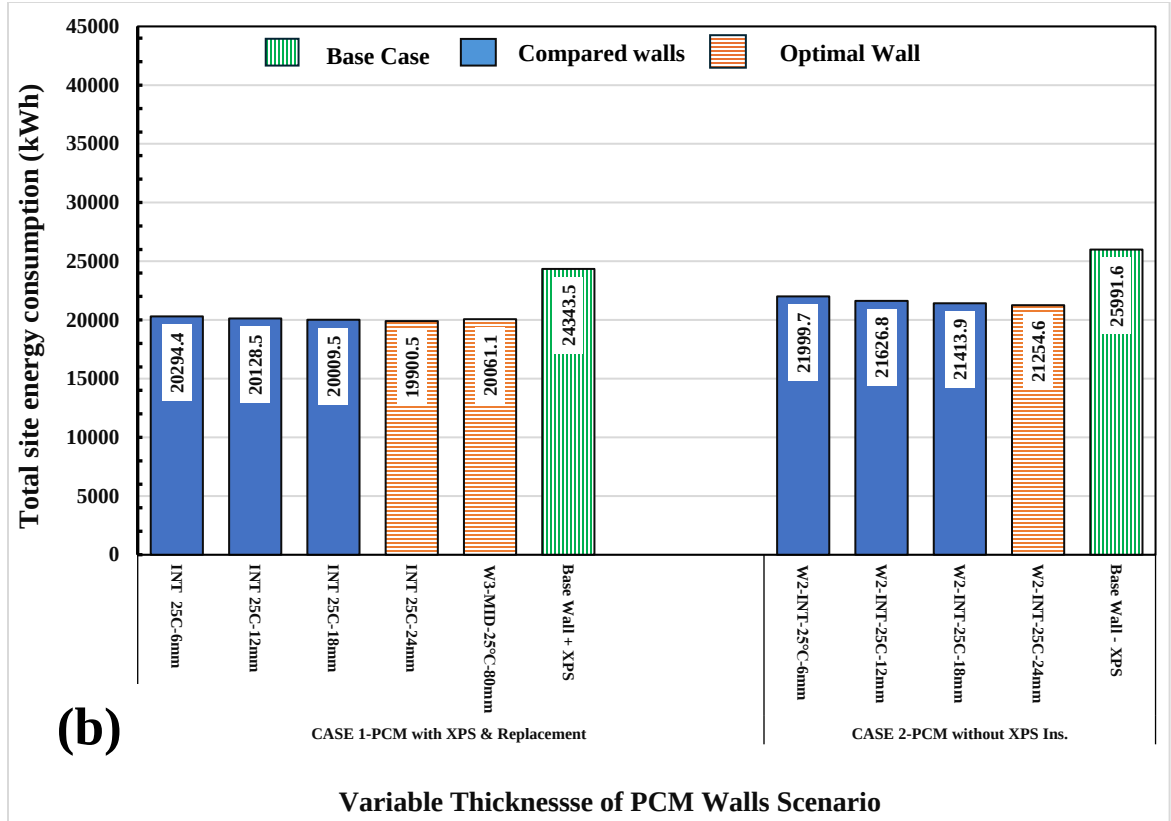


Figure 37: Total site energy comparison chart for the optimal wall case scenario of the tested PCM layer thicknesses (a) Al-Ahsa and (b) Taif

4.11 Environmental Viability

Integrating phase change materials (PCMs) into building envelopes significantly enhances sustainability by reducing energy consumption and associated CO₂ emissions. InfiniteR PCMs are non-toxic and recyclable, preserving indoor air quality while aligning with circular economy principles and minimizing waste throughout their lifecycle. Utilizing Saudi Arabia's grid-specific emissions factor of 0.5059 kg CO₂e/kWh (Gütschow, 2021), the annual CO₂ mitigation potential of PCM-integrated walls was quantified. In Al-Ahsa, optimal wall configurations (Case 1-scenario 1 & 2 and case 2-scenario 1) achieved energy savings of 3,336.1 kWh, 7,197 kWh, and 3,016.8 kWh per year, corresponding to annual CO₂ reductions of 1,687.7 kg, 3,640.96 kg, and 1,526.2 kg, respectively. In Taif, the

optimal walls (Case 1-scenario 1 & 2 and case 2-scenario 1) achieved energy savings of 4,443.0 kWh, 4,282.5 kWh, 4,736.7 kWh, and 4,732.0 kWh per year, leading to reductions of 2,247.7 kg, 2,166.5 kg, 2,396.3 kg, and 2,393.9 kg of CO₂ emissions, respectively.

These reductions result from PCM's effectiveness in stabilizing indoor temperatures, thereby decreasing reliance on HVAC systems in a region where fossil fuels dominate electricity generation. The findings affirm that PCMs serve as a dual-benefit solution, effectively reducing operational carbon footprints while supporting material circularity. This represents a critical advancement for sustainable construction in extreme climates, emphasizing the importance of innovative materials in addressing environmental challenges.

4.12 Research Results/Findings Summary

A comparative analysis of the two PCM-integrated wall cases (W1 and W2) across three scenarios was conducted against conventional base case walls with and without XPS insulation. This investigation utilized a dynamic coefficient of finite differences simulation based on 2023 weather files for Al-Ahsa (very hot and dry) and Taif (hot and dry) in DesignBuilder Version 7.3 (V 7.3). Key findings revealed that PCM integration shifted peak cooling loads by 2–4 hours, reducing grid strain and enabling HVAC downsizing (e.g., 20% capacity reduction in Al-Ahsa), while maintaining operative temperatures within 23–28°C (ASHRAE 55, 2022). It is found that the peak load reduction demand in all the investigated optimal PCM wall cases and scenarios for the two climate ranges from 12.4–26.7%. The Peak shifting reduces strain on grid during highest solar gain supporting Saudi Vision 2030 energy sustainability goals. Table 11 presents a comprehensive overview of the key findings regarding optimal PCM integration including

but not limited to the optimum transition/melting temperatures that was discovered from the genetic algorithm, PCM sheet positions, and thicknesses in the composite wall assemblies cases. These configurations were evaluated for their ability to minimize energy consumption while adhering to ASHRAE thermal comfort criteria.

Key findings indicate that:

- W1-S1-INT-27°C-24mm@25°C CST (Wall Case 1, Scenario 1) achieved a total energy reduction of 12.6% (32,023 kWh), with corresponding savings of 12.6% in cooling and 35% in heating, demonstrating the effectiveness of interior PCM placement in synchronizing phase change with HVAC cycles for Al-Ahsa. In contrast, W1-S2-INT-25°C-24mm@25°C CST for Taif resulted in an 18% total energy reduction (4,443.0 kWh), achieving 30.5% cooling and 61% heating energy reductions, highlighting the higher efficiency of PCM in the moderately cold climate of Taif compared to the humid conditions in Al-Ahsa.
- For W1-S2-MID-29°C-80mm@26°C CST in Al-Ahsa, total energy savings reached 6.34% (2,241 kWh reduction) with HVAC load reductions of 17.05% in cooling and 14% in heating, indicating trade-offs associated with thicker PCM layers. In Taif, W1-S2-MID-25°C-80mm@26°C CST delivered 13% total energy savings (4,282.5 kWh reduction) with load reductions of 32.2% in cooling and 53% in heating. Notably, while replacing XPS insulation with PCM of the same thickness (80 mm) resulted in considerable energy savings in both climates, Taif demonstrated greater overall savings. If economic considerations allow, using PCM of the same thickness as traditional insulation materials like XPS can yield up to 20% more savings.

- W2-INT-25°C-24mm@26°C CST (Wall Case 2, Scenario 1) for Al-Ahsa achieved 18.4% total energy savings, with a 60% reduction in heating loads and a 21.6% reduction in cooling loads, illustrating PCM's enhanced efficacy in non-insulated walls for winter resilience. Similarly, W2-INT-25°C-24mm@26°C CST for Taif resulted in an 18.2% total energy savings (4,732 kWh reduction) with cooling and heating load reductions of 34.2% and 75.7%, respectively.
- This underscores the retrofit potential in the integration of PCM in Non-Insulated Walls: For instance, in Case 2, PCM alone achieved 18.4% energy savings in Al-Ahsa and 18.2% in Taif, with heating load reductions up to 75.7%, demonstrating PCM's standalone efficacy in retrofits for winter resilience.

In summary climate-specific shows PCM optimization: In Al-Ahsa (extremely hot-dry), optimal PCM integration (INT-27°C-24mm) reduced total energy consumption by 12.6% (32,023 kWh) with 12.6% cooling and 35% heating savings. For Taif (hot-dry), a lower melting point PCM (INT-25°C-24mm) achieved 18.2% total energy reduction (4,443 kWh), emphasizing PCM's adaptability to milder diurnal temperature swings.

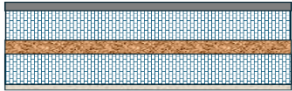
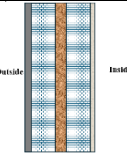
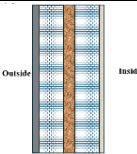
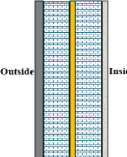
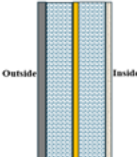
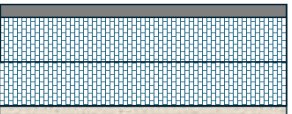
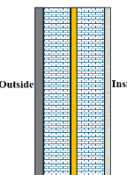
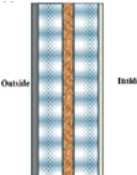
- The Peak Load Shifting show the integration of PCMs in all the wall cases shifted peak cooling loads by 2–4 hours, resulting in a 12.4–26.7% reduction in peak load demand across various scenarios, significantly alleviating grid strain during peak solar gain periods.

All optimal configurations prioritized a 24 mm PCM thickness, effectively balancing latent heat storage capacity with material cost-effectiveness. Interior positioning consistently

outperformed middle or exterior placements by stabilizing indoor temperatures within $\pm 1.5^{\circ}\text{C}$ of CSTs ($24\text{--}26^{\circ}\text{C}$) and reducing annual thermal discomfort by 16–22% compared to base cases. In Taif, the placement of the PCM sheet from middle to interior showed negligible improvement (0.002%), allowing users to choose their preferred configuration. However, placing the sheet closer to the interior is advisable for ease of maintenance, enhanced indoor comfort, and extended lifespan.

This study revealed that summer optimization conditions yield the most significant reductions in annual energy consumption, given the heightened demand for cooling energy. These results align with findings by (Al-Absi *et al.*, 2021; Sovetova *et al.*, 2019b), which emphasize 24 mm as the critical thickness for arid climates and the benefits of interior placement for peak load shifting. Collectively, the data validates the viability of PCM in extreme climates, achieving 10–76% HVAC load reductions without compromising adaptive comfort thresholds.

Table11: Results summary of optimal parameters of the different wall cases scenario

Wall Cases & Scenario	Position/ Configuration		Image/Figure		Opt. Melting Temperature (°C)		Thickness or Quantity (mm)		Annual Energy Saving (kWh) & Percentage (%)		Annual Energy Use Index (EUI) kWh/m2		CO2-Emmission Savings (Kg) (%) savings)	
	Ahasa	Taif	Ahasa	Taif	Ahasa	Taif	Ahasa	Taif	Ahasa	Taif	Ahasa	Taif	Ahasa	Taif
Base Case wall with XPS Insulation	—				—		—		35359.4	24343.5	142.67	90.06	17888.3	12315.4
W1-S1- Optimum PCM wall with XPS	INT	INT			27	25	24	24	31065.2 (12.6%)	19900.5 (18.3%)	135.5	83.3	15715.9 (12.1%)	10067 (18.2%)
W1-S2- Optimal 80mm PCM replacing XPS.	MID	MID			29	25	80	80	33117.5 (6.34%)	20061.1 (17.6%)	141.53	84.4	16744.2 6.4%)	10148.9 (17.6%)
Base Case without XPS insulation	—				—		—		39217.3	25991.6	154.5	85.73	19828.3	13,149. 15
W2-S1-Optimal PCM wall without - XPS	INT	MID & INT			25	25	24	24	33829.1 (18.4%)	21254.9 (18.2%)	148.16	76.06	17114.1 (13.7%)	10752.9 (18.2%)

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS (GUIDELINES)

The integration of Phase Change Materials (PCMs) into building envelopes presents a transformative solution to mitigate energy inefficiencies in extreme climatic conditions, particularly in regions like Saudi Arabia, where cooling demands dominate 50–70% of residential energy consumption. This research systematically evaluated the energy performance and thermal comfort benefits of PCM-enhanced exterior walls across two distinct climatic zones Al-Ahsa (extremely hot and dry) and Taif (hot and dry)—through a robust simulation-optimization framework. By leveraging EnergyPlus/DesignBuilder and genetic algorithms, the study advanced region-specific guidelines for PCM deployment, addressing critical gaps in whole-building analyses under extreme climatic conditions.

5.1 Key findings and contributions:

- **Optimal PCM Configurations:** Interior placement of 24 mm thick InfiniteR PCM (melting temperature: 25–27°C) emerged as the most effective configuration, reducing total energy consumption by 12.6–18.4% in Al-Ahsa and 13–18.2% in Taif. This positioning synchronized PCM’s latent heat storage with indoor thermal cycles, stabilizing operative temperatures within $\pm 1.5^{\circ}\text{C}$ of cooling setpoints (23–26°C) and minimizing annual thermal discomfort by 14–22% compared to conventional walls.
- **Climate-Specific Performance:** In Al-Ahsa’s extreme heat (peak $>45^{\circ}\text{C}$), PCM reduced cooling loads by 12.6–21.6%, while in Taif’s milder climate, heating demand decreased by 53–75.7%, showing PCM’s dual role in offsetting both cooling and heating extremes.

- **Peak Load Shifting & Grid Resilience:** PCM integration shifted peak cooling loads by 2–4 hours, reducing grid strain during peak solar hours. For example, Al-Ahsa’s peak load dropped by 17.4% (13.64 kWh → 11.27 kWh), enabling 20% HVAC downsizing and aligning with Saudi Vision 2030 sustainability targets.
- **Thickness and Material Synergy:** A 24 mm PCM layer demonstrated cost-effective energy density, balancing latent heat saturation and material costs. While thicker layers (e.g., 80 mm) showed diminishing returns, replacing XPS insulation with PCM of equivalent thickness yielded up to 20% greater savings in Taif, highlighting its standalone viability in retrofits.
- **Environmental Impact:** Optimal configurations reduced CO₂ emissions by 1,526–3,640 kg/year per villa, aligning with Saudi Arabia’s Vision 2030 sustainability targets. PCM’s non-toxic, recyclable properties further support circular economic principles.

5.2 Recommendations for Practice

- Deploy inorganic PCMs (e.g., InfiniterR) with melting points tailored to local climates: 27°C for Al-Ahsa (extremely hot and dry) and 25°C for Taif (hot and dry) to align with HVAC setpoints, achieving 12.6–34.2% cooling and 35–80% heating reductions.
- **New Construction** should Prioritize interior-layer macro-encapsulated PCMs (24 mm thickness, 25–29°C melting range) in exterior walls, combined with XPS insulation, to synchronize phase-change cycles with HVAC operations.
- **Retrofits:** Replace non-insulated wall cavities with 24–80 mm PCM panels (melting temperature $\approx 2^\circ\text{C}$ above regional average nighttime lows) to leverage thermal buffering in extreme diurnal climates.
- Integrate PCM with XPS insulation in new builds; placing PCM after insulation blocks exterior heat while buffering indoor temperatures, achieving 12.6% energy savings.

- Leverage EnergyPlus/DesignBuilder simulations with genetic algorithms to calibrate PCM parameters (melting point, thickness) for localized performance, ensuring 10–30% energy savings and compliance with Saudi Vision 2030.
- Promote PCMs for carbon mitigation (1,527–3,641 kg CO₂/year reduction per villa) and incentivize adoption via revised building codes (SBC 601/602) and ROI-driven policies (5–7-year payback in desert climates).
- **Codes and Standards:** Update Saudi Building Code (SBC 601) to mandate PCM integration in residential envelopes for regions with greater than 15°C diurnal swings, emphasizing climate-specific melting temperatures and interior positioning.

5.3 Guidelines for Phase Change Material (PCM) Integration in Building

Envelopes

Following the below structured guidelines, stakeholders and engineers can effectively integrate PCMs into building envelopes, enhancing energy performance, improving indoor comfort, and contributing to sustainability goals in extreme climatic conditions. These guidelines provide a comprehensive framework from material selection through practical application and regulatory compliance, ensuring a holistic approach to energy-efficient building design. Figure 38 shows a structured framework on the procedural guidelines on PCM applications in building envelopes.

1. Material Selection & Climate-Specific Tuning

Step 1: Climate Analysis

- Conduct a localized climate analysis to determine diurnal temperature ranges (e.g., Al-Ahsa: 15–48°C; Taif: 20–40°C).
- Prioritize regions with diurnal swings >15°C for PCM deployment.

Step 2: PCM Type and Melting Temperature

- Inorganic PCMs: Select non-flammable, thermally stable PCMs (e.g., salt hydrates like InfiniteR).
- Melting Point:
 - Hot-arid climates (Al-Ahsa): 25°C - 27°C ($\pm 1^\circ\text{C}$) to align with peak daytime heat absorption.
 - Hot-dry/moderate climates (Taif): 25°C ($\pm 1^\circ\text{C}$) to address milder daytime peaks and cooler nights.

Step 3: Encapsulation Method

- Use macro-encapsulation (e.g., panels, pouches) for ease of installation and durability.

2. Design & Integration Protocol

Step 4: Positioning in Wall Assembly

- New Construction:
 - Place PCM on the interior side of exterior walls, after insulation (e.g., XPS layer), to directly buffer indoor temperatures.
 - Maintain a 24 mm thickness for optimal latent heat storage-to-cost ratio.
- Retrofits:
 - Replace non-insulated wall cavities with 24–80 mm PCM panels, prioritizing interior placement.

Step 5: Thickness Optimization

- For cost-effectiveness, use 24 mm PCM in most cases.
- For retrofits requiring higher thermal buffering, consider 80 mm PCM but validate via simulation (ROI may vary by climate).

Step 6: Synergy with Insulation

- Combine PCM with XPS insulation ($R\text{-value} \geq 5$) in new builds to block conductive heat gain while leveraging PCM's latent storage.

3. Retrofitting Existing Structures

Step 7: Wall Preparation

- Remove non-insulated wall sections and install PCM panels (e.g., 24 mm) in cavity spaces.
- Seal joints with vapor barriers to prevent moisture ingress.

Step 8: Climate-Specific Retrofit Thickness

- Al-Ahsa: Prioritize 24 mm PCM for peak load shifting.
- Taif: Use 24–80 mm PCM based on heating/cooling demand balance.

4. Simulation & Performance Calibration

Step 9: Pre-Installation Modeling

- Use EnergyPlus/DesignBuilder with genetic algorithms to simulate PCM performance.
- Calibrate parameters:

- Melting temperature ($\pm 1^{\circ}\text{C}$ of regional average daytime peak).
- Thickness (24–80 mm).
- Position (interior/middle).

Step 10: HVAC Synchronization

- Align PCM's discharge phase with HVAC off-peak hours (e.g., nighttime cooling in Al-Ahsa).
- Set cooling setpoints to 25°C (fixed) for ASHRAE 55 compliance.

5. Regulatory & Compliance Alignment

Step 11: Code Revisions

- Update Saudi Building Code (SBC 601/602) to mandate PCM integration in regions with diurnal swings $>15^{\circ}\text{C}$.
- Specify:
 - Minimum PCM thickness: 24 mm.
 - Melting temperature ranges: 25°C – 27°C (climate-dependent).

Step 12: Fire Safety & Durability

- Mandate fire-resistant PCMs (e.g., inorganic salts) and encapsulation to meet NFPA 285 standards.

6. Economic & Environmental Incentives

Step 13: ROI-Driven Policies

- Offer subsidies for PCM retrofits with 5–7-year payback periods in desert climates.
- Highlight CO₂ reductions: 1,526–3,640 kg/year per villa.

Step 14: Lifecycle Assessment (LCA)

- Promote PCMs under Saudi Vision 2030's circular economy goals, emphasizing recyclability and non-toxicity.

7. Maintenance & Monitoring

Step 15: Post-Installation Checks

- Monitor thermal performance annually using embedded sensors (e.g., surface temperature loggers).
- Inspect encapsulation integrity in regions prone to sandstorms.

Step 16: Adaptive Recalibration

- Re-simulate PCM parameters if regional climate patterns shift (e.g., rising baseline temperatures).

8. Future-Proofing & Research

Step 17: Hybrid Systems

- Integrate PCM with radiative cooling coatings or PV façades to amplify energy savings in ultra-arid climates.

Step 18: Durability Studies

- Partner with manufacturers to test PCM performance under UV/sandstorm exposure over 10–20-year lifespans.

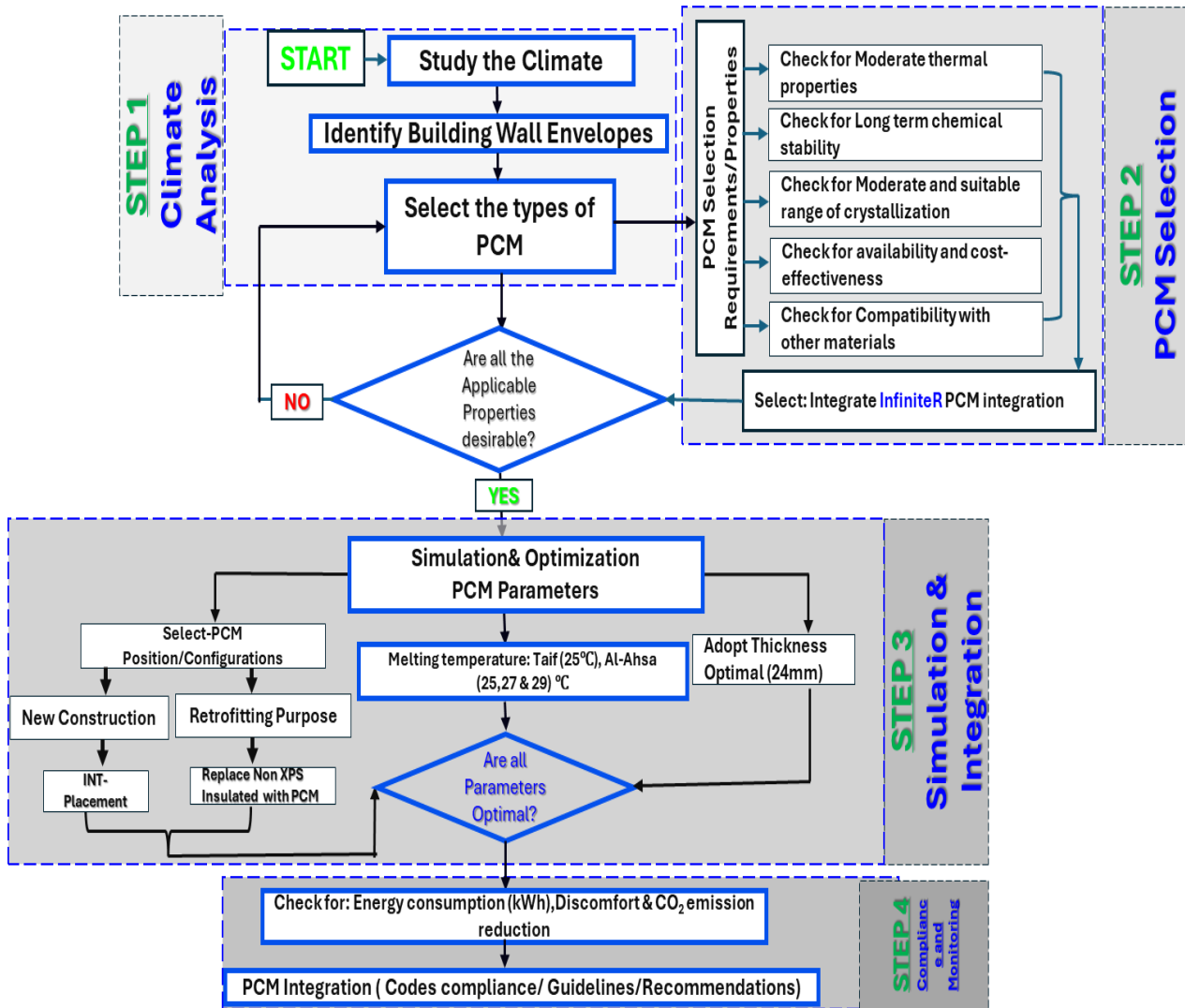


Figure 38: PCM integration guidelines (Framework)

5.3 Future Research Directions

- Investigate hybrid systems combining PCMs with radiative cooling coatings or photovoltaic fades to increase energy savings in ultra-arid climates.
- Conduct long-term durability studies on inorganic PCMs under sandstorm exposure and UV degradation, focusing on microencapsulation techniques for enhanced lifecycle performance.
- Expand whole-building analyses to high-rise structures and mixed-use developments, integrating PCMs with smart HVAC controls for demand-side grid management.
- Develop cost-benefit frameworks for PCM deployment in GCC countries, addressing payback periods under subsidized energy tariffs and lifecycle embodied carbon trade-offs.

This work bridges theoretical PCM potential with actionable, climate-specific implementation strategies, directly supporting Saudi Arabia's Vision 2030 goals for sustainable urbanization. By harmonizing energy resilience, occupant comfort, and material innovation, PCM-enhanced envelopes emerge as a cornerstone for decarbonizing building stocks in thermally extreme environments.

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APPENDIX A

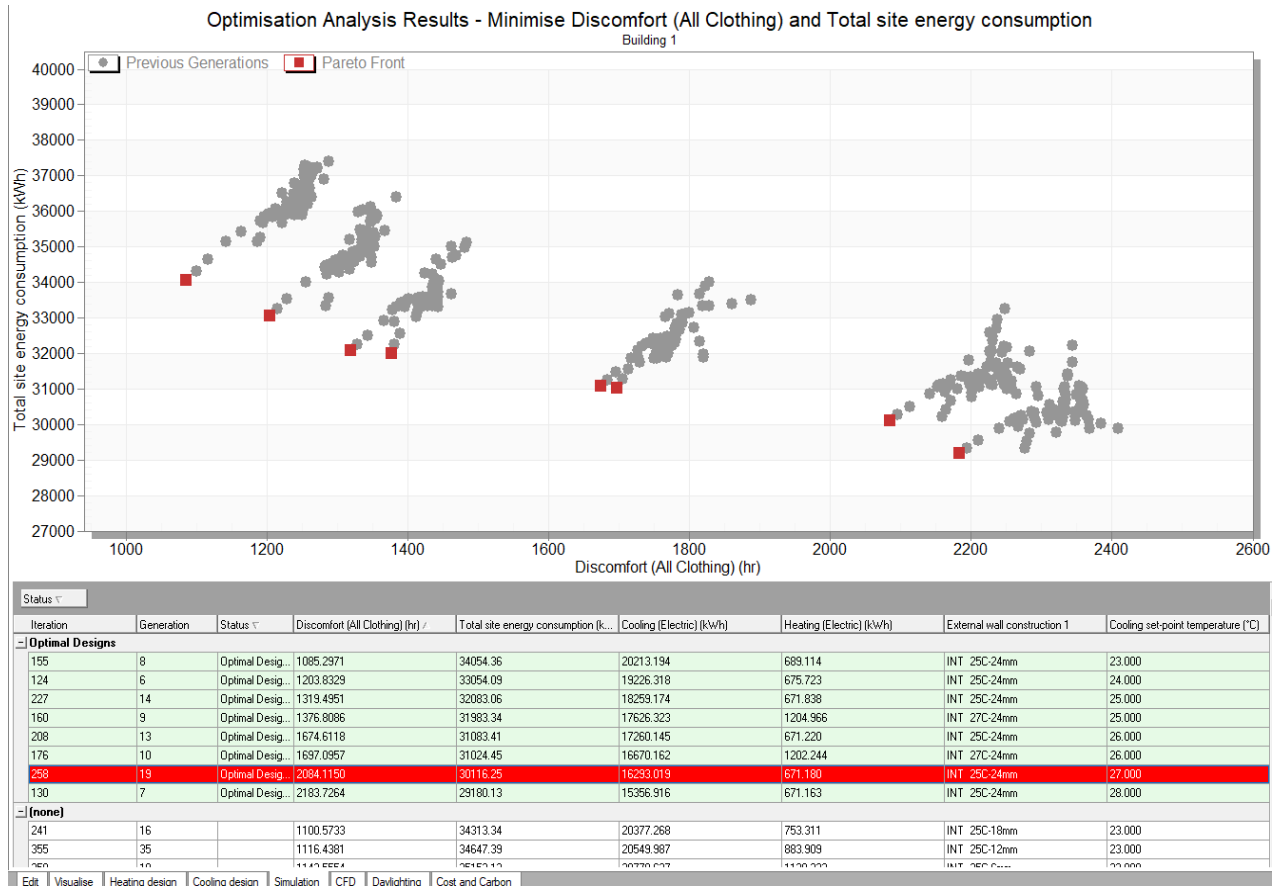
Simulation and Optimization Results

Section A: SIMULATION AND OPTIMIZATION RESULTS

This section the appendix presents the outcomes of the multi-objective optimization analysis conducted to minimize thermal discomfort hours and total site energy consumption across the investigated climates of Al-Hasa (extremely and dry) and Taif (hot and dry).

SECTION A.

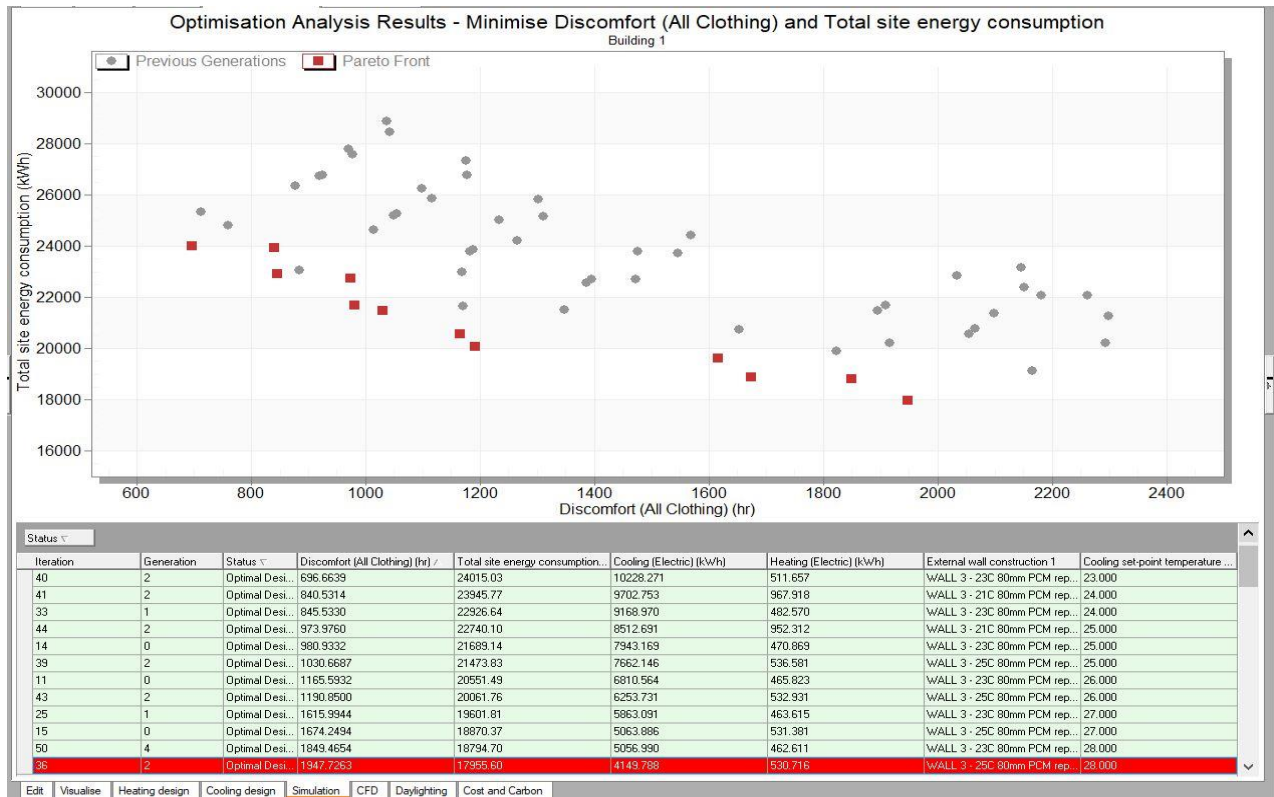
WALL CASE 1- SCENARIO 1: PCM integration into external residential wall with XPS insulation



SECTION (A).

Info			Objective		Extra Output		Variable	
Iteration	Generation	Category	Discomfort (All Clothing) (hr)	Total site energy consumption (kWh)	Cooling (Electric) (kWh)	Heating (Electric) (kWh)	External wall construction 1	Cooling set- point temperature (°C)
0	0		1777.353584	32471.11741	17579.81	1677.814	EXT 29C- 12mm	26
130	7	Optimal Designs	2183.72635	29180.12717	15356.916	671.163	INT 25C- 24mm	28
245	17		2194.361618	29328.97	15412.902	733.305	INT 25C- 18mm	28
174	10		2276.415846	29334.06503	14980.135	1201.882	INT 27C- 24mm	28
216	14		2279.641002	29520.36134	15082.707	1254.892	INT 27C- 18mm	28
1	0		2210.271076	29546.80276	15471.75	861.56	INT 25C- 12mm	28
185	10		2283.770817	29747.25443	15189.524	1344.237	INT 27C- 12mm	28
59	3		2321.289101	29782.56398	15184.412	1446.104	MID-INT-27C- 6mm	28
84	4		2368.680586	29869.35332	15011.379	1675.211	MID EXT 31C-18mm	28
175	10		2239.93262	29885.56949	15536.258	1105.05	INT 25C-6mm	28
300	24		2409.547985	29887.96816	14988.551	1655.156	INT 29C-6mm	28
186	11		2267.007476	29936.04334	15460.524	1262.025	MID-INT-25C- 12mm	28
67	3		2384.76005	30010.87117	15068.609	1728.768	MID-INT-29C- 12mm	28
54	2		2292.317709	30060.53884	15317.486	1498.791	INT 27C-6mm	28
152	8		2254.401383	30062.64501	15473.13	1437.467	MID-INT-23C- 24mm	28
57	3		2329.642578	30076.72879	15416.737	1507.943	EXT 25C - 24mm	28
204	13		2348.080952	30110.42291	15367.694	1559.966	MID EXT 27C-18mm	28
258	19	Optimal Designs	2084.11505	30116.24679	16293.019	671.18	INT 25C- 24mm	27
385	42		2327.030198	30124.43519	15447.817	1493.855	MID EXT 25C-18mm	28
266	20		2367.021453	30125.33173	15280.813	1661.756	EXT 33C- 18mm	28
386	42		2310.263902	30126.61013	15458.787	1515.775	EXT 23C- 24mm	28

SECTION B: Wall Case 1- Scenario 2: PCM replacing the 80mm XPS insulation in external walls.

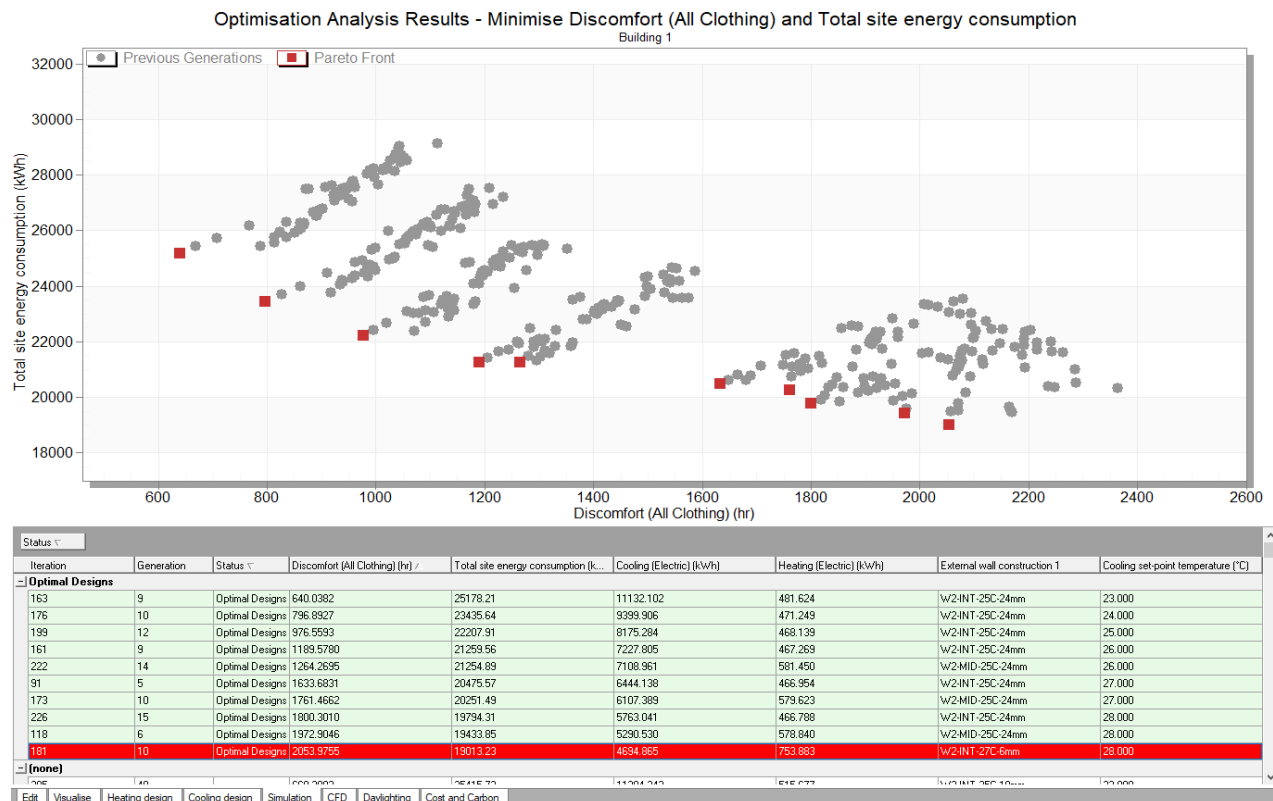


SECTION B: PCM replacing the 80mm XPS insulation in external walls

Info			Objective		Extra Output		Variable	
Iteration	Generation	Category	Discomfort (All Clothing) (hr)	Total site energy consumption (kWh)	Cooling (Electric) (kWh)	Heating (Electric) (kWh)	External wall construction 1	Cooling set-point temperature (°C)
34	2	Optimal Designs	2399.029314	30011.5028	14341.114	2395.29	WALL 3 - 29C 80mm PCM replaced Insulation.	28
30	1	Optimal Designs	2172.621363	30761.88535	16034.161	1452.625	WALL 3 - 23C 80mm PCM replaced Insulation	28
42	2		2201.247009	30887.65582	16245.722	1459.171	MID-INT-27C-18mm	27
53	5		2237.44643	30918.62376	16009.721	1633.804	WALL 3 - 25C 80mm PCM replaced Insulation	28
121	6		2163.614294	30918.9542	16443.326	1262.135	MID-INT-25C-12mm	27
354	35		2332.251359	30981.93189	16026.461	1803.423	MID-INT-37C-24mm	28
125	6		2181.144583	30988.21871	16245.056	1498.902	INT 27C-6mm	27

209	13		2251.317593	30993.46647	16257.491	1583.927	EXT 31C-24mm	27
268	20		2358.398818	30995.64574	16054.584	1789.014	MID-INT-33C-24mm	28
394	43		2257.470571	31018.64531	16226.872	1639.725	EXT 33C-24mm	27
176	10	Optimal Designs	1697.095714	31024.45469	16670.162	1202.244	INT 27C-24mm	26
309	25		2356.146286	31044.27515	16056.972	1804.541	MID-INT-33C-18mm	28
168	9		2152.387783	31046.19212	16455.62	1438.524	MID-INT-23C-24mm	27
371	38		2332.923364	31049.1013	16048.557	1817.782	MID-INT-37C-18mm	28
51	2		2292.067787	31049.80792	16149.85	1655.697	INT 29C-6mm	27
83	4		2212.166666	31052.68368	16420.891	1479.744	MID EXT 25C-24mm	27
1	0		2430.623892	31062.80287	15341.804	2445.9	WALL 3 - 31C 80mm PCM replaced Insulation.	28
208	13	Optimal Designs	1674.611839	31083.41263	17260.145	671.22	INT 25C-24mm	26
295	23		2353.614551	31084.67952	16050.739	1820.447	MID-INT-33C-12mm	28
193	11		2155.074377	31095.8589	16548.39	1364.706	INT 23C-18mm	27
187	11		2208.641917	31096.68894	16436.542	1508.099	EXT 25C -24mm	27
115	6		2230.543174	31110.15685	16348.141	1609.968	MID EXT 27C-24mm	27
139	7		2171.800867	31112.49524	16510.146	1358.088	MID-INT-25C-6mm	27
188	11		2246.317225	31121.45048	16338.514	1630.888	MID EXT 29C-24mm	27

SECTION C: WALL CASE 2- SCENARIO 1: PCM integration into external residential wall without XPS insulation



SECTION C:

Info			Objective		Extra Output		Variable	
Iteration	Generation	Category	Discomfort (All Clothing) (hr)	Total site energy consumption (kWh)	Cooling (Electric) (kWh)	Heating (Electric) (kWh)	External wall construction 1	Cooling set- point temperature (°C)
181	10	Optimal Designs	2053.9755	19013.23082	4694.865	753.883	W2-INT-27C-6mm	28
118	6	Optimal Designs	1972.904595	19433.85201	5290.53	578.84	W2-MID-25C- 24mm	28
17	0		2170.352846	19442.05377	5025.181	852.39	W2-MID-27C- 24mm	28
81	4		2170.352846	19442.05377	5025.181	852.39	W2-MID-27C-6mm	28
239	16		2056.821642	19473.44846	5020.085	826.453	W2-INT-27C- 12mm	28
5	0		2168.837007	19501.8922	5071.891	834.305	W2-MID-27C- 18mm	28
21	1		2070.456032	19524.4211	5264.14	695.799	W2-EXT-25-24mm	28
115	6		1976.129295	19594.70873	5404.305	594.708	W2-MID-25C- 18mm	28
165	9		2165.206868	19640.42592	5166.652	846.864	W2-MID-27C- 12mm	28
150	8		2070.851206	19764.57023	5407.571	761.303	W2-EXT-25-18mm	28
226	15	Optimal Designs	1800.30097	19794.31153	5763.041	466.788	W2-INT-25C- 24mm	28
298	23		1853.220139	19845.43054	5770.153	510.795	W2-MID-23C- 24mm	28
112	6		1952.2557	19863.46776	5569.317	729.668	W2-EXT-23-24mm	28
106	5		1818.068361	19909.9488	5591.511	753.956	W2-INT-27C-6mm	27
211	13		1818.068361	19909.9488	5591.511	753.956	W2-INT-27C- 24mm	27
323	27		1968.734978	20034.8871	5662.109	777.082	W2-EXT-23-18mm	28
140	8		1826.061354	20063.36902	5876.646	559.813	W2-INT-25C- 12mm	28
279	21		1985.057928	20137.21566	5688.38	790.639	W2-MID-25C-6mm	28
74	4		2083.9436	20149.3383	5630.247	892.181	W2-EXT-25-12mm	28
11	0		1887.394231	20163.63678	5749.875	849.28	W2-EXT-21-24mm	28
177	10		1904.990097	20243.09952	6130.254	548.363	W2-INT-23C- 24mm	28
173	10	Optimal Designs	1761.466208	20251.49472	6107.389	579.623	W2-MID-25C- 24mm	27
339	30		1920.73624	20326.9908	6153.33	577.965	W2-INT-23C- 18mm	28
174	10		2363.274515	20334.39675	5792.651	977.264	W2-INT-29C- 24mm	28
381	37		2247.629499	20341.04479	5973.177	803.385	W2-EXT-29C- 24mm	28

SECTION C:

Shows the selected optimal walls cases from the optimization analysis they are selected based on using the main objective functions and post processing with energy and percentage discomfort reduction. Its figures are shown in section 4.4 of the energy consumption analysis from the thesis.

Wall Selection Based on energy consumption reduction (kWh) and (%).

	Wall Type	Base Case	Energy Savings (Differences)	% Reduction/Savings
CASE 1	Base case + XPS	35359.4		
	OPT PCM + XPS Walls	31065.1	3336.1	12.60
	PCM replacing XPS	33117.5	2241.9	6.34
CASE 2	Base Case- XPS	39217.3		
	OPT PCM WALLS - XPS	33829.1	5388.2	18.40

SECTION D:

The following result in the table is a list of optimal wall cases values with melting temperatures, Total Energy Consumption and percentage discomfort (%)

Wall Case	Optimal Walls Melting Temperature	Total Energy Consumption	Discomfort (%)
Wall CASE 1	Base Case + XPS	35359.4	27%
	S1'-INT-25C-24mm @ 24CST	33102.8	13.8%
	S1"-INT-27C-24mm@26CST	31065.1	17.4%
	S1'''-INT 27C-24mm@25CST	32023.3	15.7%
	S2'-MID-29°C-80mm@26CST	33117.5	18.4%
	S2" - MID-29°C-80mm@25CST	34554.5	16.0%
	S2'''-MID -27°C-80mm@25CST	35052.0	15.5%
Wall CASE 2	Base Case Without XPS	39217.3	26.0%
	S1'-INT-25°C-24mm@26CST	33829.1	19.0%
	S1"-INT-25°C-24mm@25CST	35033.4	15.3%
	S1'''-INT-25°C-24mm@24CST	36334.5	14.0%

Vitae

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- A post-occupancy performance evaluation study on user satisfaction with university student housing facilities. <https://doi.org/10.1108/F-04-2024-0064>
- Evaluating the Impact of Indoor Air Quality and Ventilation in Educational Facilities on Occupant Health, Comfort, and Well-Being (Building Engineering). Kanu and Mohammad ,2025 (Under Review)
- Industry 4.0 Digital Technologies for Energy Efficiency in Buildings (ScienceDirect). Kanu, et al. 2024 (Under Review)
- Benefits of Advanced Smart Insulation Materials in Buildings (ScienceDirect). Kanu, and Asif, 2024 (Accepted)

Rashid Kanu is now a dedicated civil and architectural engineering professional driven by a commitment to excellence and innovation. His academic journey started with an undergraduate honors degree in Civil Engineering, funded by a Sierra Leone Government Scholarship awarded for his exceptional performance in the West African Senior School Certificate Examination (WASSCE). During his studies, he distinguished himself as a proactive leader, heading critical projects such as the design of landslide-resistant residential structures (e.g., the Locust Housing Project), which addressed pressing environmental challenges in his community. Graduating as the second-ranked student in his faculty, Rashid earned multiple accolades, including leadership awards and debate competition victories, while

balancing roles as a civil project manager, site engineer, and part-time lecturer—experiences that honed his technical and managerial expertise.

In pursuit of advanced knowledge, Rashid secured a fully funded scholarship to the King Fahd University of Petroleum and Minerals (KFUPM), a globally renowned institution ranked 101st in the 2024 QS World University Rankings. At KFUPM, he pursued a master's degree in architectural engineering, immersing himself in cutting-edge research on sustainable building technologies. His academic strength and leadership flourished as he collaborated with internationally recognized scholars at conferences and seminars, while leading impactful projects such as the Design of Green Walls and Roofs for Sustainability and Affordability. He served as Secretary General and Welfare Officer of the KFUPM International Students Club, fostering inclusivity and support for a diverse student body.

Rashid's research focuses on energy-efficient building design, advanced building envelopes, and smart construction systems—interests rooted in his vision to bridge academia and industry. His thesis, *The Impact of Phase Change Materials in Building Envelopes on Energy Performance in Extreme Climates*, exemplifies his ability to translate theoretical insights into practical solutions for sustainable urbanization. Equally comfortable in academic and industry settings, Rashid aspires to contribute to climate-responsive architectural practices, aligning with global sustainability. His journey reflects a blend of scholarly curiosity, leadership, and a steadfast commitment to creating resilient, energy-efficient built environments.