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OPTIMIZING ENERGY EFFICIENCY IN BUILDINGS THROUGH THE
INTEGRATION OF PHASE CHANGE MATERIALS INTO BUILDING
ENVELOPES

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Optimizing Energy Efficiency in Buildings through the Integration of Phase Change
Materials into Building Envelopes

MASTER'S THESIS

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Statement of supervision

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SUMMARY

This study explores the integration of Phase Change Materials (PCMs) into building envelopes as a strategy to improve energy efficiency, thermal comfort, and operational performance across diverse climate conditions. Three representative cities were selected to reflect a wide range of climatic profiles: Dubai (hot and humid), Riyadh (hot and arid), and Amman (temperate). By addressing both extreme and moderate environments, the study offers a comprehensive understanding of PCM behaviour in different thermal contexts. PCMs were strategically embedded within wall and roof assemblies, with their placement and melting points tailored to the climate-specific demands of each location. Melting point selection was guided by detailed analysis of weather data, diurnal temperature patterns, and seasonal energy demand profiles, ensuring that each PCM configuration aligns with local conditions and optimizes phase transition cycles for energy storage and release. The analysis was conducted using DesignBuilder, powered by the EnergyPlus simulation engine, to model baseline and PCM-integrated buildings. A comprehensive parametric study evaluated the impact of critical variables on heat transfer, annual energy demand, seasonal energy demand, and thermal comfort. The simulation results demonstrated consistent improvements across all climates studied, with heat flux reductions of up to 40% in wall facades and up to 72% in roof assemblies, depending on configuration, thickness and climate. The highest performance gains were observed in Riyadh for both roof and walls; similar wall performance was also noted in Dubai. These findings confirm the value of climate-responsive PCM integration, particularly when configurations are optimized for local thermal loads and building envelope design. Overall, the study establishes that tailored PCM application, when supported by modelling and climatic analysis, can serve as an effective pathway toward the development of low-energy, climate-adaptive buildings. The results highlight the importance of customized material selection, optimal placement configurations, and integrated design strategies to support the practical implementation of phase change solutions for enhanced building performance.

Keywords: Phase Change Materials (PCM), Placement Strategy, Melting Point Optimization, Latent Heat Storage, Building Envelope, Envelope Orientation, Passive Cooling, Energy Efficiency, Heat Flux Reduction, Dynamic Simulation, Parametric Analysis, Climate-Responsive Design, DesignBuilder, EnergyPlus.

1. INTRODUCTION AND OBJECTIVES

Global energy consumption has been steadily increasing due to population growth, urbanization, and economic development, with the building sector accounting for nearly 34% of this demand and 37% of global energy-related greenhouse gas (GHG) emissions [1], making them one of the largest contributors to climate change. According to the International Energy Agency, buildings and construction together represent nearly 40% of global CO₂ emissions when both operational and embodied energy are considered [2]. This is primarily due to the heavy reliance on fossil fuels for space heating, cooling, lighting, and ventilation. The operational energy demand of buildings especially in regions with extreme climates, poses a significant challenge to sustainability goals. As climate targets become more urgent under frameworks like the Paris Agreement [3], improving the energy efficiency of buildings has become a global priority in mitigating carbon emissions and promoting sustainable development.

1.1 Background

Improving the thermal performance of building envelopes is recognized as one of the most effective strategies for reducing building energy consumption and related greenhouse gas emissions [4]. Among passive energy-saving solutions, Phase Change Materials (PCMs) have gained increasing interest due to their capacity for latent heat storage, enabling thermal regulation, peak load reduction, and enhanced indoor comfort [5].

Over the last two decades, the integration of PCMs in buildings has evolved significantly from early attempts embedding PCMs in structural concrete [6] to more advanced applications using encapsulated systems in walls, roofs, ceilings, and glazing [7], [8]. Recent experimental and simulation-based studies have demonstrated energy savings of 20–50%, depending on application, and PCM configuration [9]. Research has also shown that optimal PCM performance relies heavily on the alignment of melting temperature, as well as strategic placement within the envelope assembly. More advanced studies have begun to address envelope orientation, thermal mass clustering [10], roof enclosure innovations [11], and PCM integration in hybrid systems such as HVAC ducts or solar-thermal systems [12].

Early research explored the use of paraffin, salt hydrates, and eutectic PCMs within concrete and plaster, showing energy savings between 20% and 30% in cold and temperate climates. However, excessive PCM content beyond 10% in structural materials was found to reduce mechanical integrity [6].

More recent studies have focused on encapsulating PCMs into non-structural layers such as walls, roofs, glazing, and ceilings, demonstrating that proper material selection and strategic placement can significantly improve building thermal performance and energy savings [7], [8]. Among available options, paraffin-based PCMs are widely favoured for their chemical stability and tunable melting points, despite the higher thermal conductivity of salt hydrates. A recurring finding is that aligning the PCM melting temperature with local climate conditions is essential to achieving frequent and efficient phase transitions [5], [13].

Recent investigations have explored PCM performance through both experimental methods and parametric simulations. Studies have shown that factors such as placement strategy, PCM thickness, façade orientation, and climate data all influence the heat storage efficiency and cooling/heating reduction potential of PCMs [10], [11], [14].

Although research on phase change materials in buildings has advanced considerably in recent years, there remains a lack of comparative, climate-responsive evaluations that consider how PCM performance varies across regions with different thermal demands. In particular, limited attention has been given to how these varying demand profiles influence the optimal selection, configuration, and placement of PCM layers within building envelopes.

This study seeks to address this gap by examining PCM effectiveness in three distinct climate zones. The analysis explores how factors such as melting point, placement strategy, orientation, and thickness affect PCM performance in both wall and roof assemblies. By combining building energy simulations with climate data and regional demand profiles, the research aims to develop insights into optimal PCM configurations that are responsive to the unique thermal dynamics of each climate context.

1.2 Climate Zones

To evaluate PCM performance under varied environmental and operational conditions, three representative cities were selected:

- Dubai, UAE (Hot and Humid): Characterized by persistently high temperatures and humidity levels, resulting in year-round cooling demand. This climate tests the PCM's effectiveness in reducing indoor heat gains and improving cooling efficiency.
- Riyadh, Saudi Arabia (Hot and Dry): Featuring extreme summer heat with low humidity, this climate imposes heavy sensible heat loads. It offers a valuable contrast for assessing PCM behaviour under high solar gain conditions.
- Amman, Jordan (Temperate): With cold winters and warm summers, Amman provides a transitional climate where both heating and cooling are required seasonally. This zone serves as a baseline for mixed-performance PCM strategies.

Middle East map of Köppen climate classification

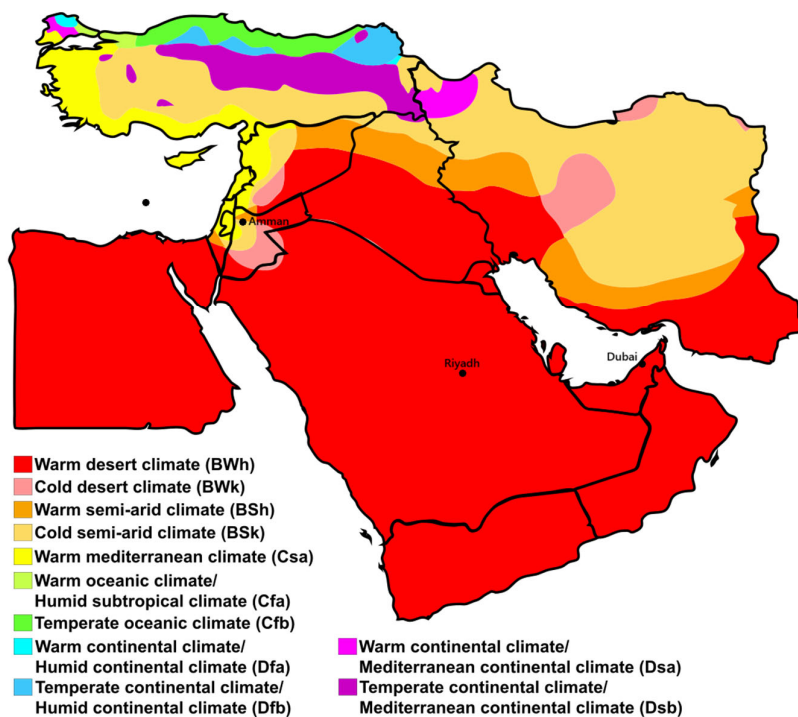


Figure 1-1: Middle East Map of Köppen Climate Classification

These diverse zones were selected to ensure a broad evaluation of PCM behaviour under varying temperature swings, humidity levels, and energy demand patterns.

1.3 Phase Change Materials: Types and Applications

Phase Change Materials (PCMs) used in building applications are broadly classified into three categories: organic, inorganic, and eutectic. Each type offers distinct thermal, physical, and chemical characteristics suited to specific design and climate needs [5], [6], [13].

Organic PCMs, such as paraffin waxes and fatty acids, are the most widely used in building envelopes due to their chemical stability, non-corrosive nature, and predictable melting/freezing behaviour [5], [6]. Paraffin-based PCMs, and are also favoured for their broad melting point range, encapsulation compatibility, and thermal reliability over multiple phase change cycles [5], [8]. However, their relatively low thermal conductivity and moderate latent heat capacity may limit performance in applications requiring rapid or high-density thermal exchange [5].

Inorganic PCMs, including salt hydrates and metallic-based compounds, offer higher thermal conductivity and latent heat capacity, making them suitable for compact or fast-response thermal storage [5], [13]. Their adoption is limited by challenges such as phase segregation, supercooling, and potential material corrosiveness [5], [6]. Ongoing research focuses on stabilizing additives and advanced encapsulation techniques to mitigate these issues [5], [14].

Eutectic PCMs are mixtures of two or more components that melt and solidify congruently at a fixed temperature. They offer improved thermal stability and customizable melting points. Depending on their formulation organic-organic, inorganic-inorganic, or organic-inorganic, eutectics provide balanced properties, though their large-scale use remains less common in buildings compared to organic or inorganic PCMs [5], [12].

In terms of application, PCMs are used in non-encapsulated or encapsulated forms. Non-encapsulated PCMs may be blended with materials like concrete or plaster but risk leakage and reduced mechanical strength [6]. Encapsulated PCMs are more practical and durable [5], [8]:

- Microencapsulated form for use in coatings, textiles, or wallboards.
- Macroencapsulated form, such as pouches, tubes, or panels, suitable for wall cavities and roof assemblies.

Macroencapsulation is typically preferred in buildings due to ease of installation, especially in retrofitting or modular construction [5], [8]. Microencapsulation, while offering seamless integration into surface materials, is more suited to coatings or composite panels. In this study, macroencapsulated paraffin-based PCMs are selected for their thermal stability, construction compatibility, and ease of integration [5], [6]. Their controlled encapsulation ensures safe installation, repeatable performance, and low maintenance in wall and roof applications.

1.4 PCM Integration in Building Envelope

PCMs are integrated into the building envelope by embedding them within external wall and roof assemblies. They are added as additional layers, placed in various configurations (outer surface and inner surface) depending on climatic requirements and performance goals.

The PCM placement and melting point are optimized for each climate zone based on its temperature profile and seasonal energy demand. The aim is to enable frequent and effective phase transitions, allowing PCMs to absorb heat during peak temperatures and release it when ambient conditions cool. This passive energy regulation reduces reliance on HVAC systems and supports thermal comfort. The configuration must also consider the interaction between PCM and adjacent envelope materials to ensure consistent performance and avoid thermal delays.

By tailoring PCM configurations to each climate, this study investigates how phase change materials can be deployed as a viable strategy for energy-efficient, climate-adaptive buildings.

2. METHODOLOGY AND MODELLING

This study employs a simulation-based methodology to evaluate the impact of Phase Change Materials (PCMs) on building energy performance and thermal comfort across distinct climate zones. The approach involves climate data analysis, baseline model development, PCM material selection, detailed energy simulations using DesignBuilder, and parametric analysis to evaluate the influence of key variables on energy performance and demand.

2.1 Weather Profiles

A detailed analysis of historical weather data was conducted for each selected climate zone to understand temperature trends, daily fluctuations, indoor environmental requirements, and seasonal energy demand profiles. This assessment was essential for identifying the ambient conditions that influence both cooling and heating demands, thereby forming the basis for appropriate PCM selection, placement strategy, and determination of optimal melting points.

Typical meteorological year (TMY) files in .epw (EnergyPlus Weather) format were used as inputs in Climate Consultant software to extract and analyse the following parameters:

- Hourly temperature profile
- Daily maximum and minimum temperatures
- Monthly average temperatures
- Solar radiation patterns
- Cooling and heating demand profiles

The three selected cities - Dubai, Riyadh, and Amman - presented a diverse range of climatic characteristics, each with distinct temperature and humidity behaviours. As illustrated in Figures 2-1 to 2-3, the cities experience varying degrees of thermal intensity and diurnal variation.

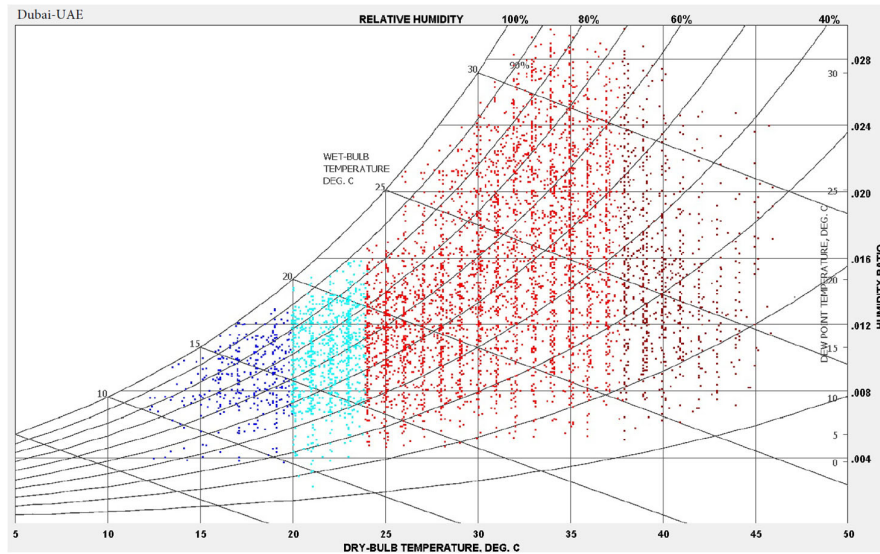


Figure 2-1: Hourly Temperature Profiles (Dubai-UAE)

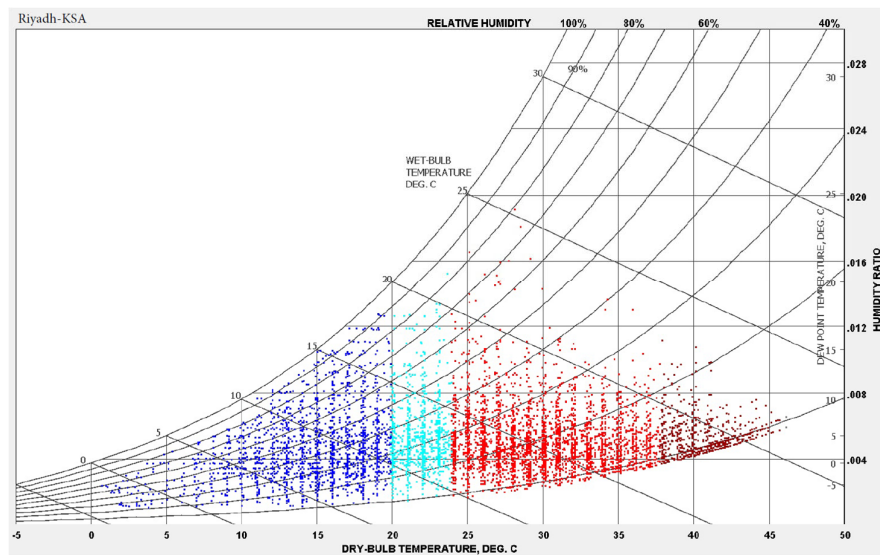


Figure 2-2: Hourly Temperature Profiles (Riyadh-KSA)

These climatic differences play a critical role in determining the activation, effectiveness, and timing of PCM behaviour, as the materials must reach specific temperature thresholds to undergo phase change and deliver the intended thermal benefits.

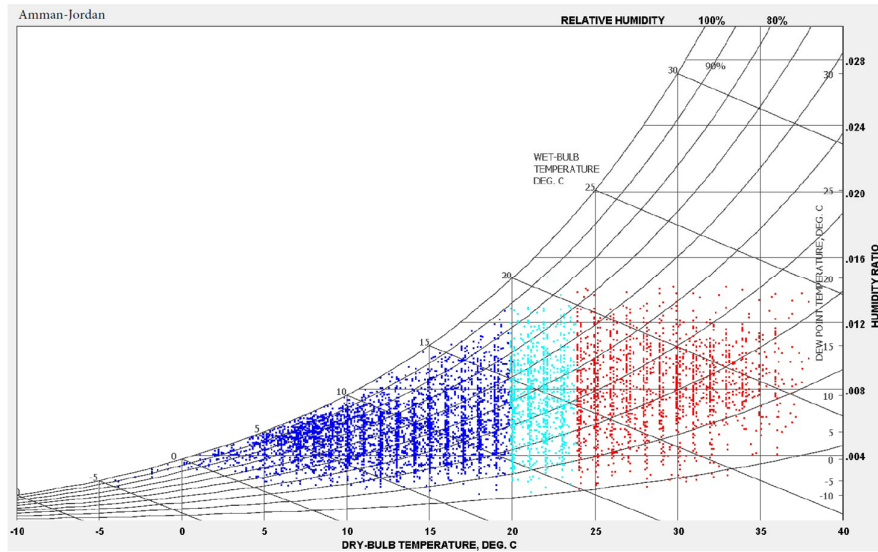


Figure 2-3: Hourly Temperature Profiles (Amman-Jordan)

Additionally, the seasonal energy demand profiles generated using the Climate Consultant program and the weather files of the selected cities [15], as shown in Figures 2-4 to 2-6, further emphasize the significant variation in cooling and heating requirements across these three climate zones.

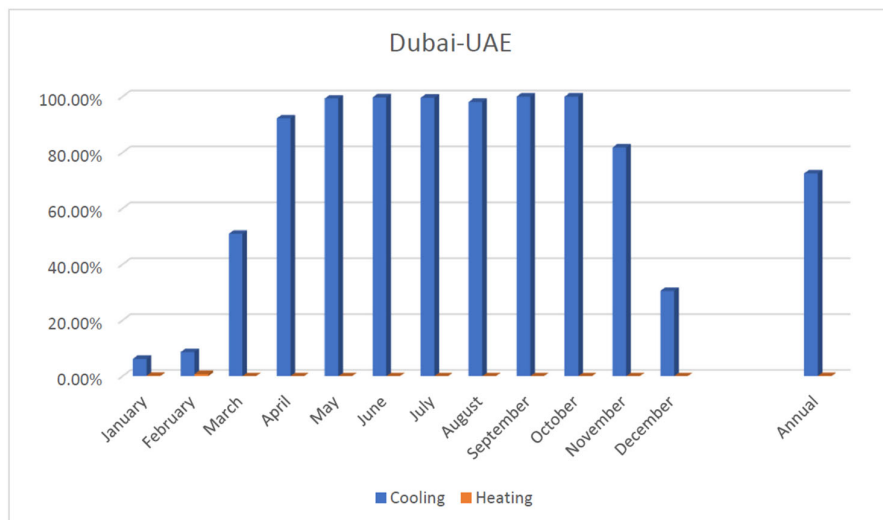


Figure 2-4: Cooling and Heating Demand Profiles (Dubai-UAE)

Each city demonstrates a unique demand curve shaped, Dubai exhibits an almost year-round cooling demand, Riyadh shows prolonged cooling periods with a short but noticeable heating season, and Amman displays a more balanced profile with substantial heating needs.

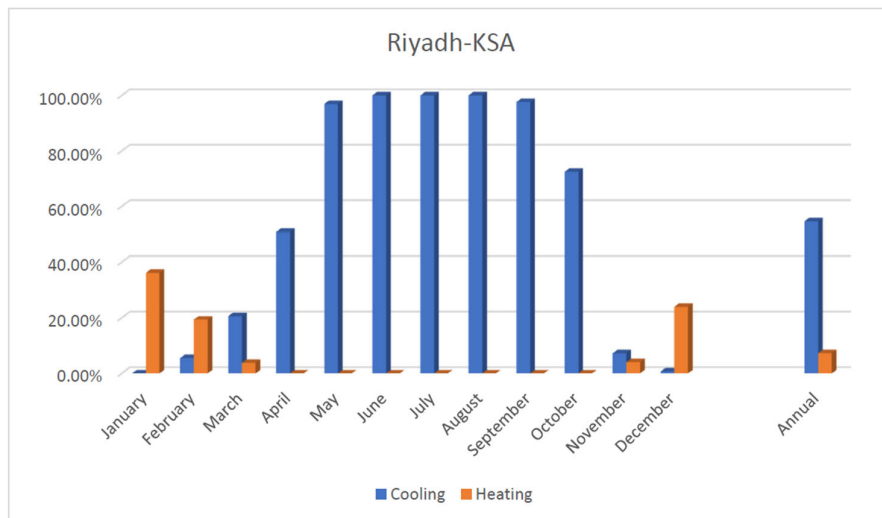


Figure 2-5: Cooling and Heating Demand Profiles (Riyadh-KSA)

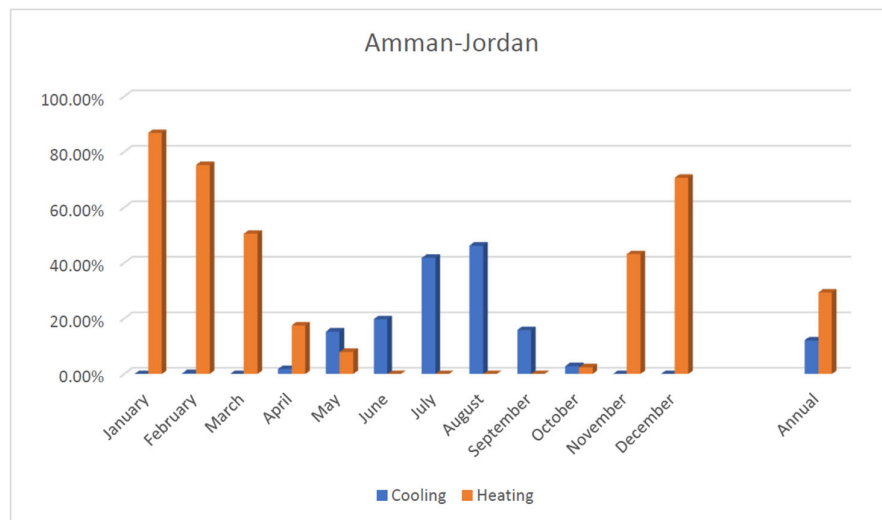


Figure 2-6: Cooling and Heating Demand Profiles (Amman-Jordan)

2.3 PCM Materials

The selection of Phase Change Materials (PCMs) is guided by a climate-responsive approach, taking into account the weather characteristics, thermal behaviour of the building envelope, and the seasonal cooling and heating demand profiles of each studied location. This strategy ensures that PCM performance is aligned with the actual thermal loads experienced by the building. To guarantee consistent and predictable performance, the study employed RT-series PCMs, a commercially available family of paraffin-based materials (see Table 2-1, Figure 2-9 and Figure 2-10) [16]. These PCMs were selected due to the availability of data across a wide range of melting points and reliable thermal storage capacities, allowing for precise adaptation to the specific climate conditions and applications under consideration. Their macroencapsulated form was assumed for all scenarios, ensuring practicality, ease of integration, and compatibility with typical construction assemblies.

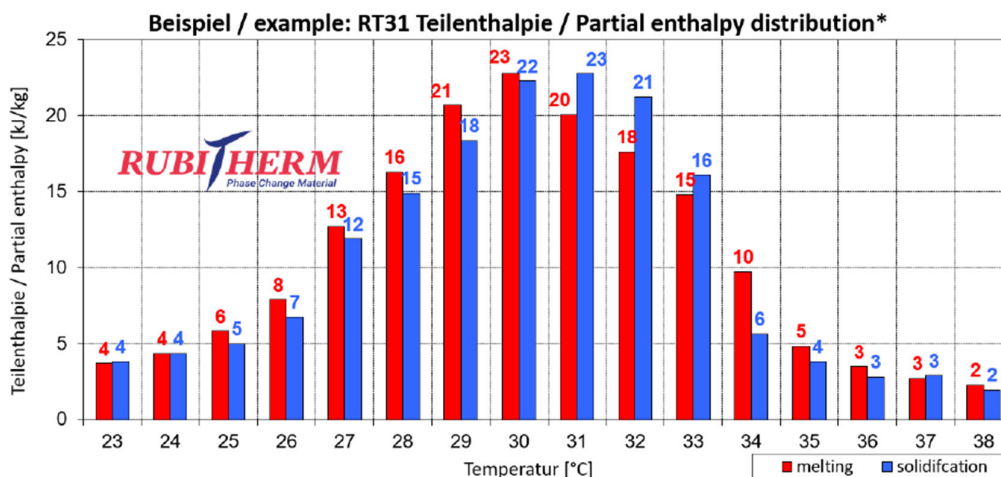


Figure 2-9: PCM RT31 Melting/Solidification Curve

RT materials with melting points customized for each zone and application were chosen based on the assessed climate, daily temperature variations, and demand profiles. The melting point of each PCM is a critical parameter, as it determines the effectiveness of thermal charging (heat absorption) and discharging (heat release) in response to diurnal temperature fluctuations. The objective is to maximize the number of phase transitions, thereby enhancing energy efficiency, reducing peak thermal loads, and improving indoor thermal comfort.

Property	RT38	RT35	RT31	RT28	RT25	RT22
Melting Point (Main Peak) (°C)	38	35	31	28	25	22
Melting -Solidification Range (°C)	34-39	34-36	29-34	27-29	22-26	20-23
Latent Heat Capacity (kJ/kg)	120	200	120	210	177	140
Specific Heat Capacity (kJ/kg.K)	2.00	2.00	2.00	2.00	2.00	2.00
Density - Solid (kg/m ³)	880	880	830	880	880	760
Density - Liquid (kg/m ³)	750	770	760	770	770	700
Heat Conductivity (W/m.K)	0.20	0.20	0.20	0.20	0.20	0.20
Volume Expansion (%)	12.5%	12.0%	12.5%	12.5%	12.5%	12.5%

Table 2-1: Properties of RT-Series - Different Melting Ranges

The tested PCM thicknesses ranged from 20 mm to 50 mm, taking into account both the thermal performance benefits and the constraints imposed by the overall building envelope thickness. This performance-driven and climate-responsive selection process ensures that PCM integration is optimized to suit the thermal dynamics of each city, ultimately contributing to reduced energy consumption, improved indoor comfort, and enhanced overall system efficiency.

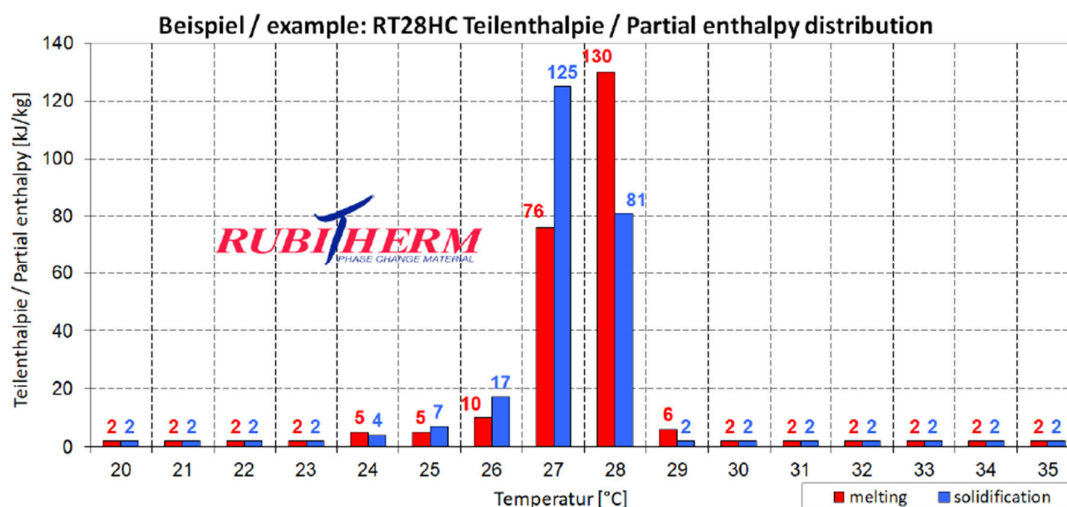


Figure 2-10: PCM RT28 Melting/Solidification Curve

2.4 Modelling and Simulation

The study methodology is based on the use of advanced dynamic simulation tools to evaluate the performance of Phase Change Material (PCM) integration in building envelopes. Simulations were conducted using DesignBuilder, a comprehensive building energy modelling software built on the EnergyPlus simulation engine. The PCM layer was defined using the Phase Change Material template in DesignBuilder, with the hysteresis method applied. Data from the RT datasheets were used to specify thermal conductivity, specific heat, and density for each phase, along with latent heat capacity across the full phase change range and the corresponding melting and freezing curve temperatures. Then Conduction Finite Difference (CondFD) method was used in the simulation for more accurately capture the non-linear thermal behaviour associated with phase change. This method divides the construction layers into discrete temperature nodes and resolves heat conduction over time, enabling simulation of latent heat storage and release as a function of temperature. This platform and calculation method enable detailed analysis of energy performance, heat transfer through envelope components, and occupant comfort levels under varying climate conditions.

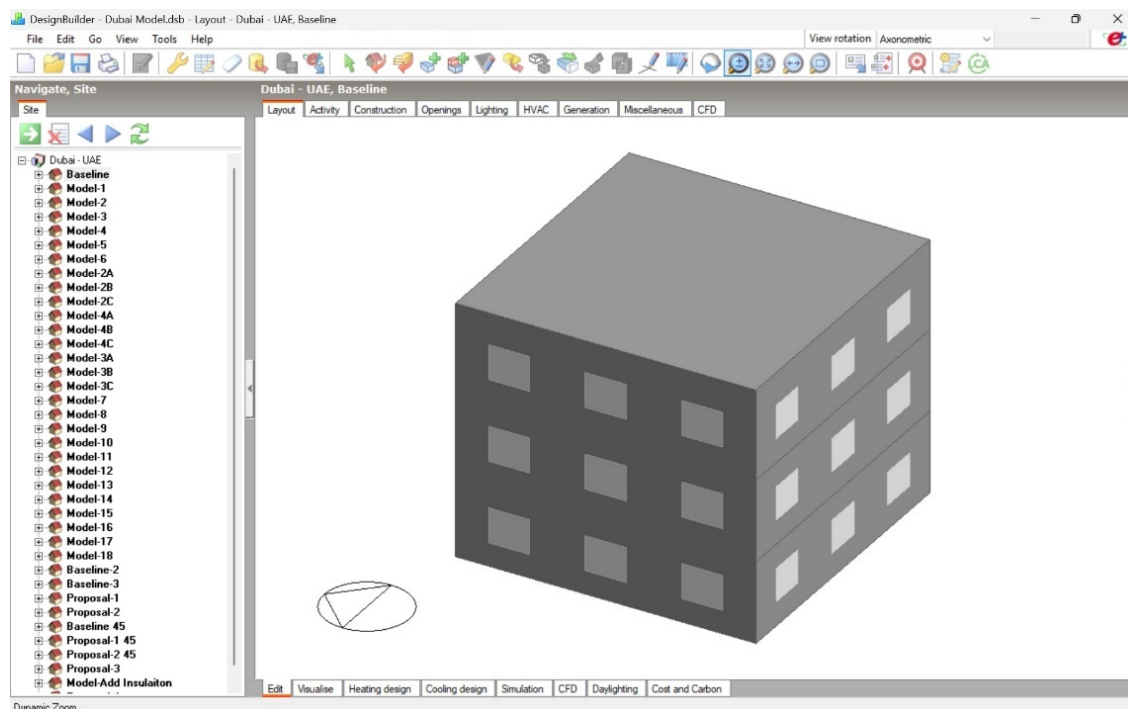


Figure 2-11: Baseline model established in DesignBuilder

A baseline building model was first developed in DesignBuilder (see Figure 2-11). The model represents a typical three-story commercial building, constructed using modern energy-efficient materials and real construction data derived from an actual project in Dubai (see Figure 2-12(a) and Figure 2-12(b)).

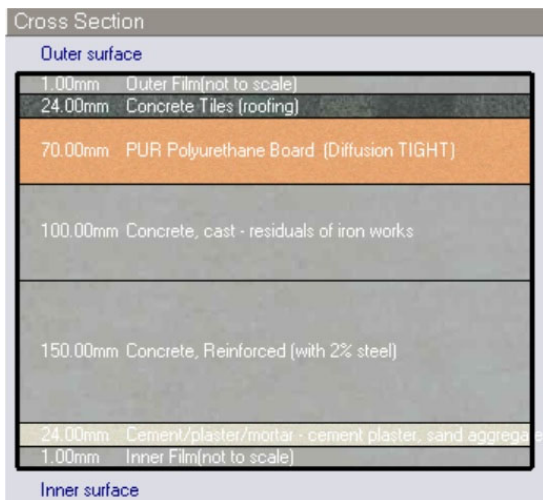


Figure 2-12(a): Baseline model, roof cross section



Figure 2-12(b): Baseline model, wall cross section

Internal gains, occupancy profiles, and HVAC schedules were implemented in accordance with ASHRAE standard 90.1-2019. The assumed indoor temperature setpoints were 24°C for cooling and 22°C for heating, with setback temperatures of 26°C and 20°C during unoccupied periods, respectively. This baseline model served as the reference case for evaluating the impact of PCM integration.

Energy simulations, with key performance indicators (KPIs), were then conducted for both the baseline and PCM-integrated models. The KPIs included (see Table 2-2 and Figure 2-13):

- Heat balance across building envelope components
- Annual energy demand and seasonal cooling/heating profiles
- Peak load reduction
- Thermal comfort performance

KPI	Unit	Description
Envelope Heat Gains/Loss (Walls and Roof)	kWh/year	Total annual heat gain/loss through opaque envelope elements into conditioned zones
Envelope Heat Gains During Cooling Season	kWh	Cumulative heat gain through the envelope during periods of active cooling
Envelope Heat Loss During Heating Season	kWh	Cumulative heat loss through the envelope during periods of active heating
Envelope Heat Gains During Peak Cooling Months	kWh	Heat gain through the envelope specifically during the hottest cooling-demand months
Envelope Heat Loss During Peak Heating Months	kWh	Heat loss through the envelope during the coldest heating-demand months
Total HVAC Energy Demand	kWh/year	Total annual energy consumed by heating and cooling systems
Indoor Dry Bulb Temperature	°C	Average indoor air temperature over the simulation period
Operative Temperature	°C	Average of air and mean radiant temperatures; key thermal comfort indicator

Table 2-2: Key Performance Indicators Used in the Simulation Study

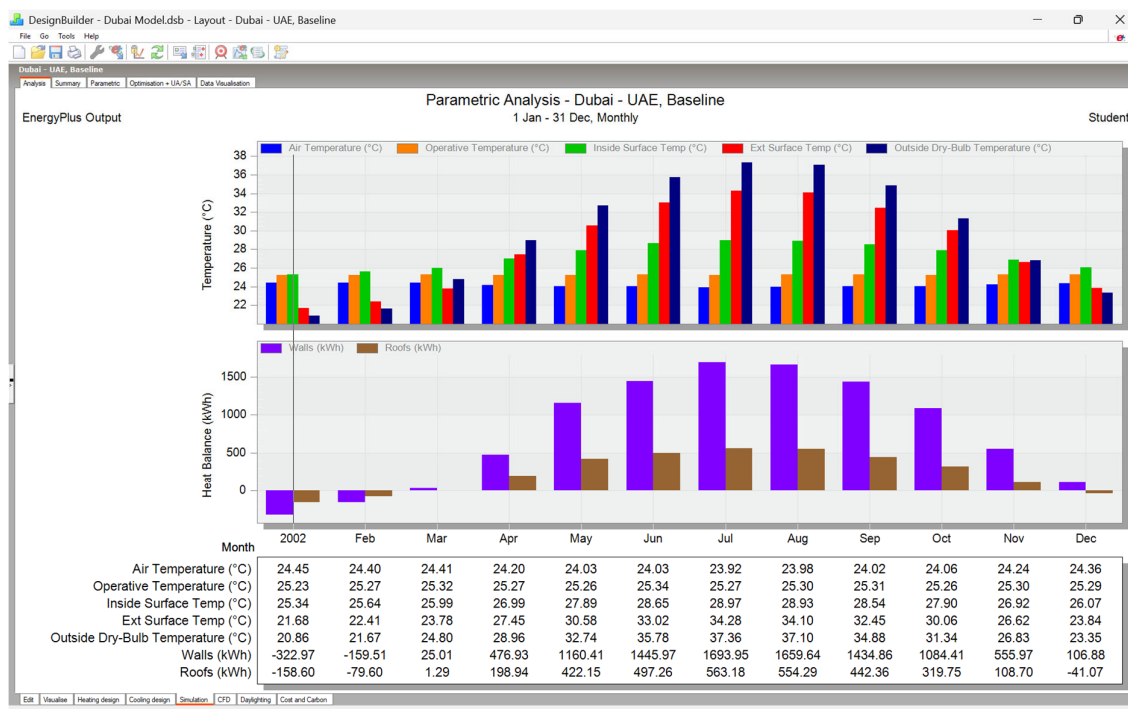


Figure 2-13: Simulation Outputs - Thermal Performance of Baseline Model (Dubai-UAE)

2.5 Parametric Analysis

To evaluate the influence of design variables on PCM performance, a comprehensive parametric analysis was conducted across the selected climate zones. A series of PCM-integrated models were developed and simulated, incorporating variations in melting points, placement strategies, and material thicknesses, while keeping all other model parameters consistent with the baseline (see Figure 2-14(a) and Figure 2-14(b)). This ensured that performance differences were solely attributed to the PCM configurations.

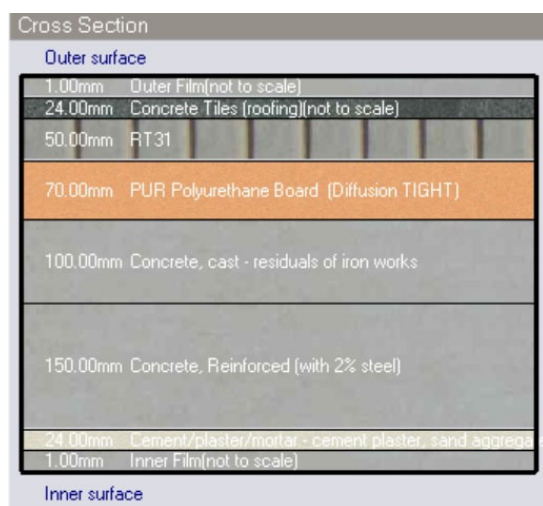


Figure 2-14(a): Roof-integrated PCM outer-placement

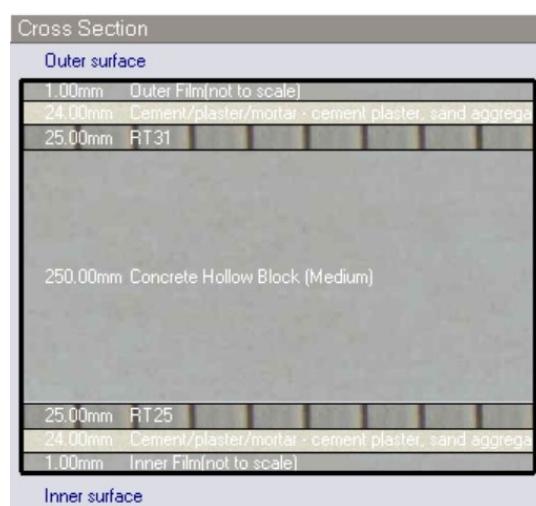


Figure 2-14(b): Wall-integrated PCM double-layer

The key variables examined in this study included:

- PCM melting point
- PCM thickness and thermal storage capacity
- Location of PCM placement (inner, outer, or double-layer)
- Building orientation and solar exposure

For each climate, multiple simulation runs were performed using a single-variable sensitivity approach, where one parameter was modified at a time while the others were held constant. This allowed for a clear assessment of the individual impact of each design factor on overall energy performance and thermal comfort.

Initially, a model was developed and simulated with external placement, applying the selected melting point for each city's climate and the maximum testing thickness. Subsequently, similar models with the same setup were tested for variations in melting point, placement, and thickness to evaluate their effects.

Finally, based on the outputs of the parametric simulations and analyses, four optimized configuration models were identified that delivered maximum efficiency and high performance.

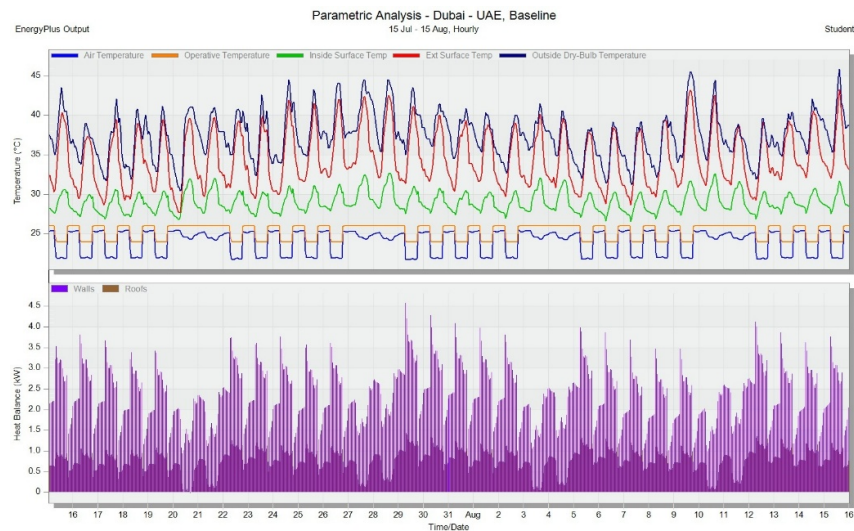


Figure 2-15: Sample result of parametric analysis

The results from these parametric simulations were then analysed to determine optimal PCM configurations that maximize energy savings, enhance thermal performance, and enable more effective phase-change activation aligned with the building's seasonal demand profile (see Figure 2-15).

Table 2-3 presents a representative overview of the parametric analysis conducted for Riyadh, highlighting the application of different configuration models and illustrating their respective performance when compared against the baseline model. The table captures the key outputs and variations observed during the analysis, providing insight into how each model responds

under the selected parameters and allowing for a clear comparison of their relative effectiveness and behaviour within the defined study conditions.

S.N.	Model	Envelope	Total Thickness (mm)	Insulation Thickness (mm)	PCM Layer				Indoor Setpoint (C)	Net Heat Balance (kWh)					
					PCM Thickness (mm)	PCM Placement	PCM Temp Range (C)	PCM Peak Melting (C)		Annual (Jan-Dec)	Annual % Model to Baseline	Cooling Demand Months (Mar-Oct)	Cooling Demand Months % Model to Baseline	Heating Demand Months (Nov-Feb)	Heating Demand Months % Model to Baseline
1	Baseline	Wall	300	250	-	-	-	-	24	5,440.91	-	7,599.84	-	-2,158.93	-
		Roof	370	70	-	-	-	-	24	1,459.72	-	2,330.35	-	-870.63	-
2	Model 1	Wall	330	250	30	Outer	42	39-43	24	7,651.26	141%	9,557.32	126%	-1,906.06	88%
		Roof	420	70	50	Outer	42	39-43	24	2,736.44	187%	3,487.53	150%	-751.09	86%
3	Model 2	Wall	330	250	30	Outer	38	34-39	24	6,044.26	111%	7,881.10	104%	-1,836.84	85%
		Roof	420	70	50	Outer	38	34-39	24	2,037.13	140%	2,710.08	116%	-672.95	77%
4	Model 3	Wall	330	250	30	Outer	35	34-36	24	5,415.24	100%	7,321.36	96%	-1,906.12	88%
		Roof	420	70	50	Outer	35	34-36	24	1,755.37	120%	2,471.21	106%	-715.84	82%
5	Model 4	Wall	330	250	30	Outer	31	29-34	24	3,447.12	63%	5,038.01	66%	-1,590.89	74%
		Roof	420	70	50	Outer	31	29-34	24	1,336.80	92%	1,420.57	61%	-83.77	10%
6	Model 5	Wall	330	250	30	Outer	28	27-29	24	4,064.90	75%	5,597.55	74%	-1,532.65	71%
		Roof	420	70	50	Outer	28	27-29	24	471.63	32%	418.14	18%	53.49	-6%
7	Model 6	Wall	330	250	30	Outer	25	22-26	24	4,066.32	75%	5,668.83	75%	-1,602.51	74%
		Roof	420	70	50	Outer	25	22-26	24	147.37	10%	447.49	19%	-300.12	34%
8	Model 3A	Wall	340	250	40	Outer	35	34-36	24	5,512.18	101%	7,378.52	97%	-1,866.34	86%
		Roof	410	70	40	Outer	35	34-36	24	1,601.85	110%	2,300.77	99%	-698.92	80%
9	Model 3B	Wall	350	250	50	Outer	35	34-36	24	5,424.49	100%	7,284.25	96%	-1,859.76	86%
		Roof	400	70	30	Outer	35	34-36	24	2,081.63	143%	2,517.02	108%	-435.39	50%
10	Model 3C	Wall	320	250	20	Outer	35	34-36	24	5,122.73	94%	7,086.79	93%	-1,964.06	91%
		Roof	390	70	20	Outer	35	34-36	24	1,666.97	114%	2,361.43	101%	-694.46	80%
11	Model 4A	Wall	340	250	40	Outer	31	29-34	24	3,288.42	60%	4,611.08	61%	-1,322.66	61%
		Roof	410	70	40	Outer	31	29-34	24	1,229.01	84%	1,529.45	66%	-300.44	35%
12	Model 4B	Wall	350	250	50	Outer	31	29-34	24	3,363.34	62%	4,514.75	59%	-1,151.41	53%
		Roof	400	70	30	Outer	31	29-34	24	1,602.98	110%	1,951.85	84%	-348.87	40%
13	Model 4C	Wall	320	250	20	Outer	31	29-34	24	4,001.27	74%	5,865.04	77%	-1,863.77	86%
		Roof	390	70	20	Outer	31	29-34	24	1,582.53	108%	2,232.30	96%	-649.77	75%
14	Model 7	Wall	330	250	30	Inner	28	27-29	24	8,076.28	148%	9,309.57	122%	-1,233.29	57%
		Roof	420	70	50	Inner	28	27-29	24	2,059.83	141%	2,320.73	100%	-260.90	30%
15	Model 8	Wall	330	250	30	Inner	25	22-26	24	1,418.54	26%	5,125.22	67%	-3,706.68	172%
		Roof	420	70	50	Inner	25	22-26	24	-365.15	-25%	1,089.35	47%	-1,454.50	167%
16	Model 9	Wall	330	250	30	Inner	22	20-23	24	4,930.97	91%	7,235.26	95%	-2,304.29	107%
		Roof	420	70	50	Inner	22	20-23	24	1,283.74	88%	2,173.72	93%	-889.98	102%
17	Model 10	Wall	330	250	30	Double	38/25	34-39	24	2,834.02	52%	6,152.82	81%	-3,318.80	154%
		Roof	420	70	50	Double	38/25	34-39	24	890.75	61%	2,159.69	93%	-1,268.94	146%
18	Model 11	Wall	330	250	30	Double	35/25	34-36	24	2,231.16	41%	5,562.08	73%	-3,330.92	154%
		Roof	420	70	50	Double	35/25	34-36	24	1,002.80	69%	2,173.52	93%	-1,170.72	134%
19	Model 12	Wall	330	250	30	Double	31/25	29-34	24	1,444.90	27%	4,749.94	63%	-3,305.04	153%
		Roof	420	70	50	Double	31/25	29-34	24	419.90	29%	1,579.83	68%	-1,159.93	133%

Table 2-3: Comparative summary of Parametric Analysis Outputs (Riyadh-KSA)

2.6 Enhanced Baseline Models

The final proposed PCM-integrated models retained the same construction as the baseline model but included an enlarged envelope to accommodate the additional PCM layers. To ensure a fair and meaningful comparison, a set of enhanced baseline models was developed with identical geometry and construction, except that the PCM layers were replaced by conventional thermal insulation of equivalent thickness. As illustrated in Figure 2-16(a) and Figure 2-16(b), an enhanced baseline model was established by replacing the 50 mm PCM layer in one of the proposed PCM-integrated models with an additional insulation layer.

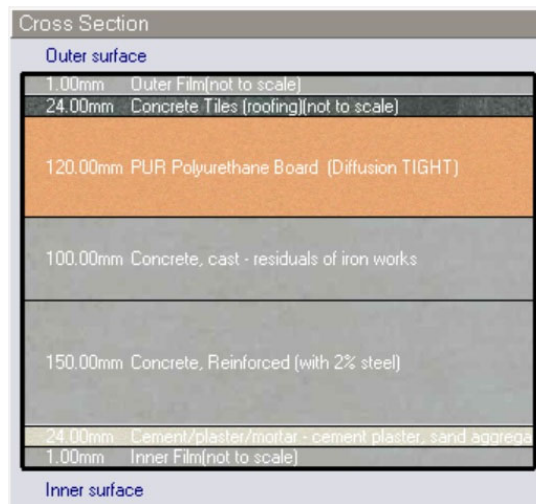
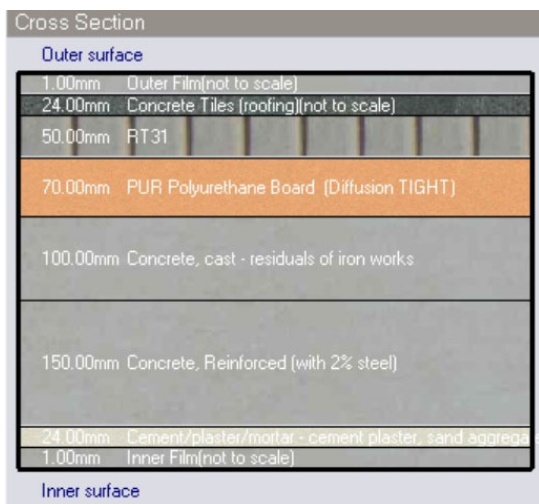


Figure 2-16(a): Roof-integrated PCM cross section

Figure 2-16(b): Enhanced Baseline Roof cross section

This approach enabled a direct performance comparison between the latent heat storage capability of PCM and the thermal resistance provided by standard insulation materials. By using the same construction parameters and dimensions, the analysis isolates the effect of PCM integration and verifies whether the observed improvements in thermal and energy performance are attributable to phase-change behaviour rather than merely increased material thickness or insulation mass.

3. RESULTS

Based on the simulation outcomes and comparative assessments against the baseline models, the integration of Phase Change Materials (PCMs) within the building envelope demonstrated notable performance improvements across all analysed climate zones and building configurations. In each location, PCM-enhanced assemblies consistently outperformed both the baseline and enhanced baseline scenarios by reducing heat gain and improving energy efficiency. While all cities exhibited measurable benefits, the magnitude of improvement varied according to local climate conditions with Riyadh showing the highest overall performance gains.

3.1 Dubai-UAE

Following extensive simulation analysis and comparative evaluation with the baseline model, the integration of Phase Change Materials (PCMs) within the building envelope for Dubai's hot and humid climate has demonstrated substantial potential in improving thermal performance. Given Dubai's climate, where cooling is required almost year-round, the use of PCM contributes notably to reducing unwanted heat gain through both walls and roof, thereby helping to reduce energy consumption.

3.1.1 PCM Placement

The parametric analysis revealed that the optimal performance during peak summer months was achieved when PCM was placed on the outer face of the wall. However, when accounting for varying seasonal conditions, particularly during the milder winter months, the double-layer PCM configuration provided a more balanced and stable performance. This configuration not only responded better to moderate thermal loads but also aligned more closely with Dubai's consistent cooling demand pattern throughout the year (see Figure 3-1 and Figure 3-2).

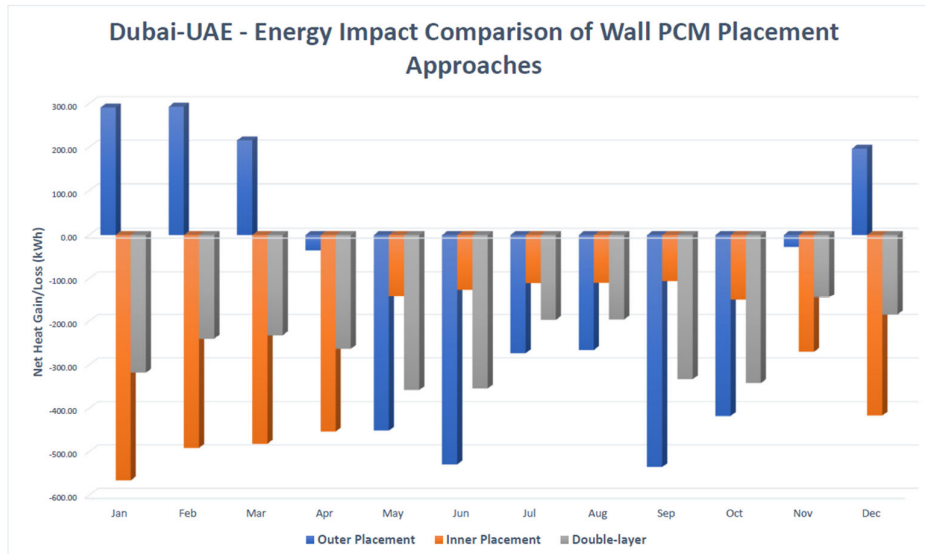


Figure 3-1: Energy Impact Comparison of Wall PCM Placement Approaches

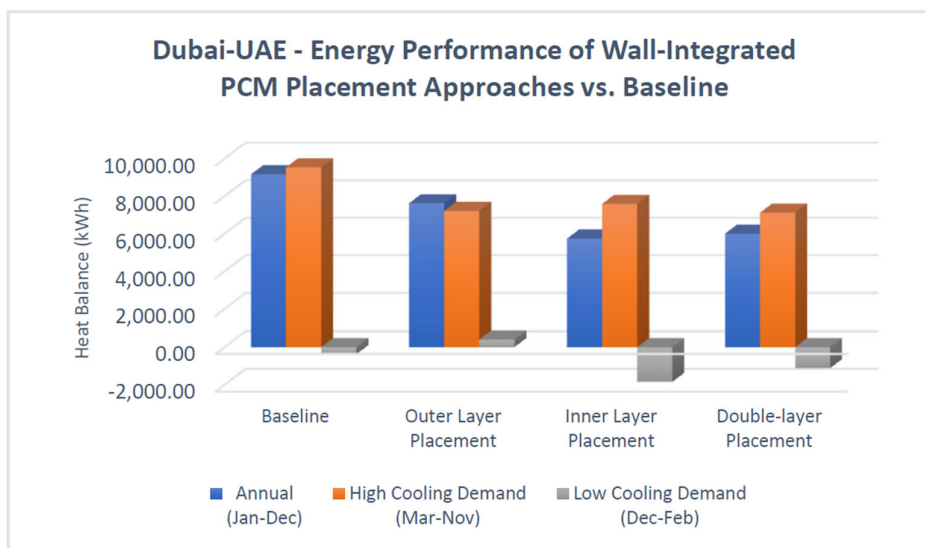


Figure 3-2: Energy Performance of Wall-Integrated PCM Placement Approach vs Baseline

A similar trend was observed for the roof assembly, where both configurations showed comparable overall annual performance. However, outer PCM placement on the roof demonstrated significantly higher performance during summer months, attributed to the increased solar exposure, enabling better utilization of the PCM’s thermal storage capacity (see Figure 3-3 and Figure 3-4).

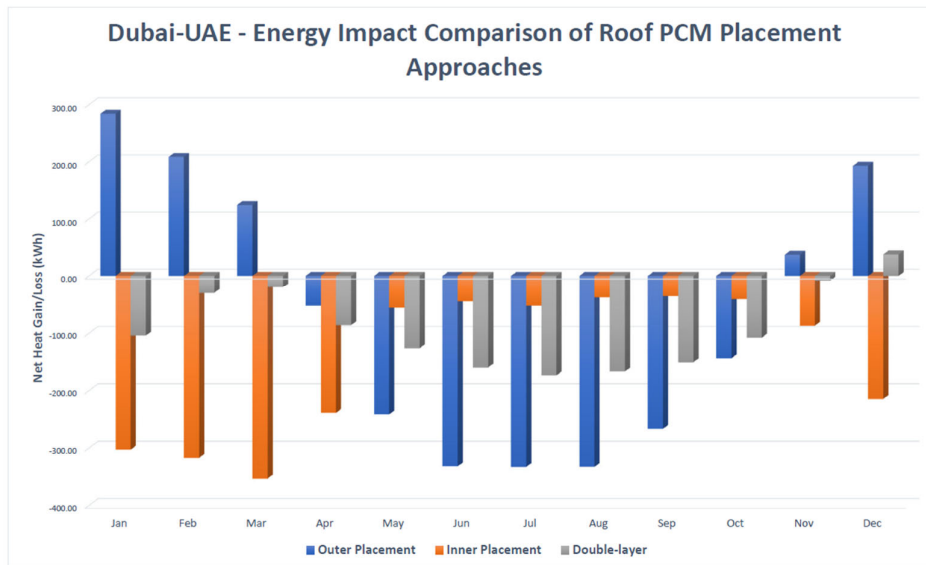


Figure 3-3: Energy Impact Comparison of Roof PCM Placement Approaches

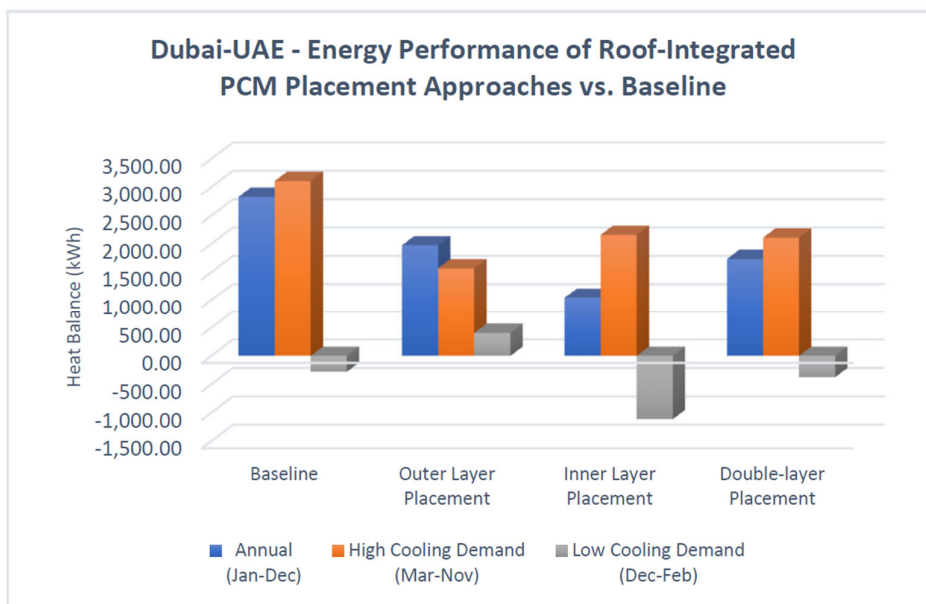


Figure 3-4: Energy Performance of Roof-Integrated PCM Placement Approach vs Baseline

3.1.2 PCM Melting Point

Performance comparisons between PCMs with different melting points revealed that for outer PCM layer RT31, with a melting range between 29°C and 34°C, delivered the highest thermal improvement when integrated into both wall and roof assemblies. This melting range was

found to be ideal for matching the outdoor temperature fluctuations typical in Dubai's climate, ensuring effective phase change behaviour (see Figure 3-5(a) and Figure 3-5(b)).

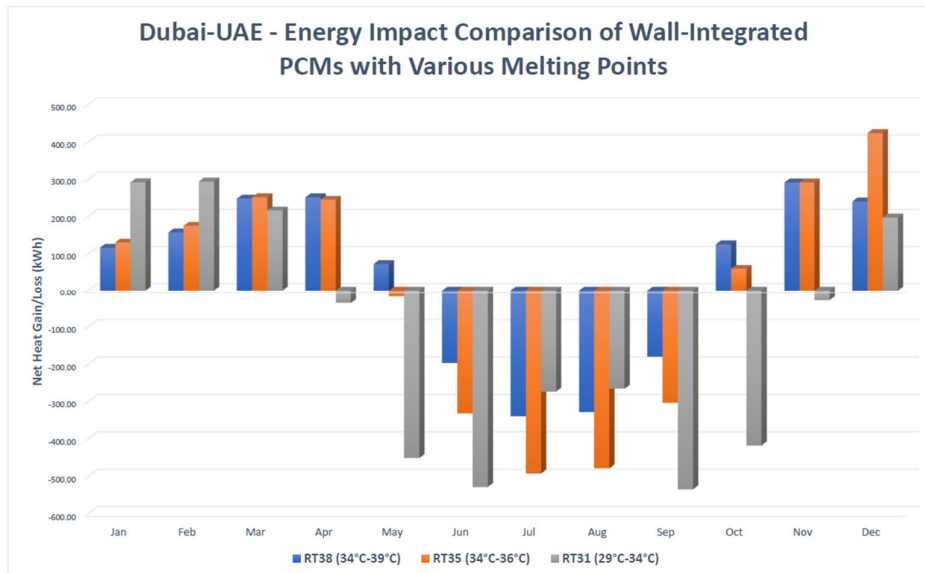


Figure 3-5(a): Energy Impact Comparison of Wall-Integrated PCMs with Various Melting Points

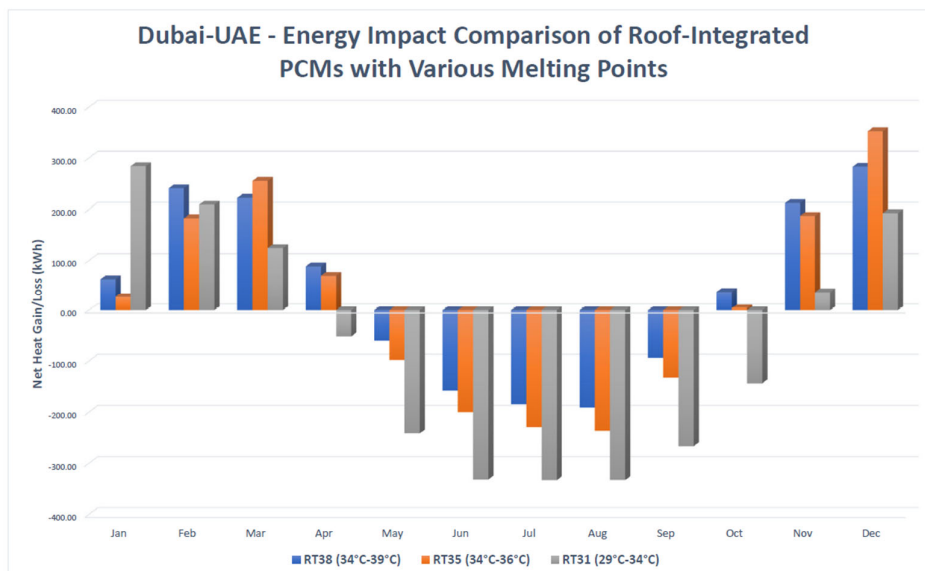


Figure 3-5(b): Energy Impact Comparison of Roof-Integrated PCMs with Various Melting Points

In the double-layer PCM configuration, RT25 was selected for the inner PCM layer (see Figure 3-6 for RT25 melting curve), as its more compatible with the controlled indoor temperatures. This strategic layering ensures that both outer and inner environments are thermally managed through PCM behaviour tailored to their respective conditions.

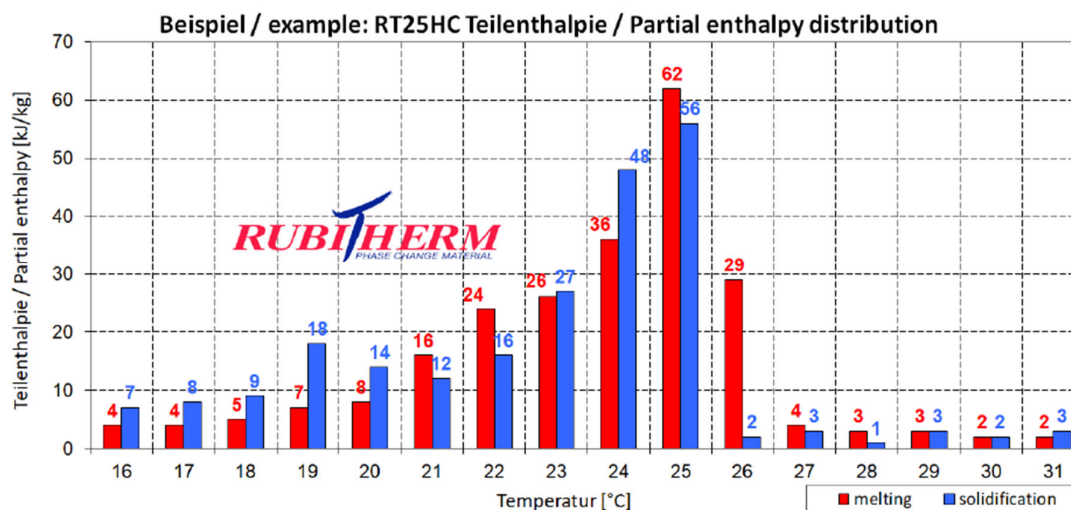


Figure 3-6: PCM RT25 Melting/Solidification Curve

3.1.3 Wall Orientation

Analysis of wall orientations showed clear differences in thermal performance with the south-facing wall consistently experienced the greatest heat reduction due to prolonged exposure to solar radiation, which better activates the PCM's latent heat absorption capabilities. Although results varied depending on whether outer or double-layer placement was used, both configurations confirmed that orientation significantly influences thermal performance (see Figure 3-7(a)).

While the south-facing façade achieved the highest total heat reduction, the north-facing façade showed the greatest percentage improvement relative to the baseline model (see Figure 3-7(b)).

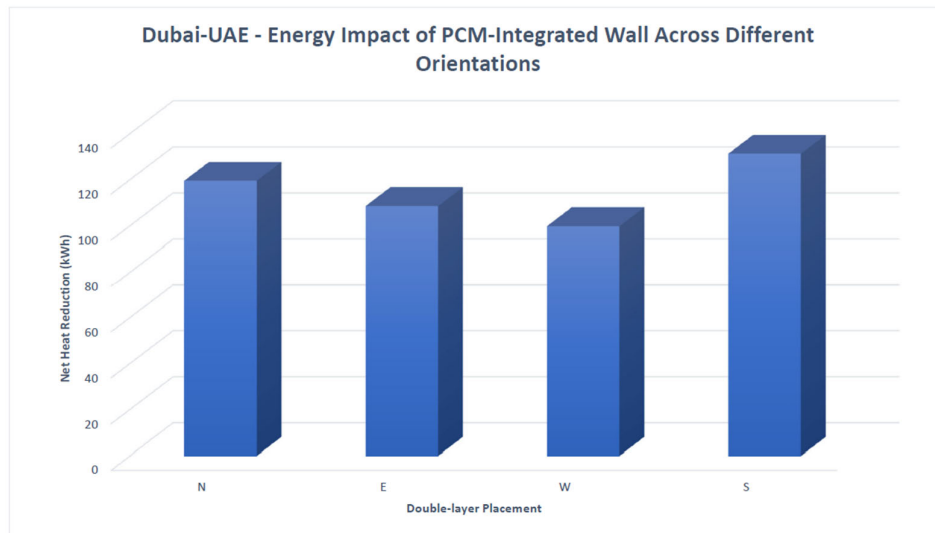


Figure 3-7(a): Energy Impact of PCM-Integrated Wall Across Different Orientations

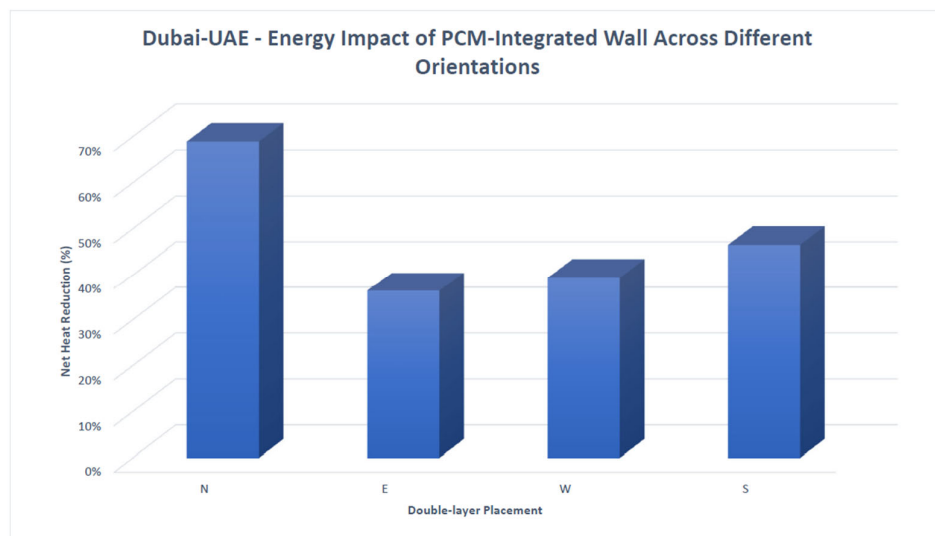


Figure 3-7(b): Percentage of Energy Reduction in PCM-Integrated Wall Orientations

3.1.4 Energy Performance of PCM-Integrated Models

The overall energy performance and heat reduction achieved by the PCM-integrated models demonstrated significant improvements and promising energy savings compared to the baseline scenario. The final four proposals developed by combining two placement configurations (outer and double-layer) with two PCM thicknesses (30 mm and 50 mm) resulted in substantial reductions in heat gain through the building envelope. During periods of

high cooling demand, the configurations achieved a net heat reduction of 26% and 40% in the walls for the 30 mm and 50 mm thicknesses, respectively (Figure 3-8), while the roof exhibited even greater improvements, with corresponding reductions of 30% and 50% (Figure 3-9).

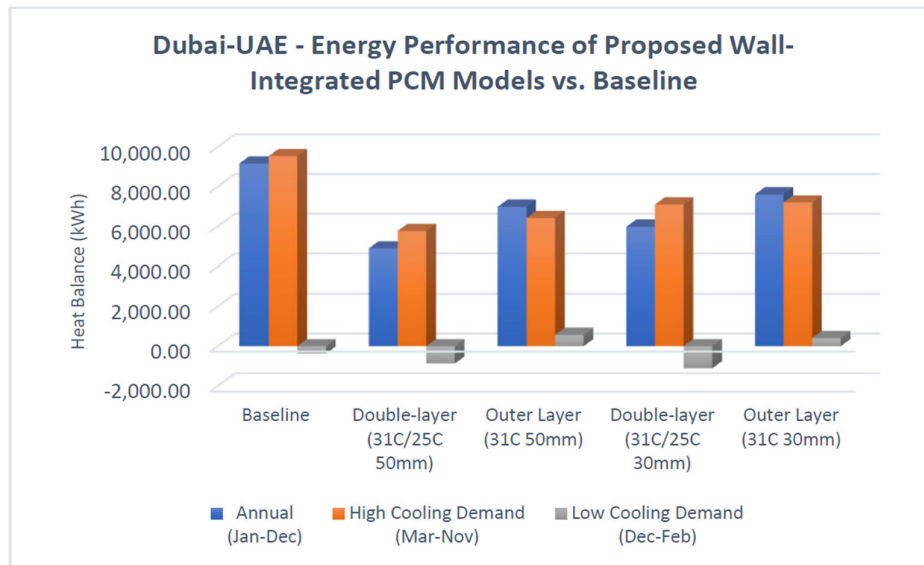


Figure 3-8: Energy Performance of Proposed Wall-Integrated PCM Models vs Baseline

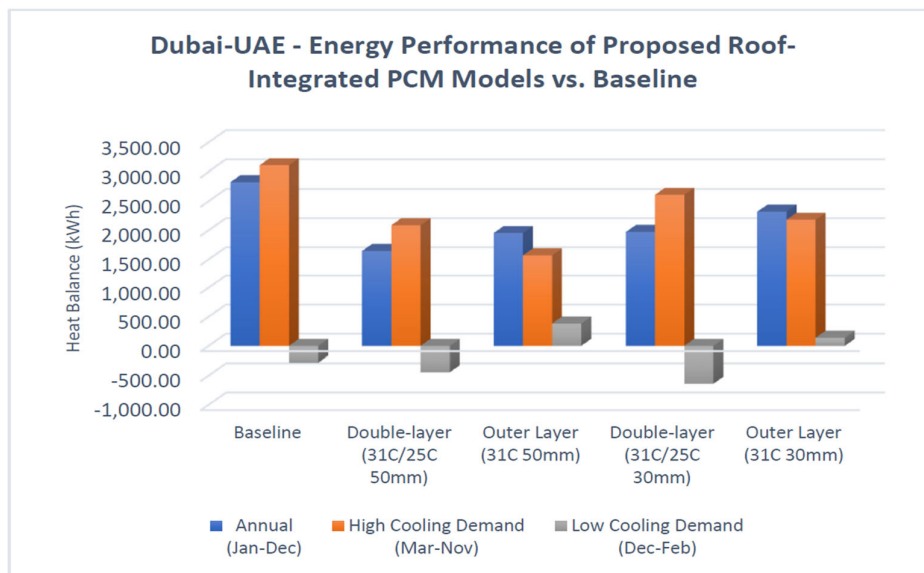


Figure 3-9: Energy Performance of Proposed Roof-Integrated PCM Models vs Baseline

These findings confirm the effectiveness of PCM integration in both wall and roof assemblies, particularly when applied with increased thickness and in configurations optimized for seasonal thermal behaviour.

In addition, a monthly breakdown of heat balance was conducted using the 50 mm PCM configurations. This assessment illustrated the distinct seasonal patterns between the outer and double-layer placements. The outer PCM configuration achieved peak performance during summer months, efficiently mitigating heat gain. In contrast, the double-layer configuration displayed more uniform performance, offering moderate and consistent heat reduction across the year, particularly beneficial during transitional seasons (see Figure 3-10 and Figure 3-11).

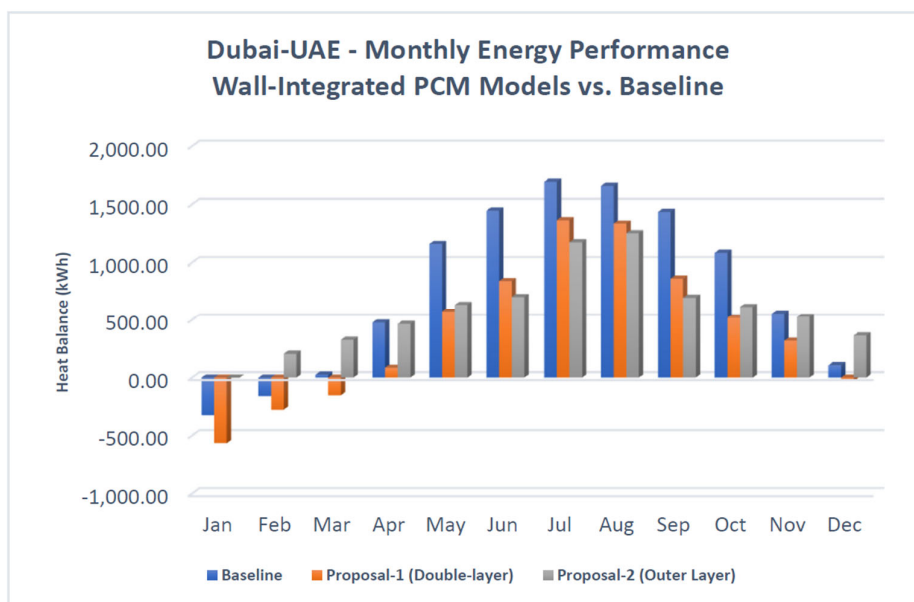


Figure 3-10: Monthly Energy Performance Wall-Integrated PCM Models vs Baseline

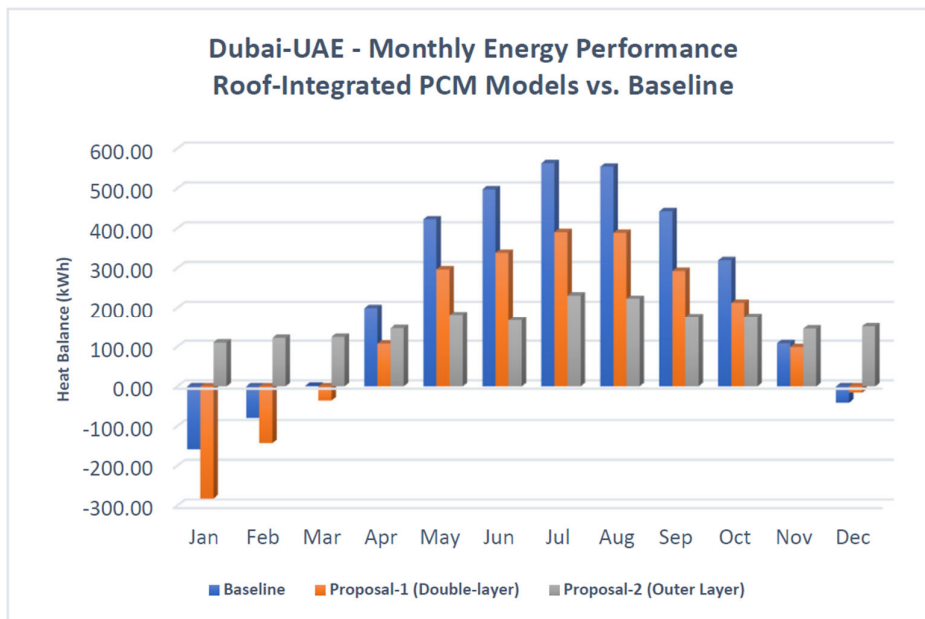


Figure 3-11: Monthly Energy Performance Roof-Integrated PCM Models vs Baseline

3.1.5 Enhanced Baseline

To further assess the performance of PCM integration, additional comparative models were developed using an enhanced baseline approach, in which the PCM layers were substituted with conventional thermal insulation of equal thickness (30 mm and 50 mm). This allowed for a direct comparison between the latent heat storage behaviour of PCM and the thermal resistance characteristics of traditional insulation materials. While the enhanced baseline models demonstrated improved performance relative to the original baseline, they were consistently outperformed by the PCM-integrated configurations across both wall and roof applications.

In wall assemblies, the PCM models delivered superior thermal performance, achieving 18% to 30% greater heat reduction compared to their insulated counterparts, depending on the applied thickness. These results are illustrated in Figure 3-12 and Figure 3-13, which show performance comparisons at 30 mm and 50 mm, respectively.

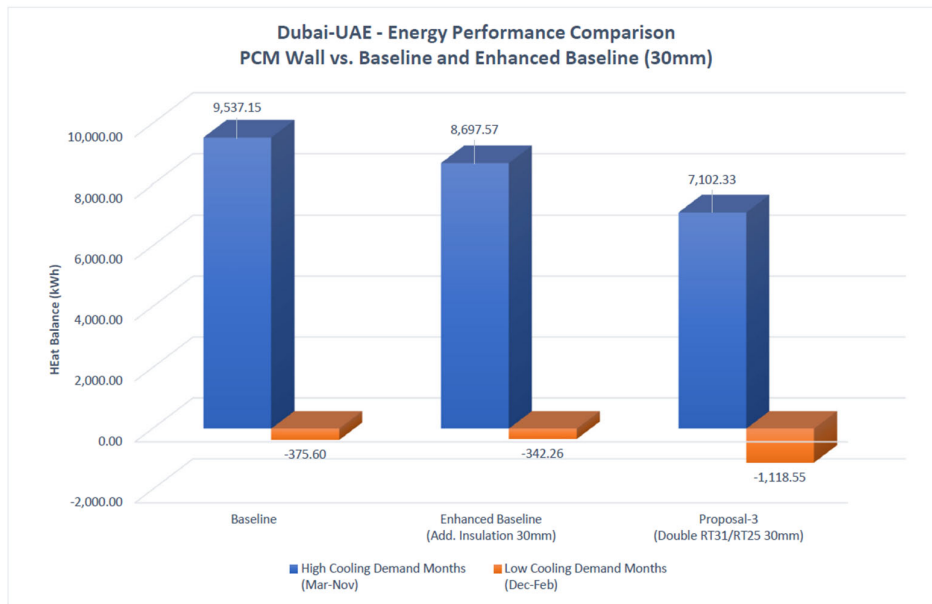


Figure 3-12: Energy Performance Comparison PCM Wall vs Baseline and Enhanced Baseline (30mm)

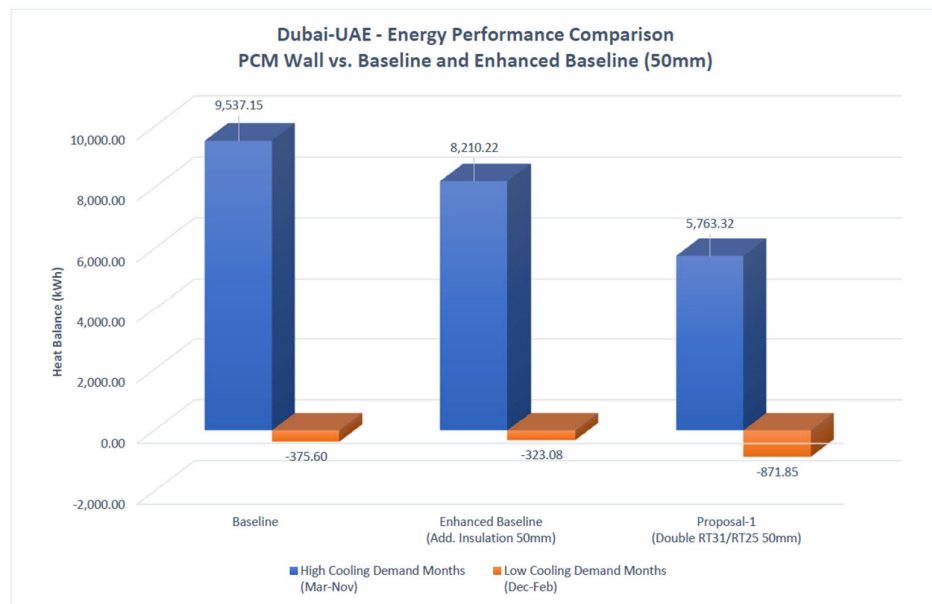


Figure 3-13: Energy Performance Comparison PCM Wall vs Baseline and Enhanced Baseline (50mm)

Similarly in roof assemblies, the PCM-integrated designs provided an additional 15% to 20% reduction in heat gain over the enhanced insulation models, as detailed in Figure 3-14 and

Figure 3-15. These findings underscore the added value of latent heat storage in PCM systems over conventional insulation methods.

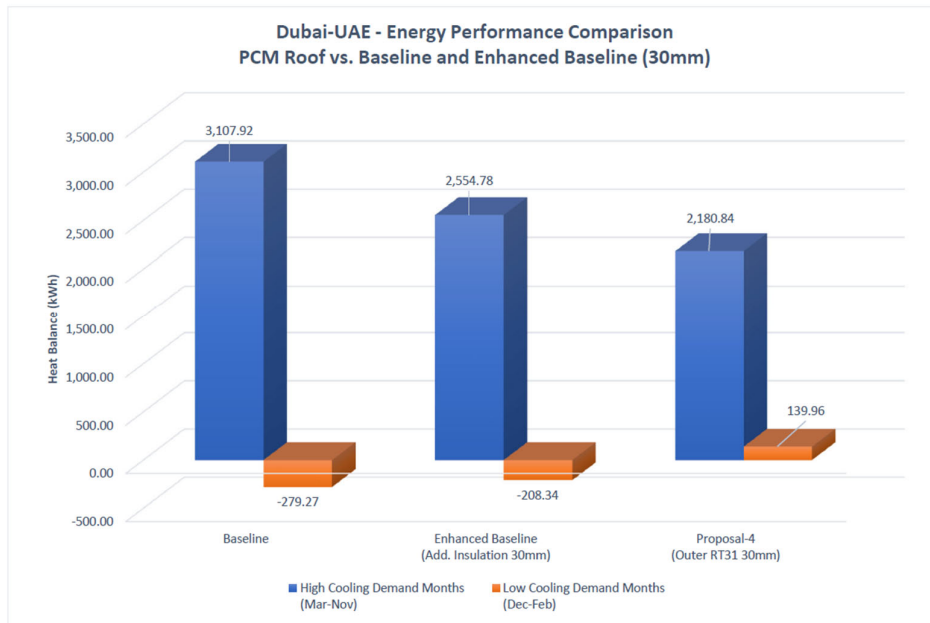


Figure 3-14: Energy Performance Comparison PCM Roof vs Baseline and Enhanced Baseline (30mm)

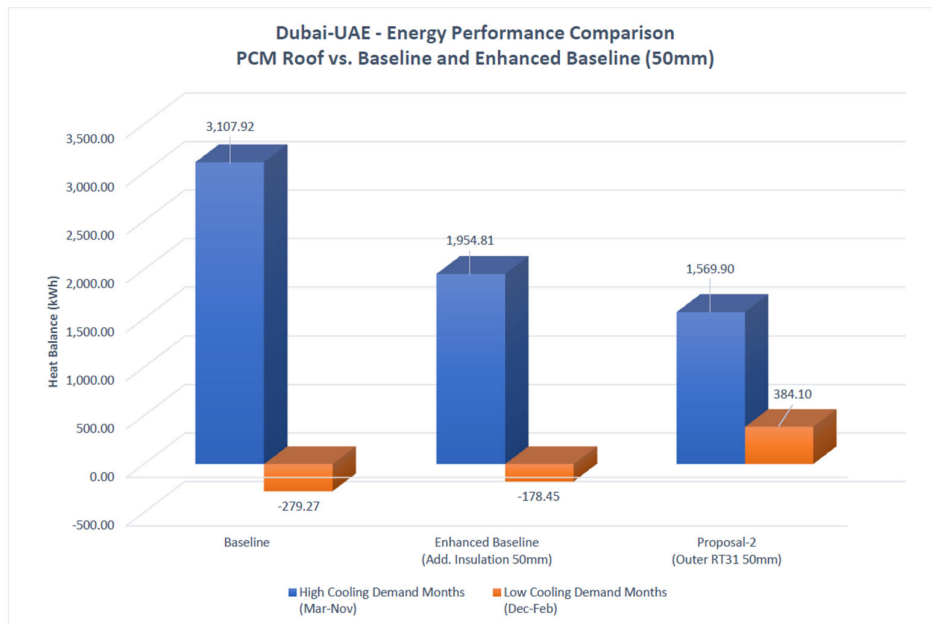


Figure 3-15: Energy Performance Comparison PCM Roof vs Baseline and Enhanced Baseline (50mm)

Table 3-1 presents a comparative analysis of the final PCM-integrated models against both the baseline and enhanced baseline models in Dubai. The results highlight the added value of PCM integration beyond conventional insulation improvements, demonstrating higher reductions in heat flux and energy demand. This comparison reinforces that latent heat storage offers superior performance over purely resistive approaches, confirming the potential of PCM as a climate-responsive strategy for high cooling demand regions.

S.N.	Description	Envelope	Total Thickness (mm)	Insulation Thickness (mm)	PCM Layer				Net Heat Balance (kWh)	
					Thickness (mm)	Placement	Peak Melting Temp. (C)	Melting Temp. Range (C)	Annual (Jan-Dec)	Cooling Demand Months (Mar-Nov)
1	Baseline Model	Wall	300	250	-	-	-	-	9,161.55	9,537.15
		Roof	370	70	-	-	-	-	2,828.65	3,107.92
2	PCM-Integrated Model-1	Wall	350	250	50	Double	31 & 25	29-34	4,891.47	5,763.32
		Roof	420	70	50	Double	31 & 25	29-34	1,645.81	2,087.34
3	PCM-Integrated Model-2	Wall	350	250	50	Outer	31	29-34	6,988.37	6,419.22
		Roof	420	70	50	Outer	31	29-34	1,954.00	1,569.90
4	PCM-Integrated Model-3	Wall	330	250	30	Double	31 & 25	29-34	5,983.78	7,102.33
		Roof	400	70	30	Double	31 & 25	29-34	1,972.73	2,611.65
5	PCM-Integrated Model-4	Wall	330	250	30	Outer	31	29-34	7,609.18	7,200.13
		Roof	400	70	30	Outer	31	29-34	2,320.80	2,180.84
6	Enhanced Baseline-1	Wall	350	300	-	-	-	-	7,887.14	8,210.22
		Roof	420	120	-	-	-	-	1,776.36	1,954.81
7	Enhanced Baseline-2	Wall	330	280	-	-	-	-	8,355.31	8,697.57
		Roof	400	100	-	-	-	-	2,346.44	2,554.78

Table 3-1: Energy Performance Comparison between PCM-Integrated and Baseline Models (Dubai-UAE)

3.2 Riyadh-KSA

Following detailed simulation analysis and comparative evaluation, the integration of Phase Change Materials (PCMs) within the building envelope for Riyadh's hot and arid climate (characterized by prolonged cooling demand across three seasons and only brief heating requirements during winter) yielded the highest energy performance improvements among the studied cities. The results indicated that PCM integration was most effective in the roof assembly, where it produced the greatest reductions in heat gain. Meanwhile, wall-integrated PCM also delivered significant thermal and energy benefits, contributing meaningfully to year-round performance enhancement.

3.2.1 PCM Placement

The parametric analysis demonstrated that the outer placement strategy yielded the best and most consistent performance, aligning effectively with the seasonal cooling-heating demand profile and matching the distribution of monthly thermal behaviour and energy requirements. In wall-integrated PCM applications, the inner and double-layer placements resulted in lower overall improvements. Moreover, these configurations exhibited noticeable misalignment with monthly demand fluctuations, offering less synchronized performance across varying seasonal conditions (see Figure 3-16 and Figure 3-17).

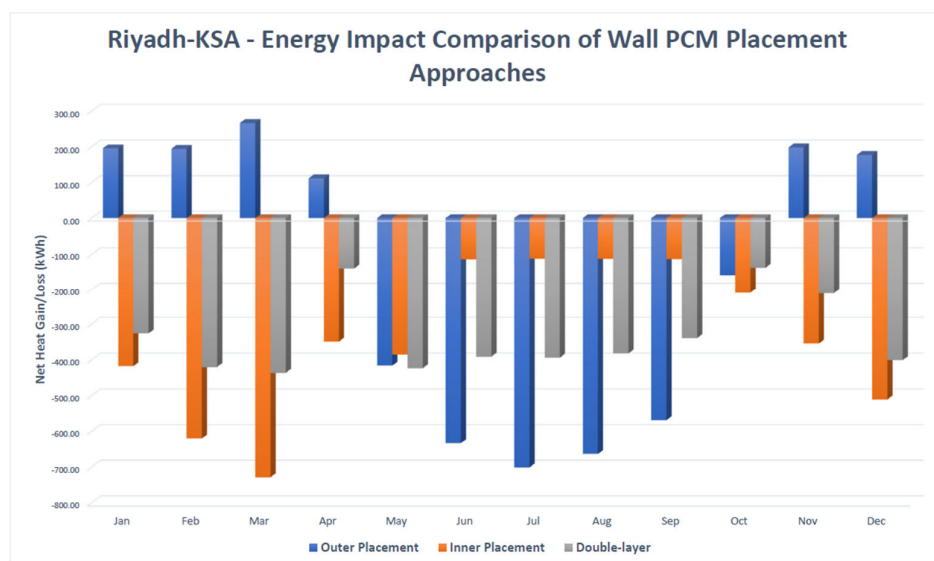


Figure 3-16: Energy Impact Comparison of Wall PCM Placement Approaches

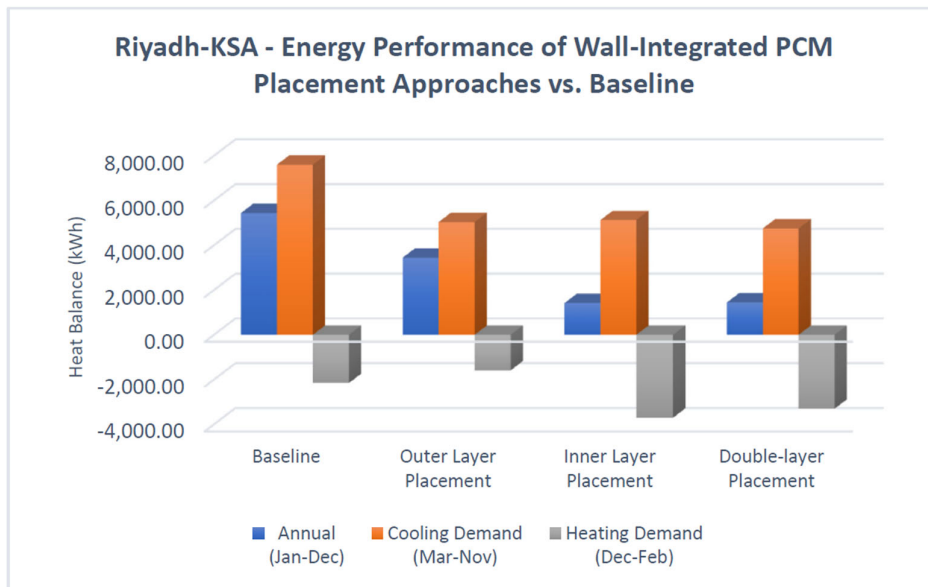


Figure 3-17: Energy Performance of Wall-Integrated PCM Placement Approach vs Baseline

In the case of roof-integrated PCM, the inner placement showed high performance during peak summer months, yet it offered no significant improvement during the cooler months when heating demand emerged. In contrast, the outer placement configuration demonstrated a more consistent thermal response throughout the year and delivered the highest overall energy performance, resulting in substantial annual energy savings (see Figure 3-18 and Figure 3-19).

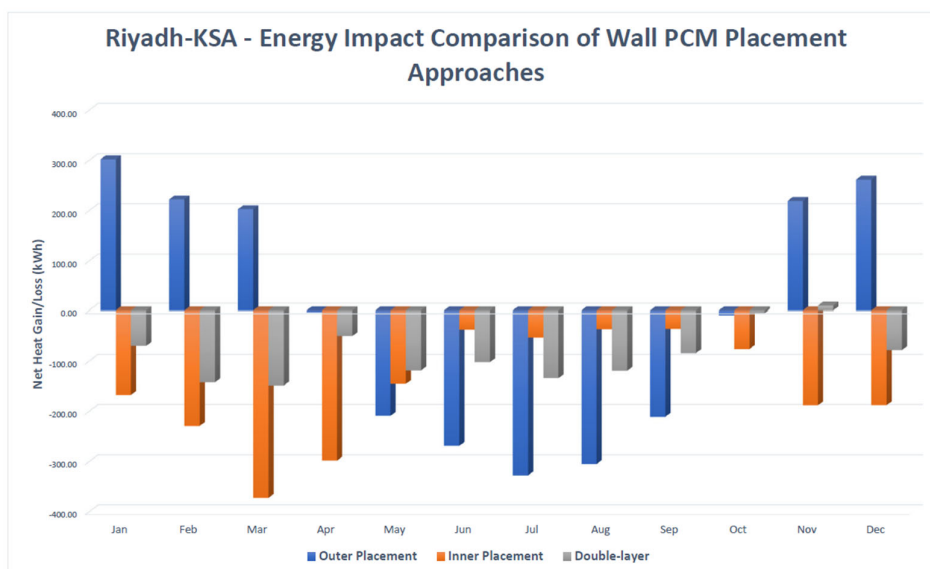


Figure 3-18: Energy Impact Comparison of Roof PCM Placement Approaches

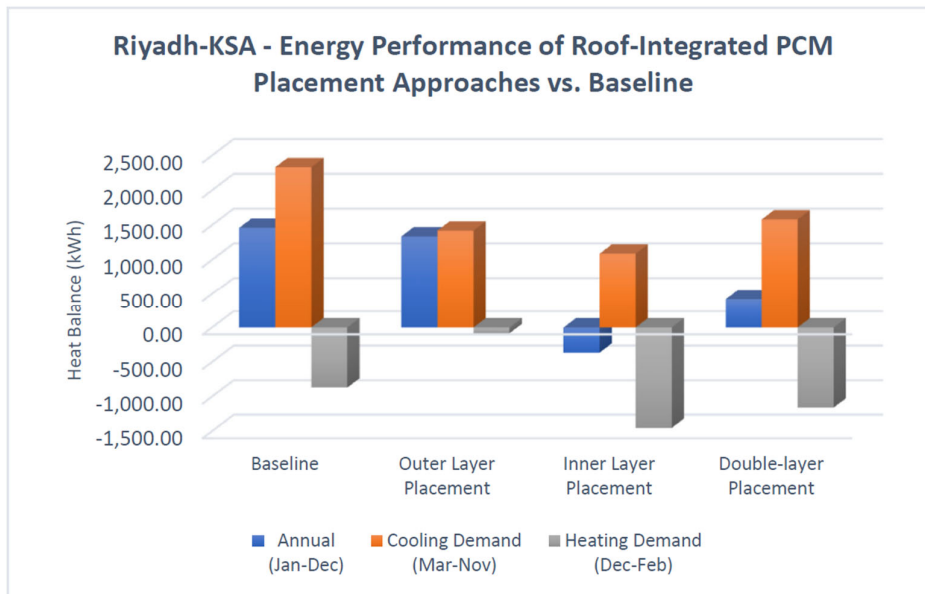


Figure 3-19: Energy Performance of Roof-Integrated PCM Placement Approach vs Baseline

3.2.2 PCM Melting Point

In the outer placement configuration, the evaluation of multiple PCM melting points showed that two specific options, R28 (melting range: 27°C to 29°C) and RT31 (melting range: 29°C to 34°C) delivered the best thermal performance compared to other tested melting point ranges.

For wall-integrated PCM, the highest performance was achieved using RT31, which aligned well with the indoor-outdoor temperature interaction and seasonal cooling demands (see Figure 3-20).

In contrast, the roof-integrated PCM showed optimum performance using R28, due to its better activation under roof surface temperature conditions, particularly during periods of intense solar exposure (see Figure 3-21).

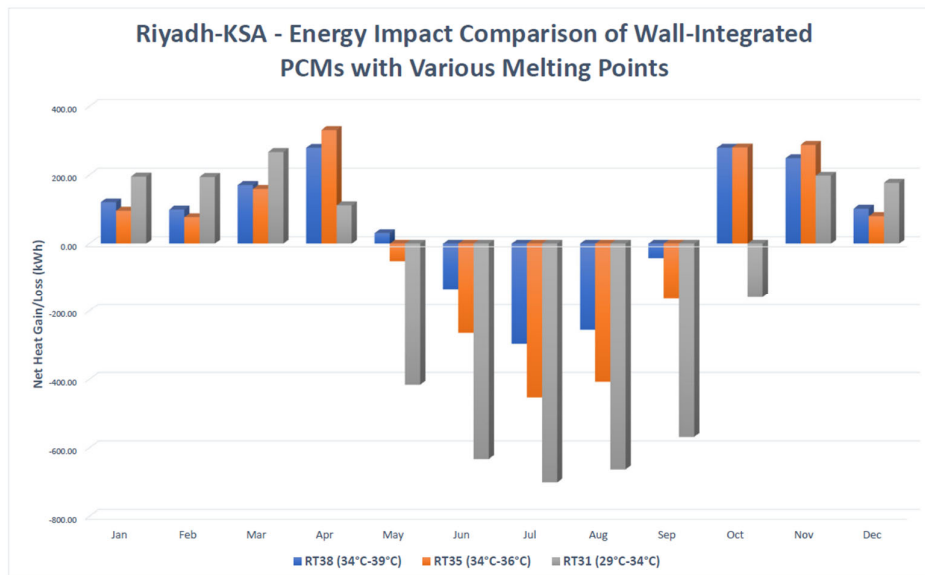


Figure 3-20: Energy Impact Comparison of Wall-Integrated PCMs with Various Melting Points

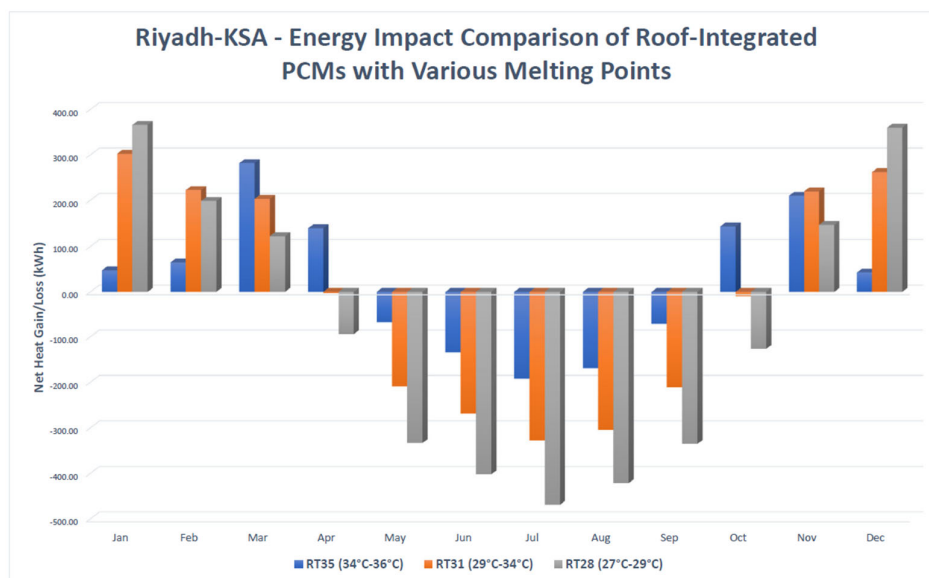


Figure 3-21: Energy Impact Comparison of Roof-Integrated PCMs with Various Melting Points

3.2.3 Wall Orientation

The results from the outer PCM placement configuration revealed noticeable performance variations across different wall orientations. Among the orientations analysed, the south-facing

façade consistently delivered the highest thermal improvement, achieving the best performance relative to the other directions studied (see Figure 3-22).

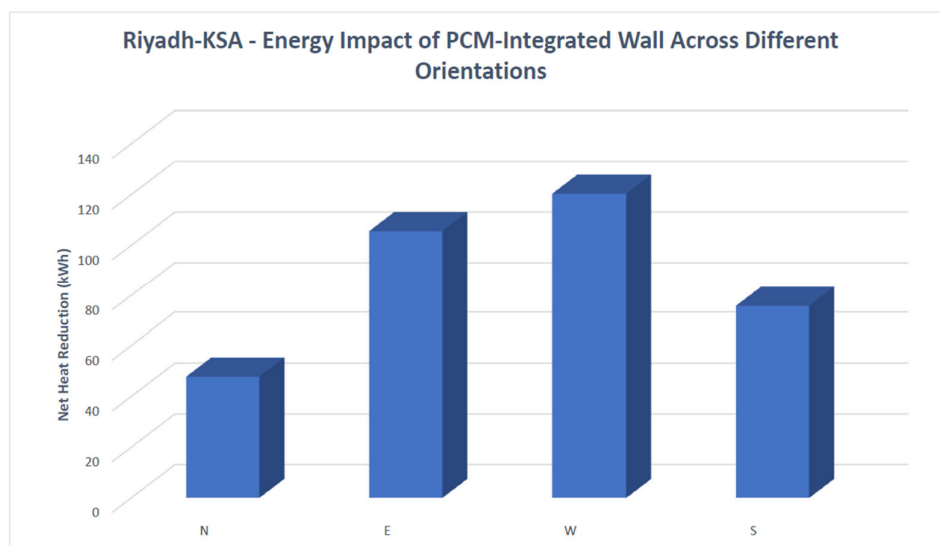


Figure 3-22: Energy Impact of PCM-Integrated Wall Across Different Orientations

3.2.4 Energy Performance of PCM-Integrated Models

The parametric analysis concluded with four proposed PCM-integrated models for walls and roofs. These models utilized two different thicknesses (30 mm and 50 mm) with RT31 applied for all wall integrations, and two options, RT28 and RT31, proposed for the roof integration.

The performance outcomes demonstrated significant thermal improvement and promising energy savings compared to the baseline model. For wall applications, the PCM-integrated systems achieved heat reduction rates of 33% and 40% for the 30 mm and 50 mm thicknesses, respectively (see Figure 3-23). In the roof assembly, even higher performance was reported, with reductions reaching 58% and 71% for the same respective thicknesses (see Figure 3-24).

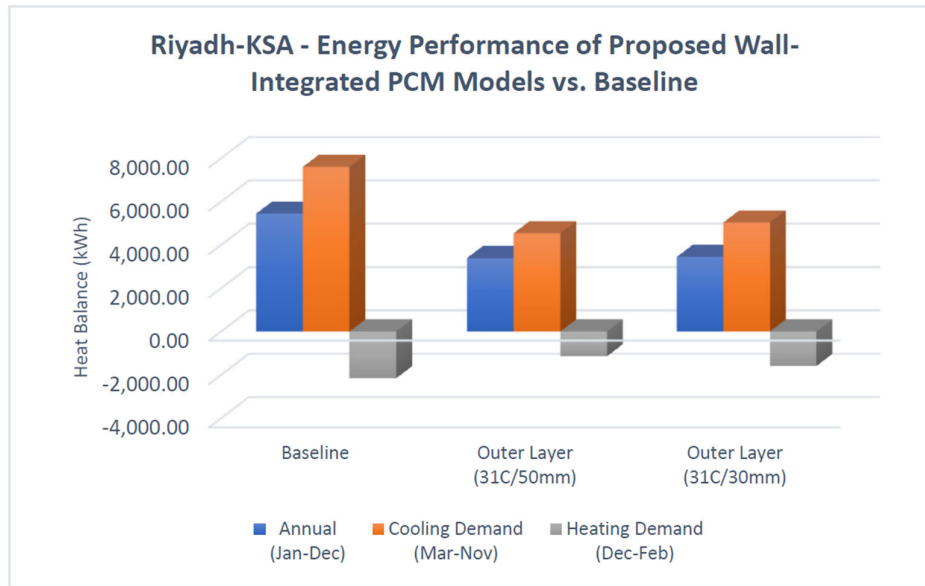


Figure 3-23: Energy Performance of Proposed Wall-Integrated PCM Models vs Baseline

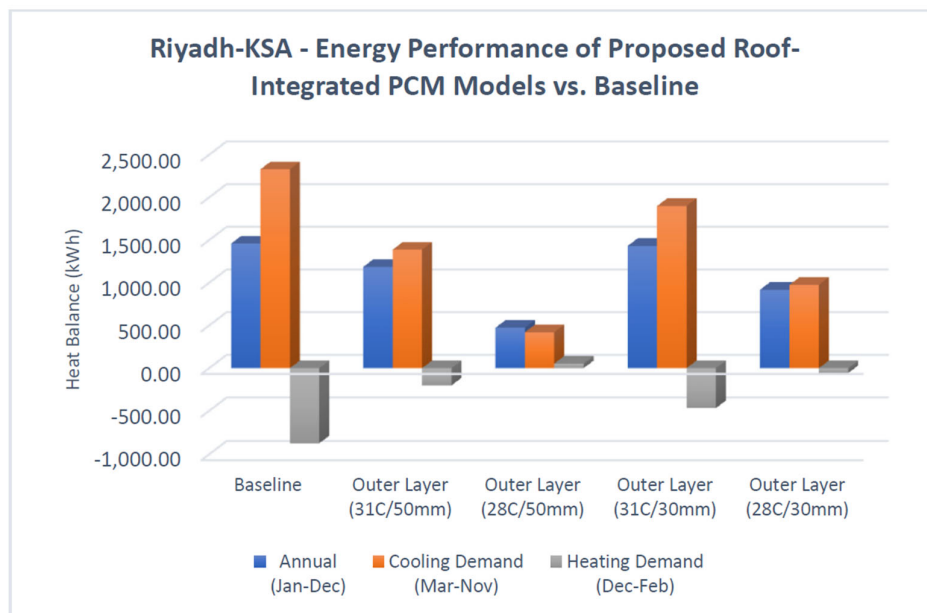


Figure 3-24: Energy Performance of Proposed Roof-Integrated PCM Models vs Baseline

Further analysis of the results focused on the performance distribution of the proposed models and their temporal alignment with the building’s cooling and heating demand profile. The findings demonstrated a high level of consistency and alignment between the thermal

behaviour of the PCM-integrated models and the actual monthly energy demand. This was clearly observed in the monthly performance distribution, which showed a strong correlation with demand patterns when compared to the baseline monthly spectra (see Figure 3-25 and Figure 3-26).

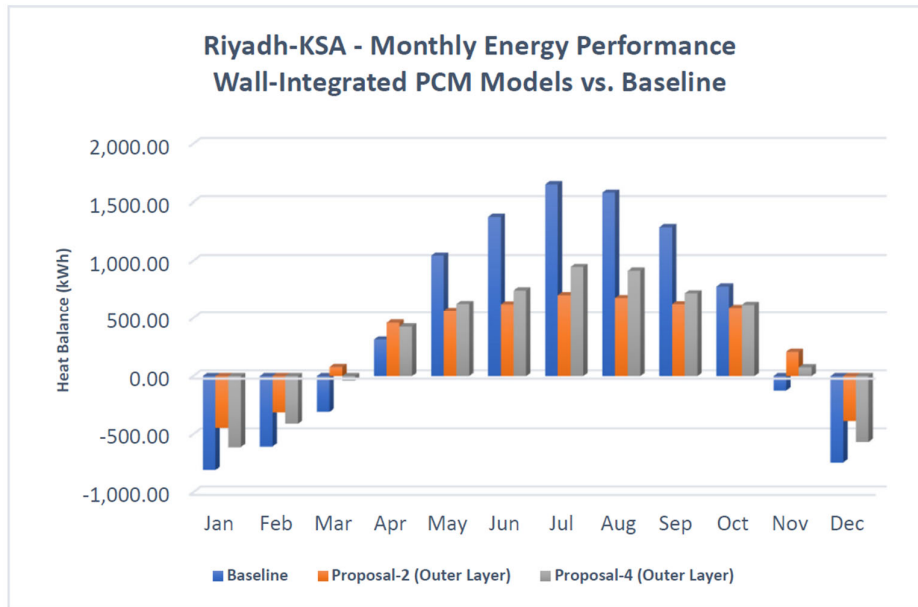


Figure 3-25: Monthly Energy Performance Wall-Integrated PCM Models vs Baseline

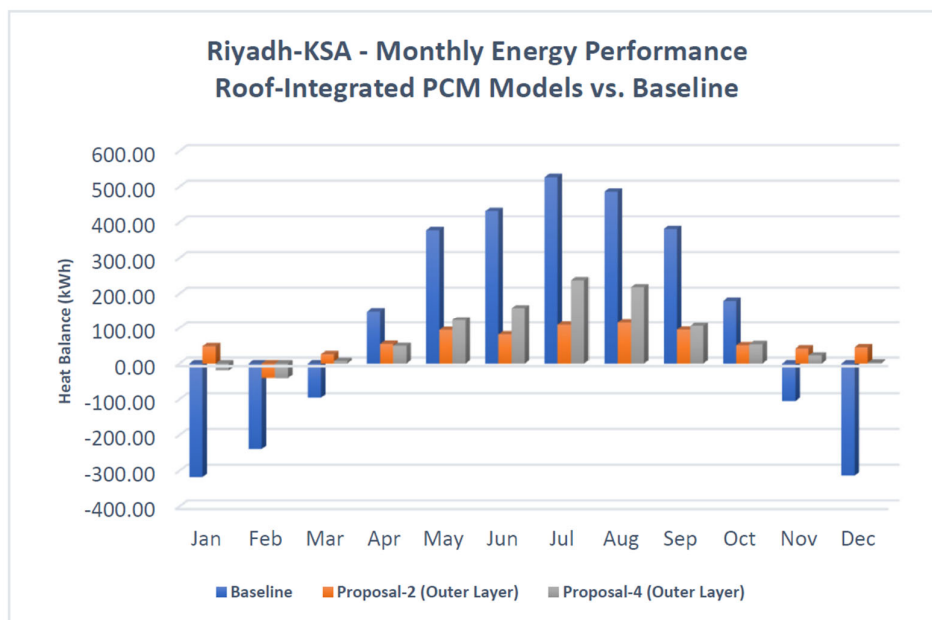


Figure 3-26: Monthly Energy Performance Roof-Integrated PCM Models vs Baseline

3.2.5 Enhanced Baseline

To maintain consistency in the evaluation approach, the PCM-integrated models were also compared against enhanced baseline models using additional thermal insulation of equivalent thickness. While the enhanced models outperformed the original baseline, the PCM-integrated configurations consistently delivered higher thermal and energy performance across both walls and roofs.

In wall assemblies, the PCM-integrated models demonstrated notable thermal advantages, achieving 28% to 31% greater heat reduction compared to the enhanced insulation counterparts, depending on the applied thickness. These performance differences are illustrated in Figure 3-27 and Figure 3-28, corresponding to the 30 mm and 50 mm configurations, respectively.

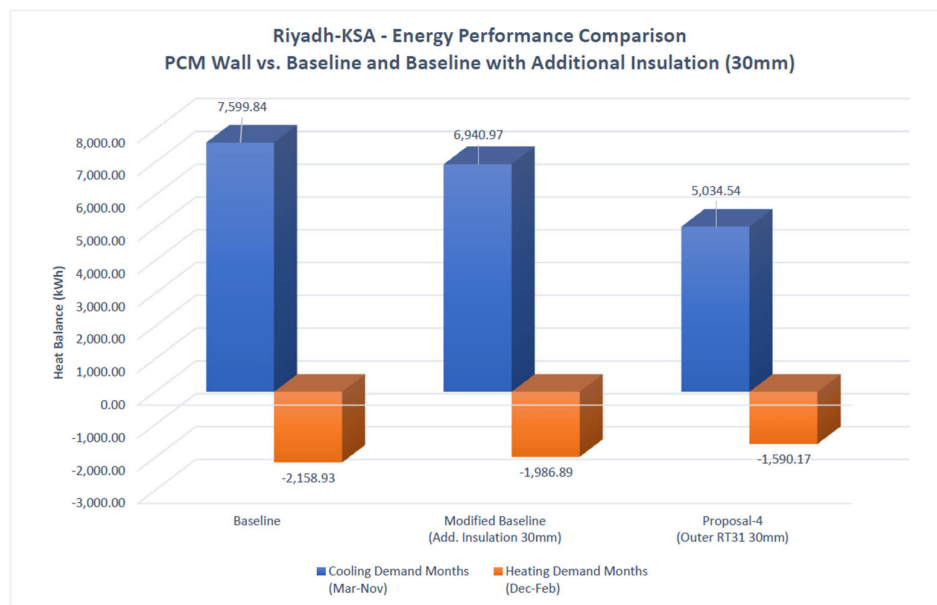


Figure 3-27: Energy Performance Comparison PCM Wall vs Baseline and Enhanced Baseline (30mm)

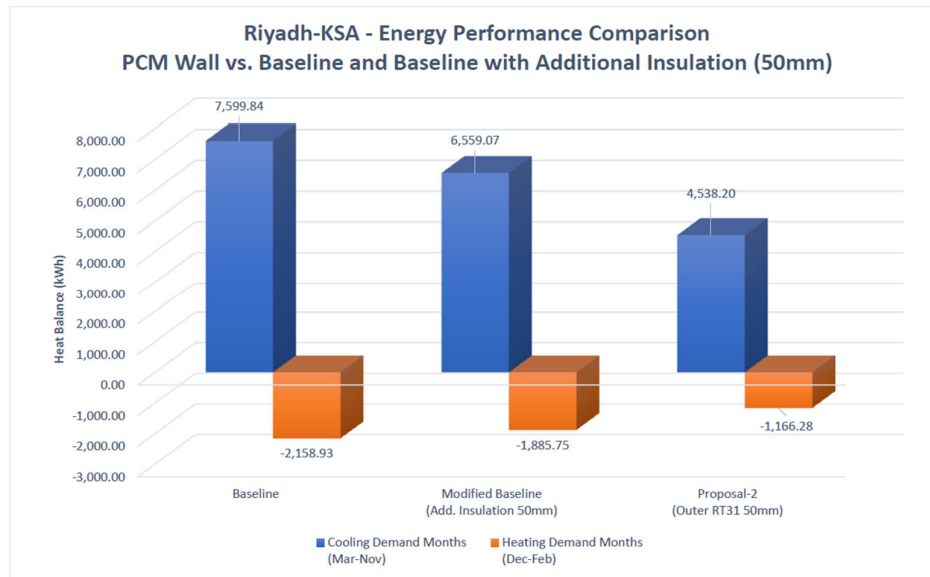


Figure 3-28: Energy Performance Comparison PCM Wall vs Baseline and Enhanced Baseline (50mm)

Similarly, in roof assemblies, the PCM-integrated designs delivered superior performance, achieving a 44% to 55% improved performance compared to the enhanced insulation models, as shown in Figure 3-29 and Figure 3-30. These findings further emphasize the distinct advantage of latent heat storage in PCM systems over traditional insulation methods, particularly in applications exposed to high solar loads.

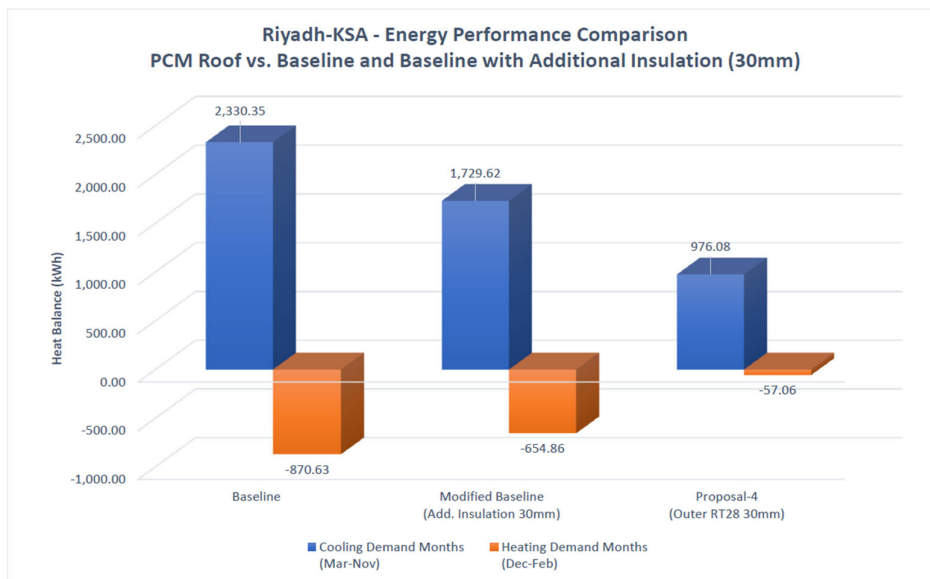


Figure 3-29: Energy Performance Comparison PCM Roof vs Baseline and Enhanced Baseline (30mm)

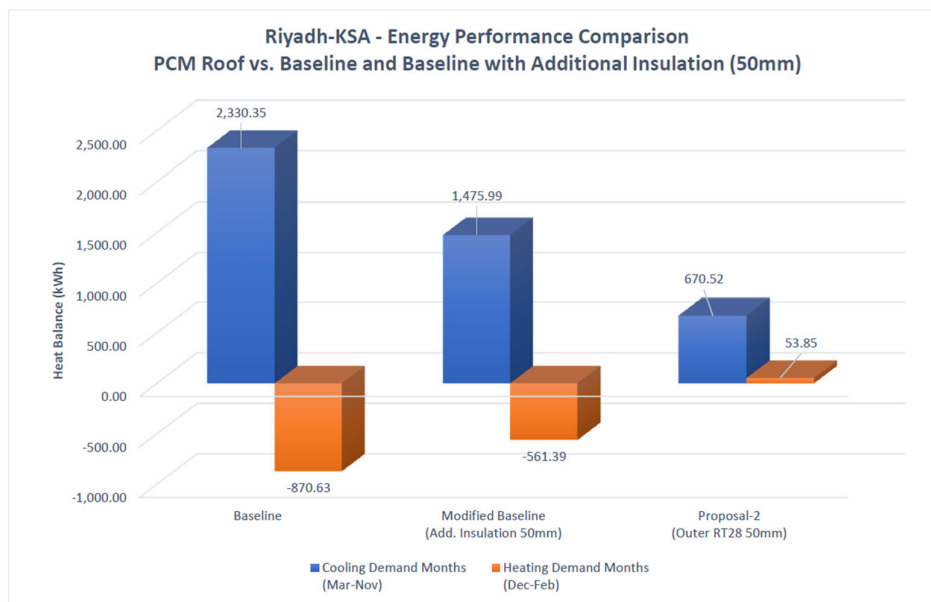


Figure 3-30: Energy Performance Comparison PCM Roof vs Baseline and Enhanced Baseline (50mm)

Table 3-2 summarizes the comparative performance of PCM-integrated, baseline, and enhanced baseline models in Riyadh, reflecting the impact of PCM configurations under hot-arid conditions with seasonal heating demand.

S.N.	Description	Envelope	Total Thickness (mm)	Insulation Thickness (mm)	PCM Layer				Net Heat Balance (kWh)		
					Thickness (mm)	Placement	Peak Melting Temp. (C)	Melting Temp. Range (C)	Annual (Jan-Dec)	Cooling Demand Months (Mar-Oct)	Heating Demand Months (Nov-Feb)
1	Baseline Model	Wall	300	250	-	-	-	-	5,440.91	7,599.84	-2,158.93
		Roof	370	70	-	-	-	-	1,459.72	2,330.35	-870.63
2	PCM-Integrated Model-1	Wall	350	250	50	Outer	31	29-34	3,394.21	4,538.74	-1,144.53
		Roof	420	70	50	Outer	31	29-34	1,186.26	1,388.56	-202.30
3	PCM-Integrated Model-2	Wall	350	250	50	Outer	31	29-34	3,371.92	4,538.20	-1,166.28
		Roof	420	70	50	Outer	28	27-29	724.37	670.52	53.85
4	PCM-Integrated Model-3	Wall	330	250	30	Outer	31	29-34	3,451.40	5,029.11	-1,577.71
		Roof	400	70	30	Outer	31	29-34	1,432.65	1,899.97	-467.32
5	PCM-Integrated Model-4	Wall	330	250	30	Outer	31	29-34	3,444.37	5,034.54	-1,590.17
		Roof	400	70	30	Outer	28	27-29	919.02	976.08	-57.06
6	Enhanced Baseline-1	Wall	350	300	-	-	-	-	4,673.32	6,559.07	-1,885.75
		Roof	420	120	-	-	-	-	914.60	1,475.99	-561.39
7	Enhanced Baseline-2	Wall	330	280	-	-	-	-	4,954.08	6,940.97	-1,986.89
		Roof	400	100	-	-	-	-	1,074.76	1,729.62	-654.86

Table 3-2: Energy Performance Comparison between PCM-Integrated and Baseline Models (Riyadh-KSA)

3.3 Amman-Jordan

Following detailed simulation analysis and comparative evaluation, the integration of Phase Change Materials (PCMs) within the building envelope for Amman's temperate climate characterized by hot summers and cold winters, demonstrated feasible and balanced performance improvements. Although the seasonal energy demand profile differs significantly from the other studied locations, the PCM-integrated models still delivered notable reductions in heat gain during the summer months, along with reasonable thermal benefits during the heating-dominated winter period. These results confirm the potential of PCM applications even in climates with mixed seasonal demands, provided that the placement and material properties are properly selected.

3.3.1 PCM Placement

The parametric analysis, conducted using the most suitable PCM melting point for each placement strategy, revealed that for wall applications, the outer placement configuration remained the optimal choice among the three options studied. Although all placement strategies demonstrated high overall annual performance, a closer look at the monthly distribution of thermal behaviour, in relation to the seasonal heating and cooling demand profile, indicated that the outer placement offers the best alignment with the building's energy requirements (see Figure 3-31 and Figure 3-32).

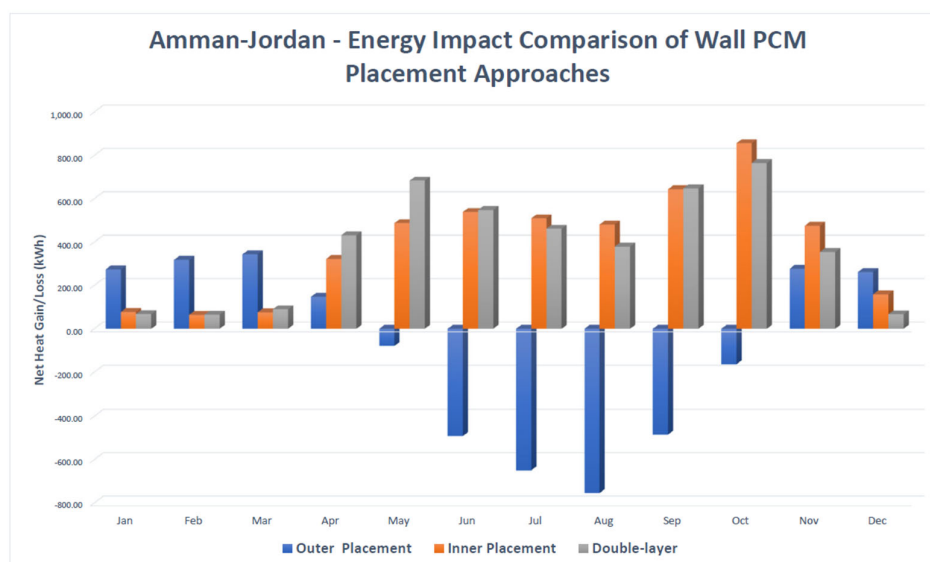


Figure 3-31: Energy Impact Comparison of Wall PCM Placement Approaches

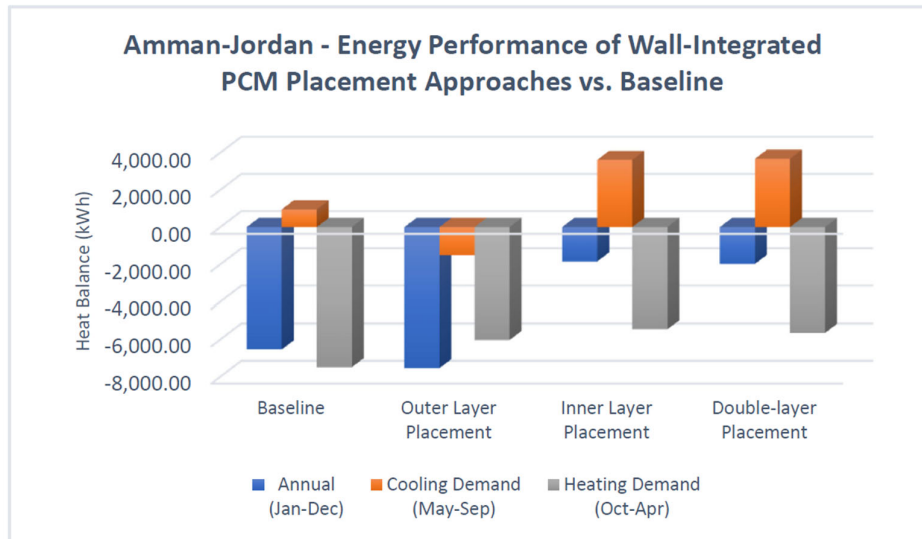


Figure 3-32: Energy Performance of Wall-Integrated PCM Placement Approach vs Baseline

The roof assembly showed closer competition between the different placement strategies, with all configurations delivering strong performance during the colder months when heating demand is dominant. However, the outer placement strategy outperformed the others during the summer cooling period, making it the most suitable overall. Its ability to effectively respond to both seasonal extremes confirm it as the most efficient configuration for Amman mixed climate conditions (see Figure 3-33 and Figure 3-34).

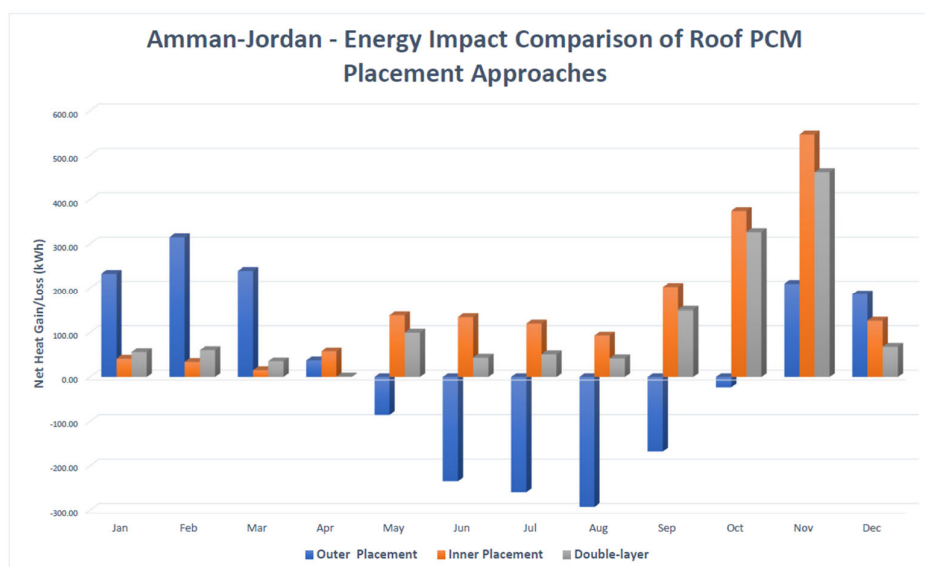


Figure 3-33: Energy Impact Comparison of Roof PCM Placement Approaches

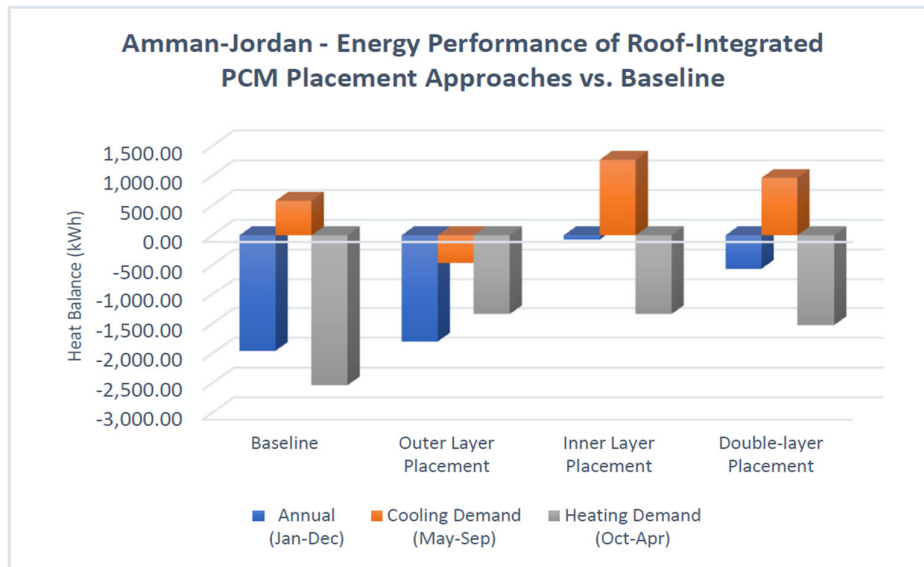


Figure 3-34: Energy Performance of Roof-Integrated PCM Placement Approach vs Baseline

3.3.2 PCM Melting Point

Using the outer placement configuration, the parametric analysis evaluated several melting point options to determine the most effective PCM for Amman’s climate. The results revealed that the best performance for both wall and roof integrations was achieved using RT25, with a melting range between 22°C and 26°C, and RT28, with a melting range between 27°C and 29°C (see Figure 3-35 and Figure 3-36).

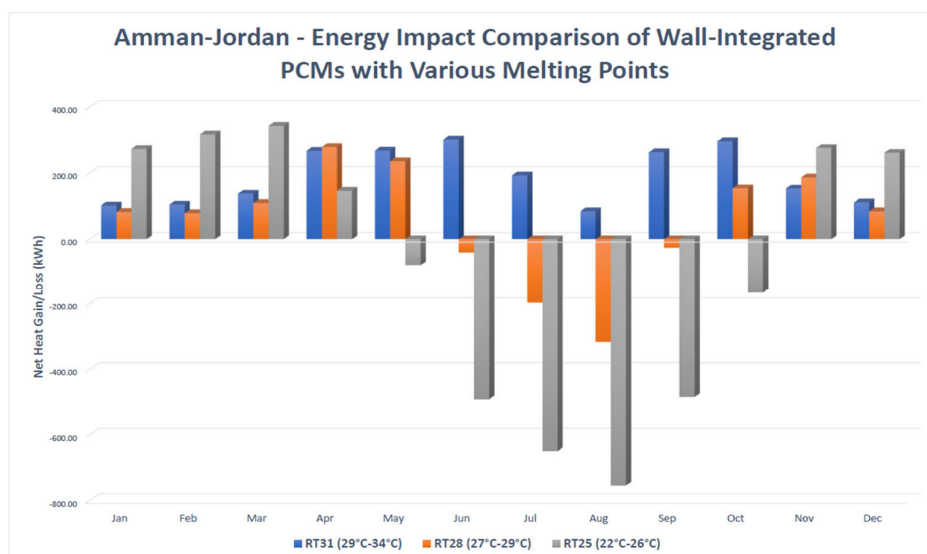


Figure 3-35: Energy Impact Comparison of Wall-Integrated PCMs with Various Melting Points

These melting points aligned well with Amman’s moderate temperature profile, particularly during transitional seasons, allowing the PCM to be effectively activated under both cooling and heating demand conditions.

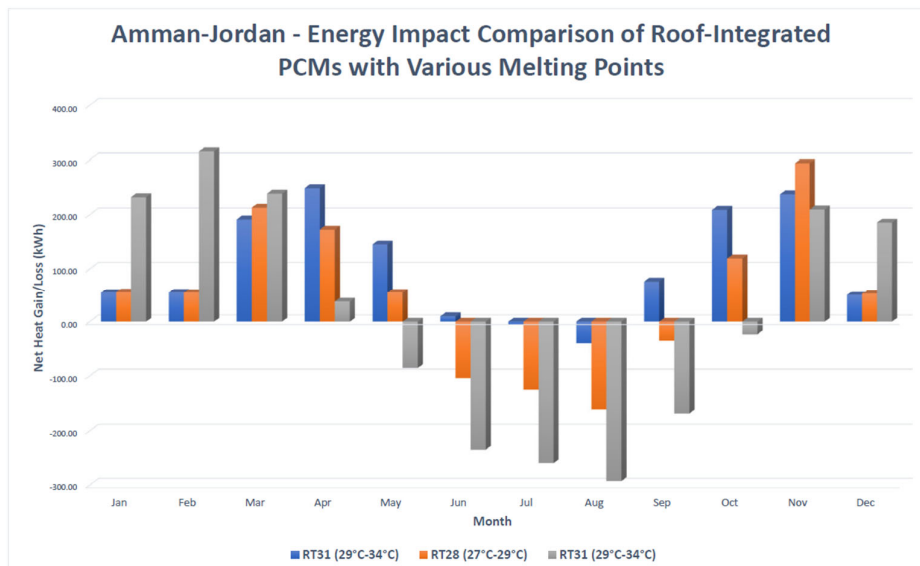


Figure 3-36: Energy Impact Comparison of Roof-Integrated PCMs with Various Melting Points

3.3.3 Wall Orientation

The results from the outer PCM placement configuration revealed clear performance variations across different wall orientations. Among the orientations analyzed, the south-facing façade consistently delivered the highest thermal improvement, proving to be superior over the other orientations, particularly during the heating-dominated months. This makes it the most effective façade for PCM application under Amman’s seasonal energy demand profile (see Figure 3-37).

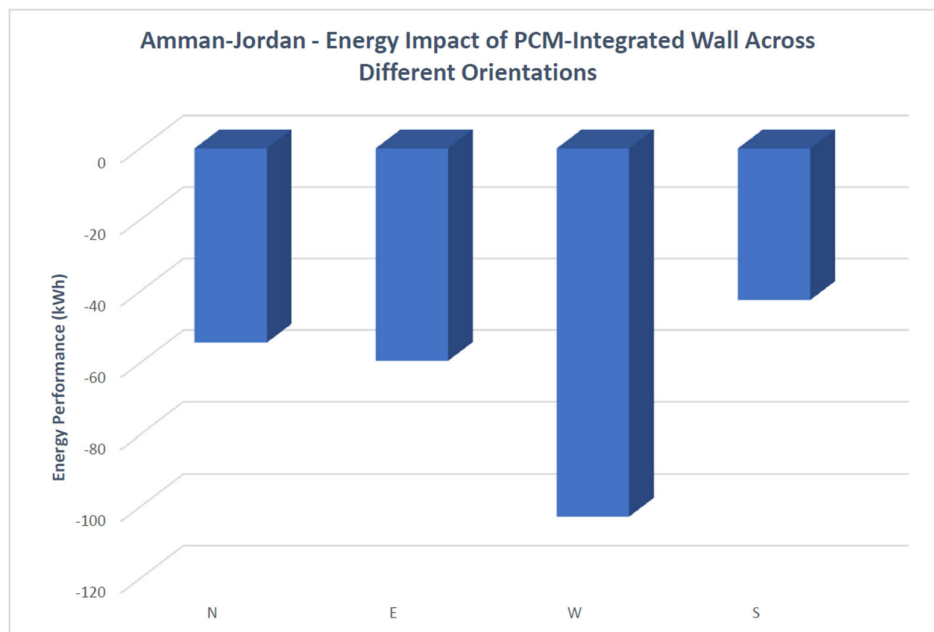


Figure 3-37: Energy Impact of PCM-Integrated Wall Across Different Orientations

3.3.4 Energy Performance of PCM-Integrated Models

The parametric analysis led to the development of four proposed PCM-integrated models, combining the two previously identified optimal melting points with two thickness options (30 mm and 50 mm).

In wall applications, performance was observed to increase with greater PCM thickness, particularly during the cold season with high heating demand. However, during the summer months, the performance difference between thicknesses was not feasible, indicating that beyond a certain point, increasing thickness yields limited additional benefit under Amman's moderate summer conditions.

Nevertheless, the overall results demonstrate promising performance across both seasonal extremes. During the cold months, the configurations achieved improved performance of 19% and 29% in the walls for the 30 mm and 50 mm thicknesses respectively (Figure 3-38). In the roof assembly, even greater improvements were recorded, with corresponding to 34% and 45% (Figure 3-39).

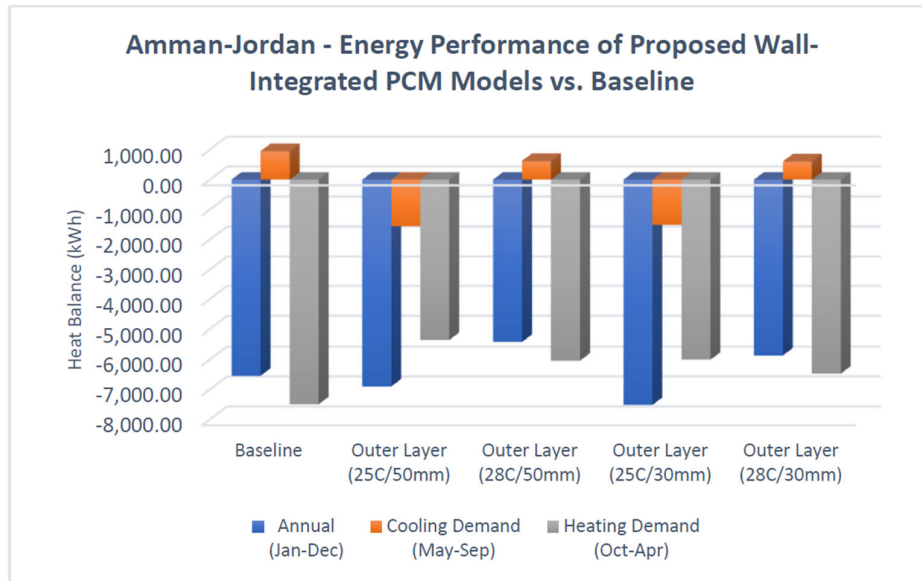


Figure 3-38: Energy Performance of Proposed Wall-Integrated PCM Models vs Baseline

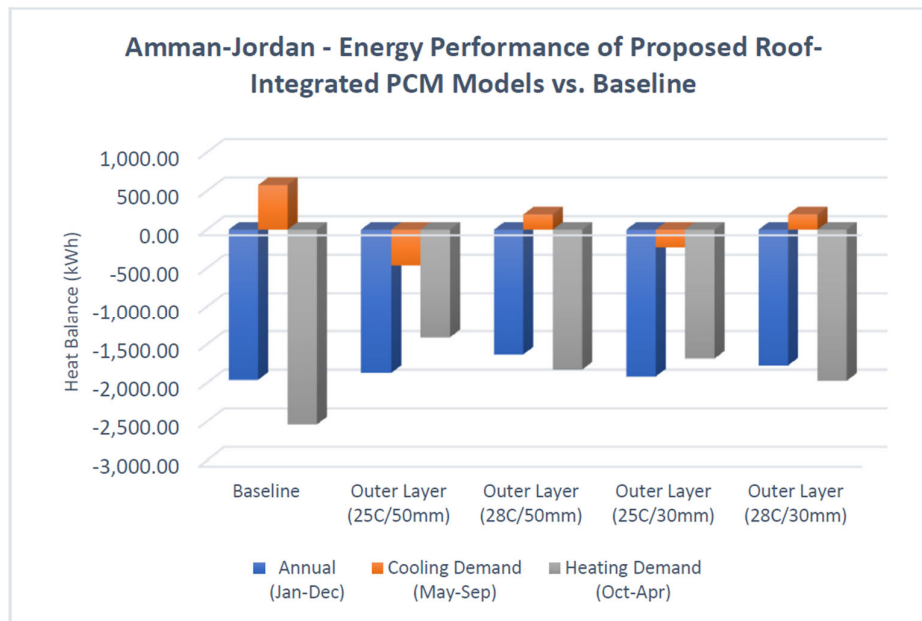


Figure 3-39: Energy Performance of Proposed Roof-Integrated PCM Models vs Baseline

Further analysis of the results highlighted a strong temporal correlation between the PCM-integrated models' performance and the building's monthly cooling and heating demand profiles. The monthly distribution of thermal performance closely mirrored the energy demand

patterns, confirming the effectiveness of PCM integration in adapting to seasonal variations and outperforming the baseline model (see Figure 3-40 and Figure 3-41).

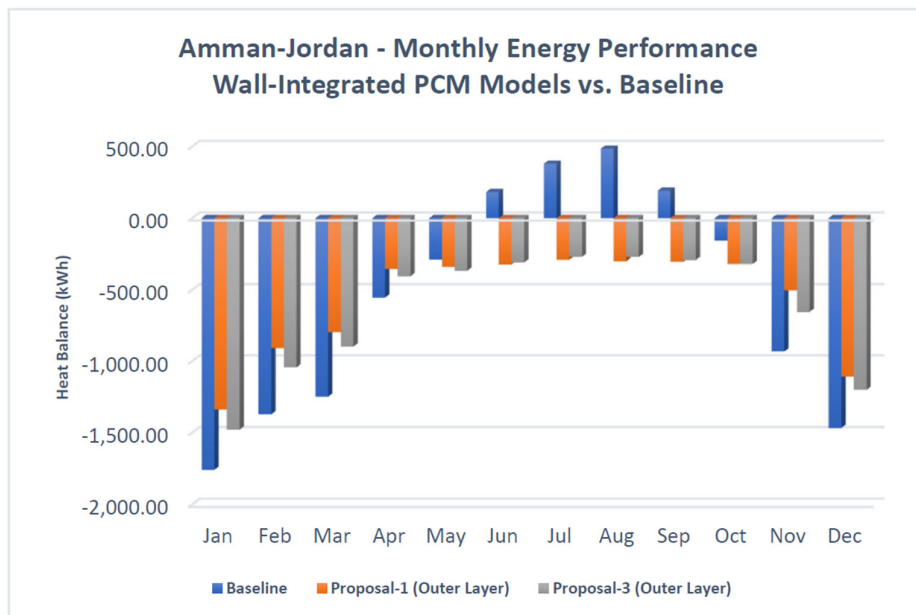


Figure 3-40: Monthly Energy Performance Wall-Integrated PCM Models vs Baseline

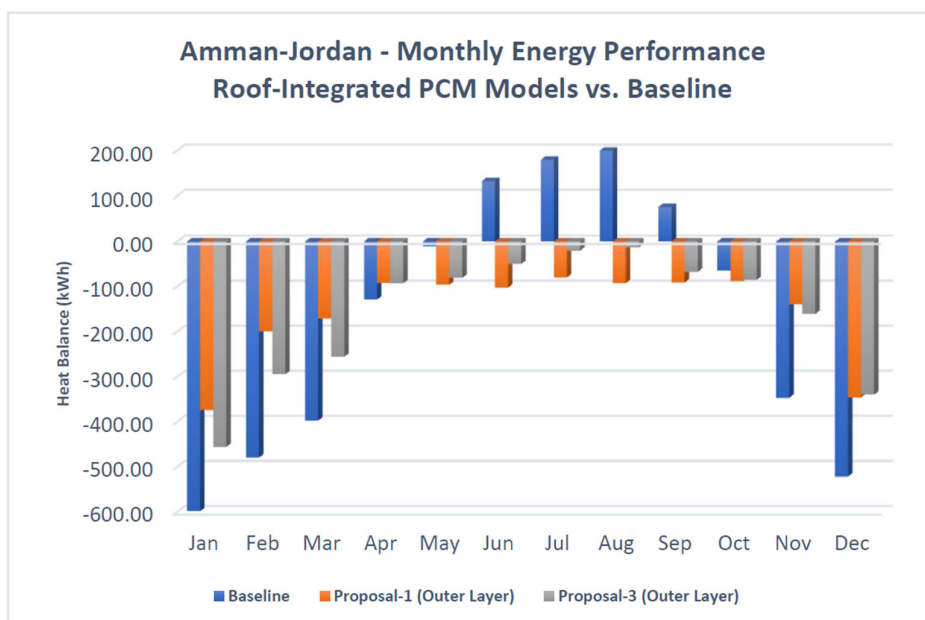


Figure 3-41: Monthly Energy Performance Roof-Integrated PCM Models vs Baseline

3.3.5 Enhanced Baseline

To maintain consistency in the evaluation approach, the PCM-integrated models were also compared against enhanced baseline models incorporating additional thermal insulation of equivalent thickness. While the enhanced models demonstrated improved performance over the original baseline, the PCM-integrated configurations consistently delivered superior thermal and energy performance across both wall and roof assemblies.

In wall assemblies, the PCM-integrated models exhibited significant advantages, achieving 15% to 21% greater performance compared to their enhanced insulation counterparts, depending on the applied thickness. These performance differences are illustrated in Figure 3-42 and Figure 3-43, corresponding to the 30 mm and 50 mm configurations, respectively.

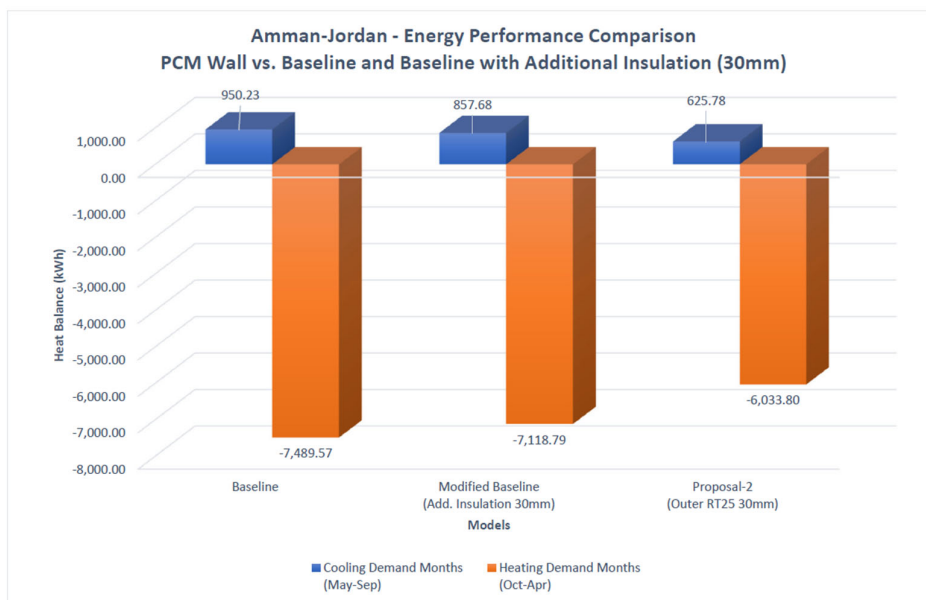


Figure 3-42: Energy Performance Comparison PCM Wall vs Baseline and Enhanced Baseline (30mm)

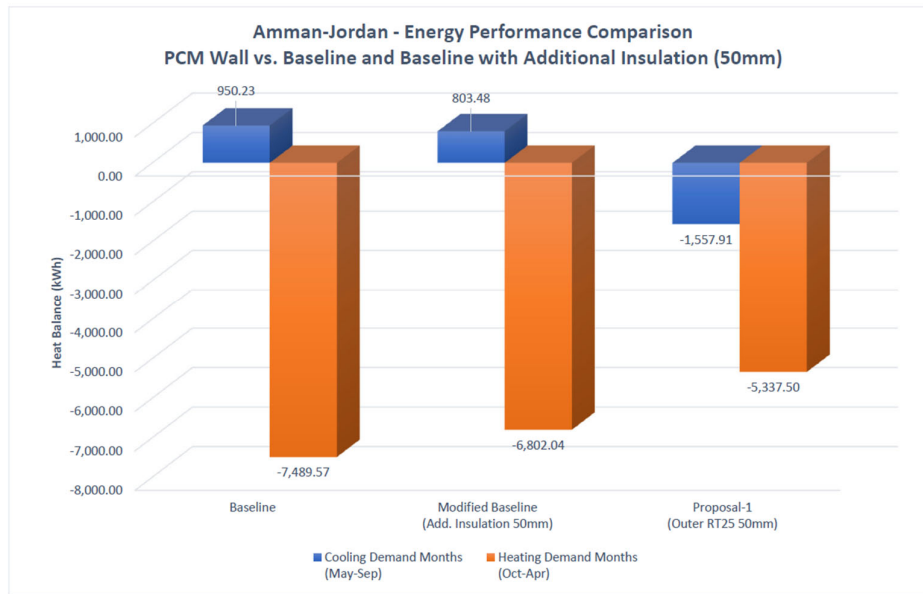


Figure 3-43: Energy Performance Comparison PCM Wall vs Baseline and Enhanced Baseline (50mm)

Similarly, in roof assemblies, the PCM-integrated designs achieved a 16% to 19% reduction in heat gain relative to the enhanced insulation models, as shown in Figure 3-44 and Figure 3-45.

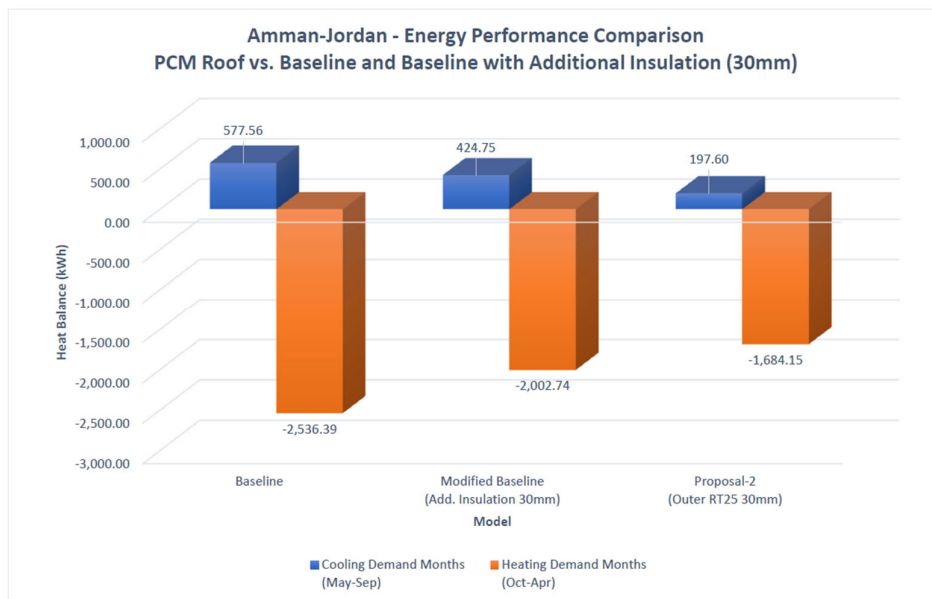


Figure 3-44: Energy Performance Comparison PCM Roof vs Baseline and Enhanced Baseline (30mm)

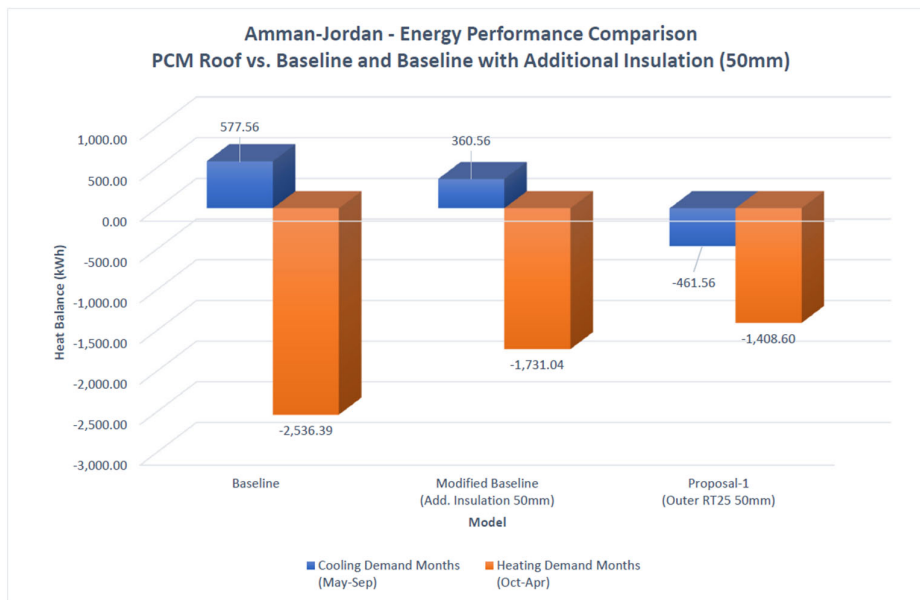


Figure 3-45: Energy Performance Comparison PCM Roof vs Baseline and Enhanced Baseline (50mm)

Table 3-3 presents the performance comparison of PCM-integrated, baseline, and enhanced baseline models in Amman, highlighting PCM behaviour under semi-arid conditions with both cooling and heating demands.

S.N.	Description	Envelope	Total Thickness (mm)	Insulation Thickness (mm)	PCM Layer				Net Heat Balance (kWh)		
					Thickness (mm)	Placement	Peak Melting Temp. (C)	Melting Temp. Range (C)	Annual (Jan-Dec)	Heating Demand Months (Oct-Apr)	Cooling Demand Months (May-Sep)
1	Baseline Model	Wall	300	250	-	-	-	-	-6,539.34	-7,489.57	950.23
		Roof	370	70	-	-	-	-	-1,958.83	-2,536.39	577.56
2	PCM-Integrated Model-1	Wall	350	250	50	Outer	25	22-26	-6,895.41	-5,337.50	-1,557.91
		Roof	420	70	50	Outer	25	22-26	-1,870.16	-1,408.60	-461.56
3	PCM-Integrated Model-2	Wall	330	250	30	Outer	25	22-26	-7,510.57	-6,002.38	-1,508.19
		Roof	400	70	30	Outer	25	22-26	-1,915.91	-1,684.15	-231.76
4	PCM-Integrated Model-3	Wall	350	250	50	Outer	28	27-29	-5,408.02	-6,033.80	625.78
		Roof	420	70	50	Outer	28	27-29	-1,629.20	-1,826.80	197.60
5	PCM-Integrated Model-4	Wall	330	250	30	Outer	28	27-29	-5,858.25	-6,466.73	608.48
		Roof	400	70	30	Outer	28	27-29	-1,772.38	-1,970.21	197.83
6	Enhanced Baseline-1	Wall	350	300	-	-	-	-	-5,998.56	-6,802.04	803.48
		Roof	420	120	-	-	-	-	-1,370.48	-1,731.04	360.56
7	Enhanced Baseline-2	Wall	330	280	-	-	-	-	-6,261.11	-7,118.79	857.68
		Roof	400	100	-	-	-	-	-1,577.99	-2,002.74	424.75

Table 3-3: Energy Performance Comparison between PCM-Integrated and Baseline Models (Amman–Jordan)

3.4 Discussions

The results and the parametric study across the three selected climate zones confirmed that integrating PCM into the building envelope can significantly enhance building energy performance and thermal comfort, provided that the configuration is optimized. The effectiveness of PCM integration strongly depends on several interrelated factors, including the local weather profile, envelope construction, PCM material properties, and indoor thermal requirements. Overall, the findings support the feasibility and scalability of PCM technology as a passive energy strategy for buildings, contributing to decarbonization targets, peak load reduction, and improved occupant well-being across different climatic conditions.

3.4.1 Climatic Data

Climate conditions play a critical role in guiding PCM selection and integration within the building envelope. Daily and seasonal temperature profiles inform the choice of appropriate melting points especially for outer-layer applications, ensuring frequent phase transitions for effective latent heat storage and release. Solar radiation also significantly affects PCM performance, particularly on sun-exposed surfaces, by increasing heat gains that can be moderated by PCM buffering. Additionally, wind conditions influence surface heat transfer through convection, indirectly impacting the rate at which PCMs absorb or release heat.

Simulation results highlighted the impact of local climate by comparing the same PCM configuration applied to two hot-climate cities (see Table 3-4). Despite similar regional locations and average temperatures, performance varied between cities throughout the year, underscoring the importance of climate-specific PCM design.

City	June, July and August		April, May, September and October	
	Wall	Roof	Wall	Roof
Dubai-UAE	22%	62%	35%	51%
Riyadh-KSA	43%	62%	30%	40%

Table 3-4: Percentage of Heat Reduction using RT31 Outer Layer Model

3.4.2 Building Envelope

The construction of the baseline envelope significantly affects PCM performance, particularly the type, thickness, and position of insulation relative to the PCM layer. These factors influence the selection of melting point, placement and how effectively the PCM can absorb and release heat. In the developed models, the PCM was positioned as the second layer from either the exterior or interior side to preserve the baseline finishing layers. Consequently, its performance became highly dependent on the thermal properties especially conductivity of the adjacent layer, which regulates the rate and amount of heat reaching the PCM. For external placement, PCM activation is indirectly influenced by outdoor conditions but primarily governed by heat transfer through the outer layer. Similarly, for internal placement, performance depends on interaction with interior layers rather than direct exposure to indoor air.

3.4.3 Cooling and Heating Profiles

Understanding the building's annual cooling and heating demand is key to determining the desired PCM behaviour. This requires analysing not just the envelope's heat balance, but also internal gains from solar radiation, occupants, lighting, and equipment. Monthly cooling and heating profiles help identify when heat should be rejected or retained, guiding the selection of PCM placement and melting point to align with seasonal thermal needs.

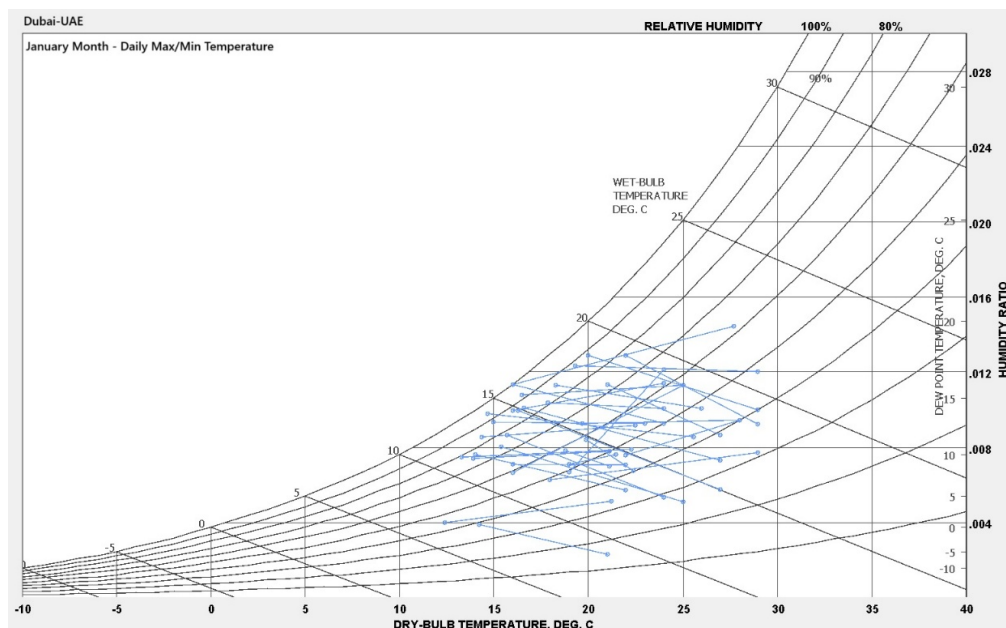


Figure 3-46(a): January Daily Max/Min Temperature Range - Dubai

Figure 3-46(a) and Figure 3-46(b) show the January daily temperature ranges for the two hot-climate cities. Although both experience similar annual heat profiles, differences in winter conditions shape distinct seasonal heating demands.

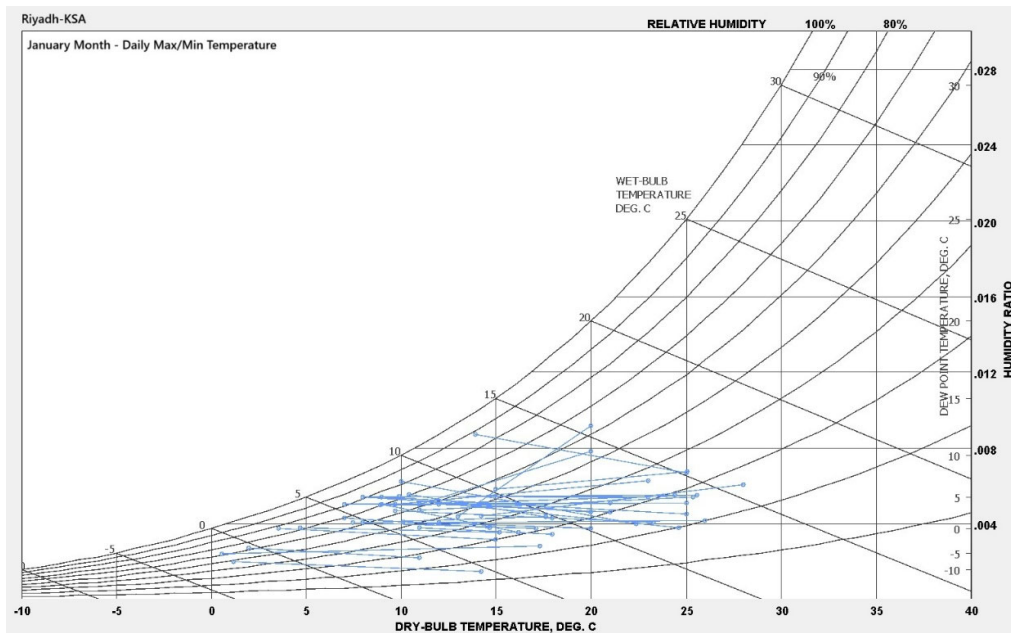


Figure 3-46(b): January Daily Max/Min Temperature Range – Riyadh

3.4.4 Indoor Environment Conditions

Indoor environmental parameters such as setpoint temperatures, setback strategies, and occupancy schedules, play a critical role in influencing the performance of Phase Change Materials (PCMs) integrated into building envelopes. These parameters directly affect the temperature differential between indoor and outdoor environments, which is one of the primary drivers of heat transfer. Consequently, any adjustment to indoor temperature conditions can significantly impact the thermal and energy performance of PCM-enhanced models.

Moreover, the scheduling of HVAC operation introduces dynamic temperature variations throughout the day, which can influence the effectiveness of PCM particularly for inner-layer placements. In scenarios where large fluctuations in indoor temperature occur, or during off-hours when HVAC systems are partially deactivated or scheduled to run at reduced capacity,

temperature differentials may become significant enough to trigger PCM phase transitions and the PCM's ability to undergo phase transitions and store or release latent heat becomes more pronounced. These conditions may influence the energy-saving potential, depending on how well they align with the thermal activation window of the selected PCM.

Overall, careful consideration of indoor environmental conditions is essential when evaluating PCM performance. These factors must be included in both simulation inputs and real-world application strategies to ensure accurate assessment and practical effectiveness of PCM integration.

3.4.5 Exposure Wall Orientations

The parametric analysis of various wall orientations revealed that PCM performance is influenced by both placement configuration and climatic conditions particularly the intensity and angle of solar radiation. Among the orientations studied, west-facing and south-facing walls alternated in delivering the highest thermal performance across the different climate zones.

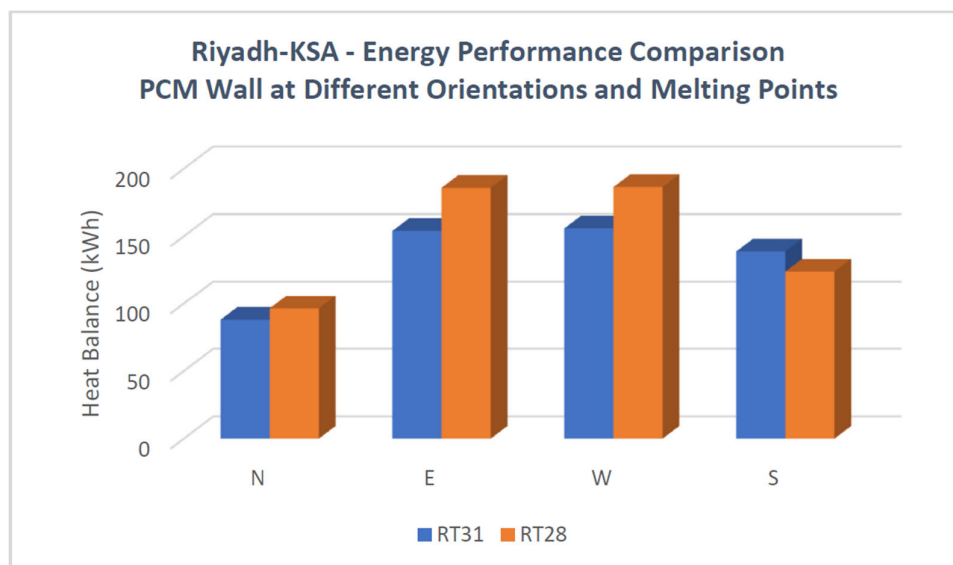


Figure 3-47(a): Comparison of PCM Performance Across Wall Orientations in Riyadh Using RT31 and RT28

These findings emphasize that the effectiveness of PCM integration is highly orientation-dependent, underscoring the need for case-specific evaluations to optimize performance. Such evaluations may lead to different choices of PCM melting point, thickness and possibly placement, based on the orientation of each façade. Moreover, shading from adjacent or nearby buildings can significantly influence PCM effectiveness by reducing solar exposure, particularly on shaded walls. In cases where a specific façade receives minimal solar gain and none of the tested PCM configurations provide substantial thermal benefit, increasing the insulation level may be a more appropriate strategy than integrating PCM.

Figure 3-47(a) illustrates this point through an orientation-specific analysis conducted for Riyadh city. When comparing the thermal performance of RT31 and RT28 across different wall orientations, three façades showed superior performance with RT31, while the south-facing wall demonstrated better results with RT28. This variation supports the conclusion that PCM configuration should be tailored to each orientation to achieve optimal thermal performance. Figure 3-47(b) further demonstrates the monthly performance of the south-facing wall, showing that RT31 performs better during the peak summer months, whereas RT28 delivers superior performance throughout the rest of the year and achieves higher overall performance.

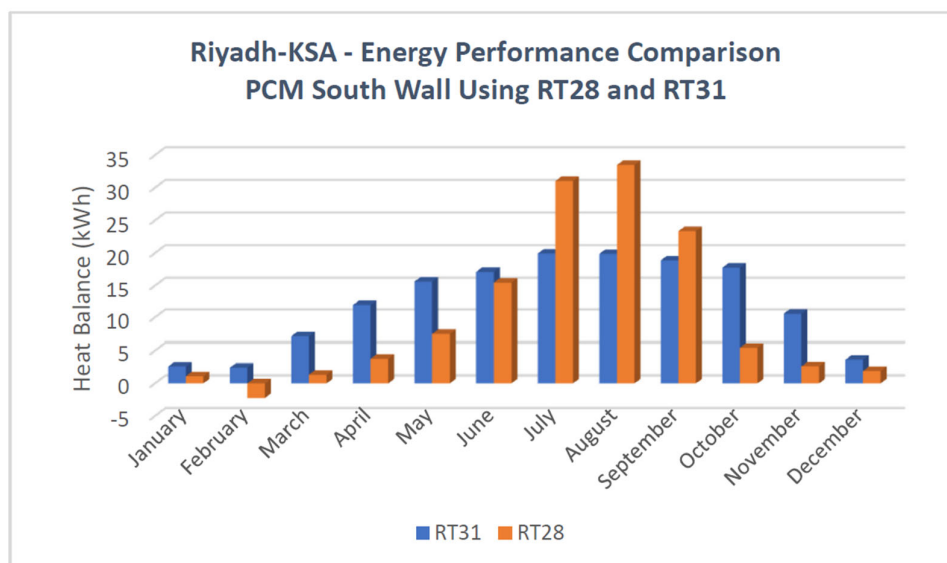


Figure 3-47(b): Monthly Heat Flux Performance of RT28 and RT31 on South-Facing Wall

3.4.6 PCM Location and Placement

Simulation results revealed that PCM performance varies notably with placement strategy and climate. Outer-layer placement, being exposed to outdoor conditions, showed the highest heat reduction during peak summer but performed poorly in colder months when temperatures fall below the PCM's melting range, limiting phase change activation.

In climates with alternating cooling and heating demands, outer placement can respond effectively to seasonal shifts. However, in cooling-dominated regions like Dubai, placement strategy depends on the objective: outer placement is ideal for peak load reduction, while double-layer placement offers more stable, year-round performance.

Placement Strategy	June, July and August		March to December	
	Wall	Roof	Wall	Roof
Outer Layer RT31	22%	62%	22%	44%
Double-layer RT31/RT25	15%	31%	27%	31%

Table 3-5: Percentage of Heat Reduction using Different Placement Strategies – Dubai

The double-layer configuration combines the benefits of outer and inner placements, offering flexibility to fine-tune performance using different melting points and thicknesses. This makes it particularly suitable where a single placement strategy cannot fully meet the building's seasonal thermal demands. Table 3-5 compares both strategies for Dubai, showing higher summer savings with outer placement and overall better performance with double-layer for wall exposures.

3.4.7 PCM Melting Point, Curve and Latent Heat Capacity

The performance of PCM integration is highly dependent on the selection of melting point, melting curve, and latent heat capacity. Simulations showed that optimizing these parameters rather than selecting based on peak conditions alone, can improve both seasonal consistency and overall energy savings.

While high summer temperatures may briefly exceed a PCM's melting point, much of the cooling season may fall below that range, limiting phase change activation. Therefore, selecting a PCM whose melting–solidification range intersects daily temperature fluctuations over extended periods is crucial for maximizing latent heat utilization.

The latent heat of fusion determines the PCM's thermal storage capacity. A higher value generally means greater buffering and improved temperature regulation. However, this capacity varies by PCM type, chemical formulation, and even across variants of the same product line.

Another key consideration is the shape of the melting curve, which affects how heat is absorbed and released:

- A narrow melting range (such as in the case of RT28 used in Riyadh's roof PCM layer) offers high latent heat capacity and can align well with frequent daily temperature ranges, maximizing energy performance in climates with predictable thermal patterns.
- A broader melting curve, while slightly less efficient in latent heat per unit temperature, offers greater operational flexibility and adaptability to varying or uncertain climate conditions. This makes it a suitable choice for mitigating risks associated with future climate change, where temperature patterns may shift beyond current expectations.

Figures 3-48(a) and 3-48(b) illustrate the melting behaviour of RT35 and RT38, showing differences in melting range width and total latent heat capacity despite overlapping temperature zones.

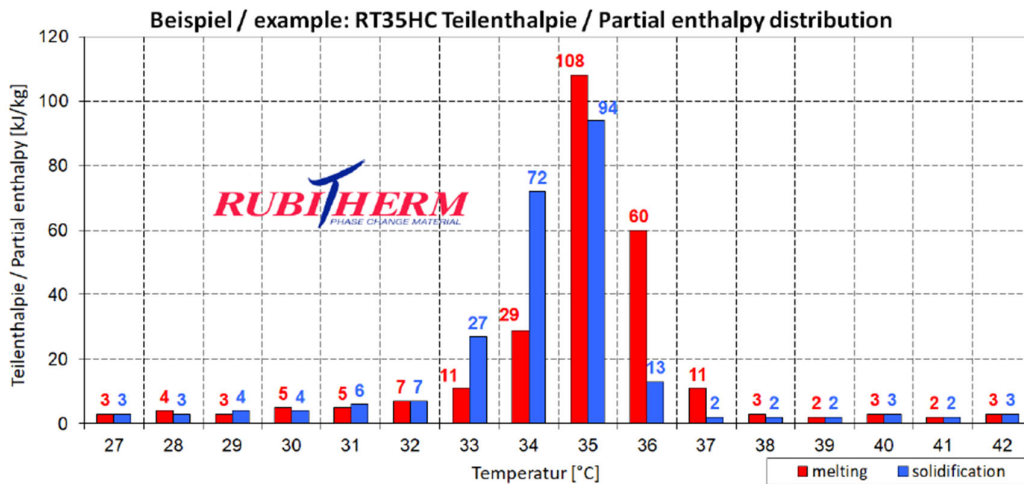


Figure 3-48(a): PCM RT35 Melting/Solidification Curve

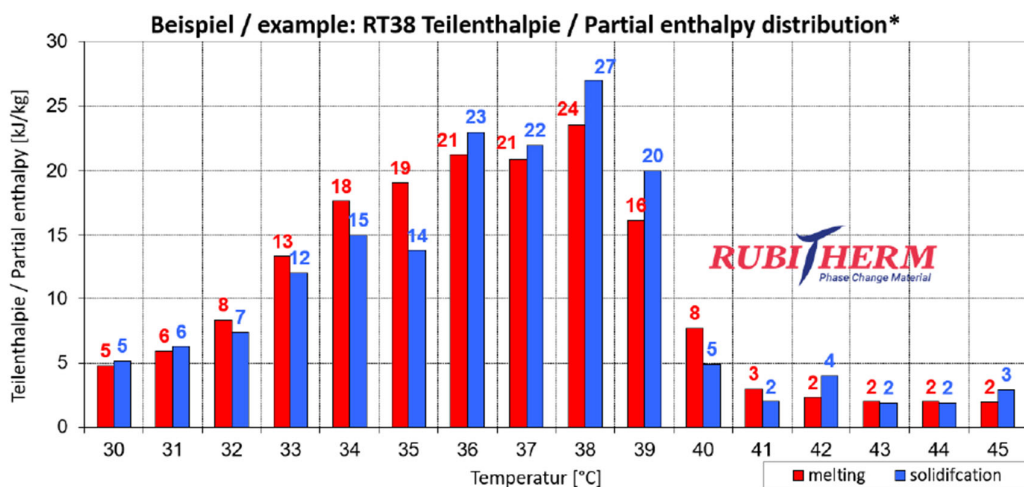


Figure 3-48(b): PCM RT38 Melting/Solidification Curve

3.4.8 PCM Specific Heat and Thermal Conductivity

Beyond melting curve and latent heat capacity, the thermal conductivity and specific heat capacity of PCMs significantly affect their performance. Thermal conductivity determines how efficiently heat is transferred to and from the PCM, influencing how well it completes daily charge–discharge cycles. Since most PCMs have inherently low conductivity, performance can be improved using additives, composites, or encapsulation techniques.

Specific heat capacity becomes especially relevant when ambient temperatures fall outside the phase change range. While latent heat dominates during transitions, the sensible heat governed by specific heat capacity ensures stable thermal behaviour in fully solid or liquid states, broadening the PCM's functional temperature range.

Equally important is the chemical and thermal stability of the PCM, particularly when it remains in the liquid phase for extended periods, common during peak summer. Without sufficient stability, the material risks degradation, phase separation, or loss of latent heat capacity over time.

Therefore, selecting a PCM requires careful evaluation of its thermal conductivity, specific heat, and long-term stability. These factors vary between organic, inorganic, and hybrid PCMs, as well as across manufacturers, and are critical for ensuring consistent performance and durability in real-world building applications.

3.4.9 PCM Thickness, Encapsulation and Structural Considerations

The results demonstrated that increasing PCM thickness (up to the maximum studied value of 50 mm) led to greater heat reduction and energy performance improvements when compared to both the baseline and enhanced baseline models. However, in all cases integrating PCM into the wall or roof assembly inherently results in an increase in total wall or roof thickness equal to the PCM layer thickness. To preserve the original net indoor area and volume, this increase must be offset by extending the building's footprint or adjusting structural dimensions (floor area and wall height). These modifications introduce significant architectural and structural implications, including the need to accommodate additional load from the enlarged structure, PCM material and its encapsulation. Such constraints may limit the acceptable thickness range of PCM and become a major factor in evaluating the economic feasibility of its integration especially when structural alterations are required.

In addition, PCM materials typically undergo volumetric expansion during melting and contraction during solidification, with a tolerance of up to 15%. This presents further

challenges for integration, particularly when PCMs are used in unencapsulated or directly embedded forms, where volume changes can lead to leakage, material fatigue, or structural instability. Encapsulation offers an effective solution, as it can be designed to tolerate volume changes while preserving structural rigidity. Moreover, customized encapsulation materials can be selected to enhance thermal conductivity selectively. For example, and especially beneficial in cooling-dominated climates with PCM placed on the outer wall, the external-facing side of the PCM can be customized to use a high-conductivity material to optimize heat exchange, while the interior-facing side uses a low-conductivity material to minimize unwanted inward heat flow.

CONCLUSIONS

This study investigated the integration of Phase Change Materials (PCMs) into building envelopes as a passive thermal energy strategy to enhance energy efficiency and thermal comfort across three distinct climate zones: Dubai (hot and humid), Riyadh (hot and arid), and Amman (temperate or semi-arid with cold winters). The simulation-based methodology involved climate analysis, baseline model development using real construction data, PCM material selection, and parametric simulations conducted in DesignBuilder, powered by the EnergyPlus engine.

Key performance indicators included envelope heat transfer, seasonal loads, energy demand, and operative temperature. PCM integration led to notable reductions in heat flux through building envelopes across all climates, with roof assemblies achieving up to 72% reduction in Riyadh and up to 40% in wall systems in both Riyadh and Dubai. These results underscore the value of climate-responsive PCM optimization and its potential to enhance energy-efficient building design.

Melting point and melting curve characteristics varied in effectiveness depending on the climate and the specific building element. RT31 (29–34°C) and RT28 (27–29°C) proved most suitable for hot climates, while RT25 (22–26°C) was more effective in Amman's cooler seasons. PCM performance depended heavily on how well ambient temperatures aligned with the PCM's melting range. When outside this range, PCMs relied on their sensible heat capacity, which offered less thermal buffering and reduced their ability to limit heat transfer.

Temperature patterns and seasonal energy demand profiles guided both PCM placement and melting point selection. Outer placement performed best in climates with distinct heating and cooling seasons, particularly for roof applications exposed to high solar radiation. Double-layer configurations, combining inner and outer layers, offered more stable and adaptable performance throughout the year, especially in climates with dominant cooling loads or

fluctuating thermal conditions. These setups allowed tuning of performance by adjusting melting points and layer thicknesses.

PCM configuration including melting point and placement strategy, showed strong dependency on the characteristics of the building envelope components and their construction. Wall orientation also significantly influenced PCM effectiveness, with south- and west-facing façades achieving the highest reductions in heat flux. These findings highlight the benefit of adopting façade-specific design strategies, where both the melting point, thickness and placement of PCM may need to be adjusted based on the orientation to maximize thermal performance.

Overall, the study confirms that PCM integration, when tailored to local climate and building characteristics, can significantly improve envelope performance, reduce energy demand, and contribute toward decarbonization. PCM-enhanced models consistently outperformed both baseline and insulation-enhanced models, validating the superior potential of latent heat storage compared to traditional thermal resistance solutions.

While PCM systems show strong potential, their practical deployment needs to address reliable encapsulation to avoid leakage or degradation over time, allow for volumetric expansion during phase change to prevent mechanical stress on surrounding materials, and ensure long-term thermal and chemical stability under fluctuating environmental conditions. Structural compatibility with conventional building materials must also be considered to enable safe integration and effective performance in real-world applications.

Further research is encouraged to build on these outcomes. This includes experimental testing under real-world conditions to validate simulation results, integrating PCM within the envelope thickness through adjustments to construction layers, and detailed thermal analysis using finite element and CFD tools to evaluate PCM performance during latent heat activation within the melting range and sensible heat behaviour outside it when temperature deviations beyond the melting curve. Broader investigations into façade-specific optimization, urban shading impacts, and the integration of PCMs into HVAC systems and glazing components will further expand their potential for energy-efficient building design.

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