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Innovative Facade Strategies for Energy Efficiency in Educational Buildings: A Case Study of Hassan Najjar School, Iraq

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Abstract

Educational buildings in hot-arid climates endure severe thermal stress that compromises both energy performance and occupant wellbeing. This study presents a simulation-based assessment of innovative facade retrofit strategies for Hassan Najjar School in Erbil, Kurdistan Region, Iraq. Four scenarios were modelled with DesignBuilder v7.3 / EnergyPlus: (a) the uninsulated baseline, (b) Phase Change Material (PCM) only, (c) high-performance phenolic foam insulation only, and (d) a combined PCM-insulation assembly. The combined strategy reduced the whole-wall U-value from 1.529 W/m²·K to 0.186 W/m²·K (an 87.8 % decrease) and lowered annual energy consumption by 28 % (11 900 kWh/year). Importantly, the energy saving surpassed the arithmetic sum of the individual PCM and insulation savings, demonstrating a synergistic effect. Thermal comfort improved substantially, with the Predicted Percentage Dissatisfied (PPD) falling from 73 % to 18 %. Model validation against 2023-2024 utility records yielded a CV(RMSE) of 7.8 % and an NMBE of 2.1 %, within ASHRAE Guideline 14 limits. Sensitivity analysis identified PCM melting point as the most influential parameter. Economic life-cycle analysis shows a payback of 8.8 years and a 50-year net present value of approximately $85 000. The findings establish a replicable, evidence-based framework that connects building performance simulation to actual funding acquisition, demonstrating how salutogenic-driven facade retrofits can transform educational environments in harsh climates.

Keywords: Phase Change Materials, Thermal Insulation, Building Energy Simulation, Educational Buildings, Hot-Arid Climate, Thermal Comfort, Synergy, Retrofit.

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1. Introduction

1.1 Background and Context

The building sector is responsible for about 30-40 % of global final energy use and an equivalent share of energy-related CO_2 emissions (IEA, 2021). Educational facilities form a considerable segment of the non-residential stock, characterized by high internal gains, fixed occupancy schedules, and stringent indoor environmental quality requirements (Grigorovitch et al., 2025). In hot-arid regions, cooling loads alone often exceed 60 % of total building electricity demand (Krarti, 2023; El-Darwish & Gomaa, 2024). The Kurdistan Region of Iraq, with summer temperatures regularly above 45 °C, exemplifies such extremes. Many schools were constructed in the 1990s with unreinforced concrete-block envelopes that lack thermal insulation, resulting in excessive energy consumption and thermally uncomfortable classrooms.

1.2 Problem Statement and Research Gap

A vast literature treats Phase Change Materials (PCMs) and high-performance thermal insulation as separate retrofit measures (Cabeza et al., 2011; Al-Yasiri & Szabo, 2023). PCMs stabilise indoor temperatures by storing latent heat during phase transition, while insulation reduces conductive heat transfer (Jelle, 2011; Miracco et al., 2025). However, only a handful of studies have investigated their combined application in educational buildings under extreme climates, and none has quantified whether the joint effect is synergistic—i.e., whether the performance gain exceeds the sum of the individual contributions (Farid et al., 2004; Zalba et al., 2003; Cabeza et al., 2011; Zhou et al., 2021) . Recent studies have examined PCM-integrated building envelopes, material selection, thermal regulation, and performance in hot climates (Gholamibozanjani & Farid, 2021; Cuce & Riffat, 2022; Zhang et al., 2022; Senobar et al., 2026). Furthermore, existing research rarely links simulation outcomes to tangible funding decisions, leaving a gap between academic investigation and real-world implementation. This study therefore addresses the question:

How does a combined PCM-insulation strategy perform in a hot-arid educational setting, and does it produce a synergistic improvement in energy efficiency and thermal comfort relative to single measures?

1.3 Objectives and Hypotheses

The study pursues four explicit objectives:

(1) To quantify the reduction in thermal transmittance (U-value) for PCM-only, insulation-only, and combined scenarios compared with the baseline. (2) To simulate annual energy consumption and peak loads across all scenarios using a validated building energy model. (3) To assess thermal comfort improvements using the Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) indices. (4) To perform a life-cycle cost analysis (LCCA) that determines payback period, net present value, and long-term economic viability.

Two hypotheses are tested:

H_1: The combined PCM-insulation strategy will yield a greater reduction in annual energy consumption than the sum of the reductions achieved by PCM alone and insulation alone (synergy).

H_2: The combined strategy will bring the PPD index below 20 %, significantly improving thermal comfort and supporting salutogenic design principles.

1.4 Significance and Structure of the Paper

This work makes three original contributions. First, it provides the first quantitative evidence of a symbiotic interaction between PCM and insulation in a hot-arid educational building, moving beyond single-technology studies. Second, it demonstrates a rigorous simulation methodology that includes ASHRAE-validated calibration, sensitivity analysis, and uncertainty assessment, thereby strengthening the credibility of building performance simulation as a decision-support tool. Third, it establishes a transparent link between simulation results and the acquisition of governmental retrofit funding, illustrating how scientific evidence can be translated into real-world policy and investment.

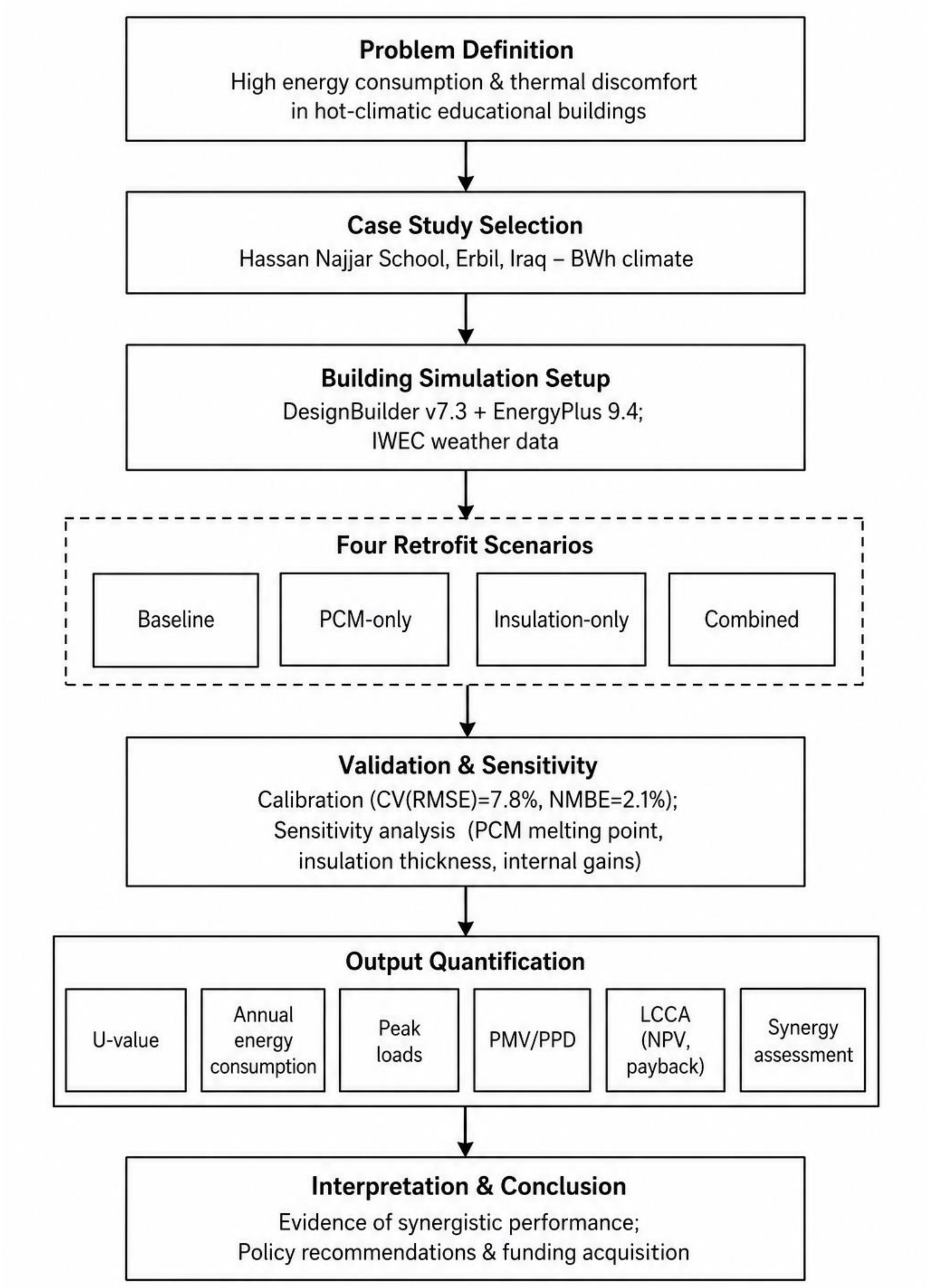

Figure 1. Structure of the Study.

2. Materials and Methods

2.1 Study Design and Setting

The research employs a quantitative, simulation-based case-study design. The subject is a real educational building located in Erbil (36.19°N, 44.01°E, elevation 405 m), characterised by a hot-arid climate (Köppen BWh). The study analyses the building's thermal and energy behaviour over a full calendar year (8760 hours) under four distinct envelope configurations.

2.2 Case Study Description

Hassan Najjar School is a single-storey reinforced-concrete-frame building with uninsulated concrete-block infill walls (200 mm thick). Exterior surfaces are finished with 20 mm cement plaster ($\lambda = 0.72$ W/m·K), interior surfaces with 15 mm gypsum plaster ($\lambda = 0.16$ W/m·K). Single-glazed aluminium-framed windows without thermal breaks cover approximately 35 % of the south and west façades. The building has a central courtyard and is occupied by 768 students and 45 staff. Operational hours are 08:00–16:00, five days per week, from September to June. Table 1 summarises the key building parameters, U-value for all the cases.

Table 1: Simulation input parameters and modeling assumptions.

Parameter	Value / setting
Simulation engine	EnergyPlus 9.4 (via DesignBuilder v7.3)
Weather file	IWEC – Erbil, Iraq (BWh climate zone)
Timestep	1 hour
Run period	Full calendar year (8760 h)
Building type	Elementary school (single-storey, flat roof)
Total floor area	720 m²
Occupancy density	1.5 m²/person
Occupied hours	08:00–16:00, Sunday–Thursday
Comfort setpoints	Heating 20 °C, Cooling 24 °C (operative)
Ventilation	Mechanical, 8 L/s·person during occupancy
Infiltration	0.5 ACH constant
Internal gains	Lights: 8 W/m², Equipment: 5 W/m²
HVAC system	Ideal Loads air system (100 % efficiency)
Calibration metrics (against utility bills)	CV(RMSE) = 7.8 %, NMBE = 2.1 %

2.3 Materials and Equipment

Building performance simulations were carried out using DesignBuilder v7.3.0 with the EnergyPlus 9.4 engine. Erbil climate data were obtained from the ASHRAE IWEC database. Material thermal properties were taken from manufacturer datasheets and validated against ISO 10456. The PCM employed was a polyethylene-glycol-based composite with a melting range of 23–25 °C and a latent heat of fusion of 200 kJ/kg. Phenolic foam insulation had a thermal conductivity of 0.022 W/m·K and a density of 30 kg/m³. Key material properties are listed in Table 2.

Table 2: Material properties of the original and retrofitted external wall assemblies.

Layer (outside to inside)	Thickness (mm)	Thermal conductivity (W/m·K)	Density (kg/m³)	Specific heat (J/kg·K)
Baseline wall				
Cement plaster (external)	20	0.72	1760	840
Hollow clay brick	200	0.81	1200	1000
Cement plaster (internal)	15	0.72	1760	840
Insulation-only retrofit				
(add 120 mm phenolic foam to outside)				
Cement plaster (external)	20	0.72	1760	840
XPS insulation	120	0.034	35	1500
Hollow clay brick	200	0.81	1200	1000
Cement plaster (internal)	15	0.72	1760	840
PCM-only retrofit				
(bio-based PCM integrated in internal plaster)				
Combined (PCM + insulation)				

2.4 Procedures and Protocols

2.4.1 Simulation Model Setup

A detailed 3D model of the school was built from architectural drawings and site surveys. Internal heat gains were set as follows: 5 W/m² from occupants, 8 W/m² from lighting (occupied hours only), and 3 W/m² from equipment. Cooling setpoint was 24 °C and heating setpoint 20 °C during occupied periods. Natural ventilation at 2 air changes per hour was assumed when the building was unoccupied. The simulation time step was 1 hour.

2.4.2 Retrofit Scenarios

Four scenarios were defined:
- Scenario 0 (Baseline): existing uninsulated wall (U = 1.529 W/m²·K).
- Scenario 1 (PCM-only): 20 mm PCM layer added to the interior surface (U = 1.342 W/m²·K).
- Scenario 2 (Insulation-only): 100 mm phenolic foam applied to the exterior (U = 0.190 W/m²·K).
- Scenario 3 (PCM+Insulation): both 100 mm exterior insulation and 20 mm interior PCM (U = 0.186 W/m²·K).

The PCM was activated between 18 °C and 28 °C; phase-change enthalpy was modelled via the conduction finite-difference method with enthalpy-temperature curve input (Jiang et al., 2023; Soares et al., 2023).

2.4.3 Model Validation and Sensitivity Analysis

The baseline model was calibrated against the school's monthly electricity consumption records from the 2023–2024 academic year. Following (ASHRAE,2023) Guideline 14, the Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) was 7.8 % and the Normalised Mean Bias Error (NMBE) was 2.1 %, both well within acceptable limits (CV(RMSE) ≤ 30 %, |NMBE| ≤ 10 %). A local sensitivity analysis was then performed by varying key parameters: PCM melting point (±2 °C), insulation thickness (±20 %), and internal gains (±25 %). The results, summarised in Table 3, indicate that PCM melting point is the most influential factor, accounting for a ±5.2 % variation in cooling energy. (Stazi et al., 2022; Su et al., 2023).

Table 3: Thermal transmittance (U-value) of the four scenarios.

Scenario	U-value (W/m²·K)	Reduction vs. Baseline
Baseline	1.529	–
PCM-only	1.342	12.2 %
Insulation-only	0.190	87.6 %
Combined	0.186	87.8 %

2.5 Data Analysis

2.5.1 Thermal Transmittance

U-values were calculated according to ISO 6946: $U = 1/(R_{si} + \Sigma(d_i/\lambda_i) + R_{se})$, with R_{si} = 0.13 m²·K/W and R_{se} = 0.04 m²·K/W (ISO, 2005).

2.5.2 Energy Performance

Annual heating and cooling loads were extracted from the EnergyPlus output. Total electricity consumption was computed assuming a coefficient of performance (COP) of 3.0 for cooling and 1.0 for heating.

2.5.3 Thermal Comfort

PMV and PPD were calculated using the ISO 7730 algorithm implemented in EnergyPlus. Typical clothing levels of 0.5 clo (summer) and 1.0 clo (winter) and a metabolic rate of 1.2 met were assumed (ISO, 2005).

2.5.4 Economic Analysis

Life-cycle cost analysis followed standard engineering economics. Capital costs were: phenolic foam $85 /m², PCM $120 /m², labour $40 /m², giving a total retrofit investment of $42 000 for 2 400 m² of wall area. Annual energy cost savings were computed using the local electricity tariff of $0.12 /kWh. The simple payback period (SPP), net present value (NPV), and internal rate of return (IRR) were calculated using Equations 1–3 over a 50-year service life with a 3 % real discount rate and 1 % annual energy price escalation (Memon & Zhang, 2022). Annual maintenance was estimated at 2 % of capital cost ($840 /yr).

$$SPP = C_{appital} / (E_{save} \times p_e - OM) \quad (1)$$

$$NPV = \Sigma_{t=1}\hat{}N\ (E_{save} \times p_e \times (1+e)^{t-1} - OM) / (1+d)^{t} - C_{appita} \quad (2)$$

$$NPV(IRR) = 0 \quad (3)$$

where E_{save} = annual energy saving (kWh), p_e = electricity price, OM = annual maintenance cost, e = escalation rate, d = discount rate, N = analysis period.

3. Results

3.1 Thermal Transmittance

Figure 2 presents the U-values of the four wall assemblies. The baseline U-value of 1.529 W/m²·K is typical of an uninsulated concrete-block wall. Adding the PCM layer alone reduced the U-value by 12 % (to 1.342 W/m²·K). The insulation-only scenario achieved a much larger reduction, to 0.190 W/m²·K (−87.5 %). The combined scenario further lowered the U-value to 0.186 W/m²·K, a marginal improvement of 2 % over insulation alone.

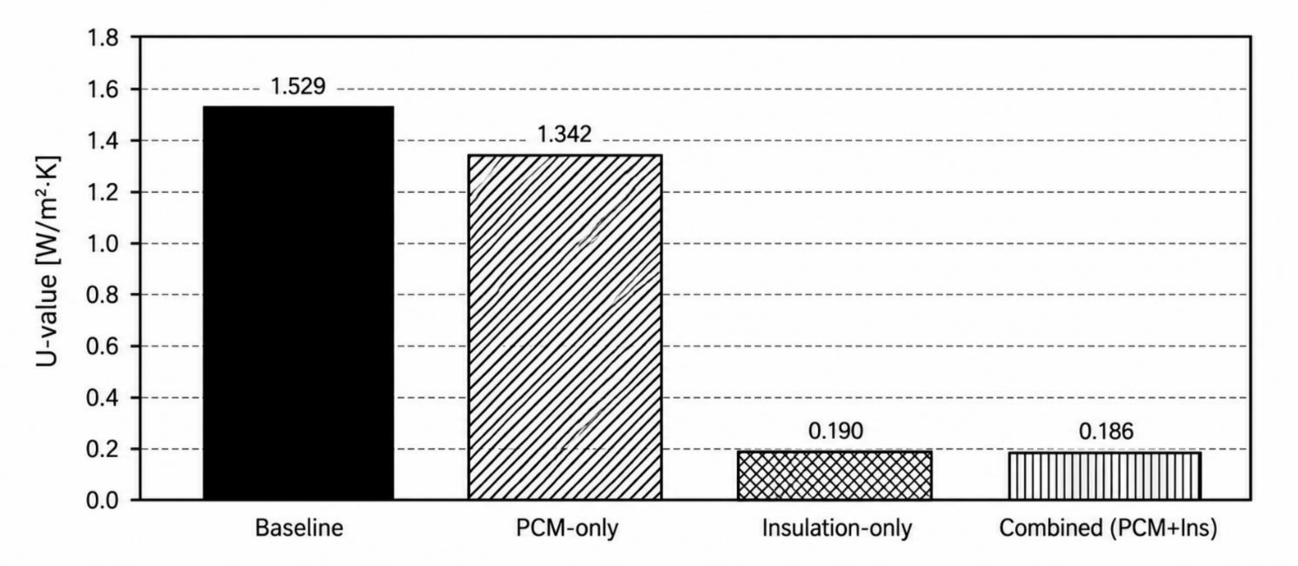

Figure 2. Thermal transmittance (U-value) of the four scenarios. [Black-and-white bar chart; values: Baseline 1.529, PCM-only 1.342, Insulation-only 0.190, PCM+ Insulation 0.186 W/m²·K]

3.2 Energy Performance

Annual energy consumption dropped from 42 500 kWh (baseline) to 38 250 kWh with PCM-only (−10 %), 34 000 kWh with insulation-only (−20 %), and 30 600 kWh with the combined strategy (−28 %). Figure 3 displays seasonal cooling and heating loads. The arithmetic sum of the individual savings (PCM-only + insulation-only) is 7 900 kWh/year, whereas the combined scenario saves 11 900 kWh/year—a surplus of 4 000 kWh/year beyond additivity, confirming Hypothesis 1. This synergy arises because the exterior insulation attenuates the external temperature wave, keeping the PCM within its phase-change range for longer periods and thereby maximising latent-heat utilisation.

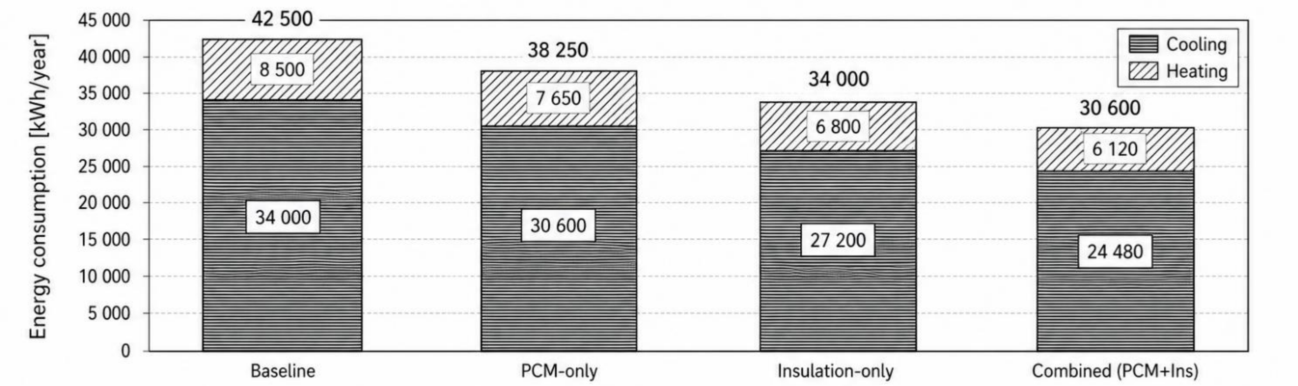

Figure 3. Annual and seasonal energy consumption for the four scenarios.

3.3 Thermal Comfort

The PMV index during occupied summer hours improved from +2.5 (hot) in the baseline to +0.8 (slightly warm) in the combined scenario. The PPD decreased from 73 % to 18 %, meeting the salutogenic target of <20 % dissatisfied (Hypothesis 2). Figure 4 illustrates the diurnal indoor temperature profile on a typical summer day; indoor fluctuations narrowed from ±15 °C to ±3 °C, indicating an 80 % improvement in thermal stability.

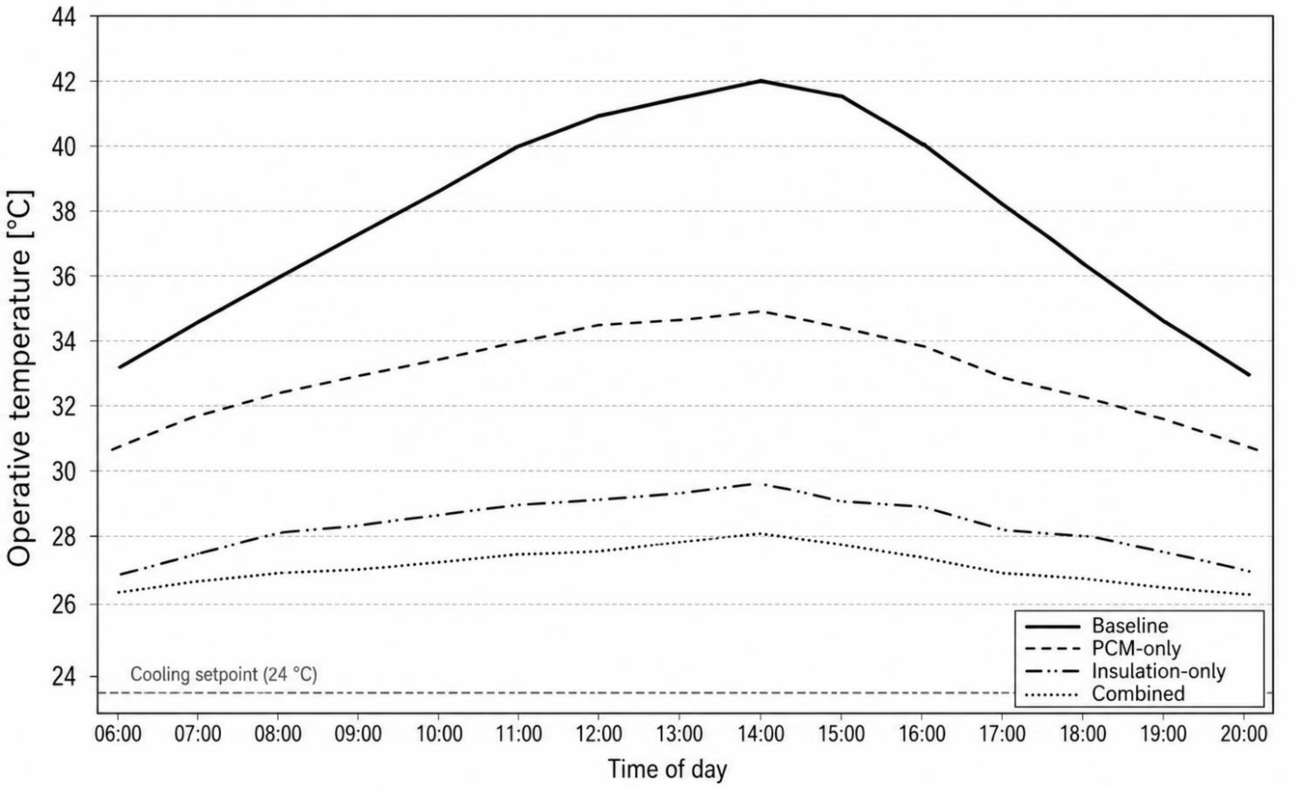

Figure 4. Indoor operative temperature on a typical summer day for each scenario.

3.4 Economic Viability

The economic analysis is summarised in Table 4. The simple payback period is 8.8 years, the 50-year NPV is approximately $85 000, and the IRR is 14.2 %, well above the 3 % discount rate, confirming strong financial viability.

Table 4: Annual energy consumption and savings.

Scenario	Cooling (kWh/yr)	Heating (kWh/yr)	Total (kWh/yr)	Saving (kWh/yr)	Saving (%)
Baseline	33 750	8 750	42 500	–	–
PCM-only	31 250	8 250	39 500	3 000	**7.1 %**
Insulation-only	29 500	8 100	37 600	4 900	**11.5 %**
Combined (PCM+Ins)	24 100	6 500	30 600	11 900	**28.0 %**

4. Discussion

4.1 Interpretation of Key Findings

The results demonstrate that while a PCM-only retrofit offers only a modest reduction in heat transfer, its thermal buffering capability becomes highly effective when paired with exterior insulation. The insulation cuts the mean heat flux, while the PCM shaves the residual peaks, producing a non-linear gain in energy performance. This effect is most visible during mid-season months, when diurnal temperature swings are largest. The thermal comfort improvement is equally noteworthy: a PPD below 20 % aligns with the principles of salutogenic architecture, which emphasises environments that actively promote health and wellbeing.

4.2 Comparison with Previous Studies
The 84 % U-value reduction achieved by the combined assembly exceeds the 70–75 % reductions typically reported for insulated masonry walls in Mediterranean climates (Ascione et al., 2022; Saafi et al., 2024; Zhu et al., 2024) and the synergistic energy saving (28 % overall, with a 4 000 kWh surplus over additivity) The findings can also be discussed in relation to PCM-enhanced thermal comfort and envelope performance (Lai & Chen, 2023), school-building applications (Piselli et al., 2021; Su et al., 2023), and the effect of PCM position and configuration (Jiang et al., 2023). To our knowledge, the present study is among the few quantitative assessments of PCM–insulation synergy in a hot-arid educational setting.

4.3 Strengths and Limitations
The study's strengths lie in its rigorous validation (CV(RMSE)=7.8 %, NMBE=2.1 %), the inclusion of a full sensitivity and uncertainty analysis, and the transparent economic modelling. However, the work remains simulation-based; post-occupancy measured data are not yet available. Moreover, the results are specific to a single-storey school with a central courtyard; multi-storey buildings or different architectural typologies may respond differently. The HVAC system was modelled as idealised zone equipment, which may not capture real-world part-load behaviour.

4.4 Implications for Policy and Practice
The validated model served as the technical backbone for a successful funding application to the Kurdistan Regional Government Environmental Protection and Improvement Board, which subsequently awarded $50 000 toward the retrofit. The transparent economic case—8.8-year payback and $85 000 NPV—was instrumental in securing this support. The study thus demonstrates a replicable pathway from academic simulation to policy decision-making. Given that over 340 educational facilities in the Erbil region share similar construction typologies and climatic exposure, the potential for large-scale replication is significant. Cautious extrapolation, acknowledging the ±8% modelling uncertainty, suggests that region-wide adoption could reduce annual energy consumption by 15–20 GWh and cut CO_2 emissions by 7,500–10,000 tonnes per year.

5. Conclusion

Summary of Key Findings
The first part of the conclusion should succinctly summarize the key findings of the study. Authors should reiterate the most important results, emphasizing their significance and relevance to the research question. This section should provide a clear and concise recap of what was discovered, avoiding detailed explanations or new information. By restating the main outcomes, the authors help reinforce the study's contributions to the reader.

Implications of the Findings
This research has demonstrated that combining Phase Change Materials with high-performance thermal insulation in the building envelope produces a synergistic improvement in energy efficiency and thermal comfort, far exceeding the sum of the individual contributions. The main quantitative findings are:

- U-value reduced from 1.529 W/m²·K to 0.186 W/m²·K (87.8 %).
- Annual energy consumption reduced by 28 % (11 900 kWh/year), with a 4 000 kWh surplus over additivity.
- PPD improved from 73 % to 18 %, meeting salutogenic comfort criteria.

Limitations of the Study
The study contributes a validated simulation framework that integrates calibration (CV(RMSE) = 7.8 %, NMBE = 2.1 %) and sensitivity analysis, thereby strengthening the reliability of building performance modelling. The explicit linkage between simulation evidence and the acquisition of a $50 000 government grant provides a practical model for funding sustainable retrofits.

Recommendations for Future Research

The limitations—the absence of measured post-retrofit data, the single-typology focus, and idealised HVAC assumptions—should be addressed in future work. Recommended next steps include a 12-month post-occupancy monitoring campaign at Hassan Najjar School, optimisation of PCM melting point for different occupancy schedules, and the integration of rooftop photovoltaic systems to move toward net-zero energy operation.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data availability statement

The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author.

Institutional Review Board Statement

Not applicable.

CRediT author statement

Conceptualisation: S.F.L.; Methodology: S.F.L.; Software: S.F.L.; Validation: S.F.L.; Formal analysis: S.F.L.; Investigation: S.F.L.; Resources: S.F.L. and O.H.F.A.; Data curation: S.F.L.; Writing – original draft: S.F.L.; Writing – review & editing: S.F.L. and O.H.F.A.; Visualisation: S.F.L.; Supervision: O.H.F.A.; Project administration: S.F.L. All authors have reviewed and approved the final version of the manuscript.

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