

Envelope energy retrofitting of an educational building in hot-dry climate: a simulation-based parametric study with TOPSIS ranking

Waleed S. Alawsey^{1*}, Yaik-Wah Lim², Tist Aziz³

^{1,2,3} Department of Architecture, Faculty of Built Environment and Surveying, University Technology Malaysia, 81310 Johor Bahru, Malaysia

*Corresponding author E-mail: saad.h@graduate.utm.my

Received Feb. 3, 2026
Revised Jul. 9, 2026
Accepted Sep. 8, 2026
Online Oct. 13, 2026

Abstract

This study presents a parametric energy simulation of envelope retrofit strategies for the Faculty of Arts Building at Al-Qadisiyah University in Al-Diwaniyah, Iraq. The three-story educational building was constructed approximately 54 years ago and remains uninsulated in a hot-desert climate, with summer peak dry-bulb temperatures reaching 47 degrees Celsius and an annual occupied discomfort burden of 1,841 hours under baseline conditions. Seven independent retrofit categories were evaluated using the DesignBuilder parametric environment with the EnergyPlus simulation engine. The baseline model was calibrated using fourteen months of on-site monitoring conducted with ESP32-based sensor nodes equipped with Si7021 and TSIC 206 sensing elements across ten zones. The calibrated model achieved a coefficient of variation of the root mean square error of 5.79 percent and a mean bias error of 1.48 percent when compared with metered utility records. The best-performing option from each retrofit category consisted of polyisocyanurate-backed plasterboard wall lining, triple-silver spectrally selective window coating, silicone-based air sealing, an extensive green roof, triple-glazed argon-filled windows, combined external louver and fin shading, and solar-screen roller shades. These seven interventions were subsequently integrated into a single combined retrofit model. The combined scenario reduced annual electricity consumption by 43.7 percent, from 306,421 to 172,604 kWh per year, while achieving a mean annual predicted percentage dissatisfied value of 19.98 percent. This was the only result among the 28 simulated scenarios that achieved a predicted percentage dissatisfied value below 20 percent, consistent with the specified thermal comfort criterion. A five-criterion Technique for Order of Preference by Similarity to Ideal Solution analysis based on energy savings, thermal comfort, discomfort-hour reduction, percentage energy reduction, and economic cost efficiency identified the combined retrofit as the highest-ranked alternative, with a closeness coefficient of 0.9113. The estimated installation cost of the combined intervention is 285,952 United States dollars, equivalent to 374,597,513 Iraqi dinars, with a projected payback period of 21.4 years under a blended electricity and generator-fuel tariff and a 25-year return on investment of 17.0 percent. Among the individual interventions, the extensive green roof produced the greatest impact,

reducing annual electricity consumption by 8.8 percent and annual discomfort hours by 28.4 percent through the cooling effect of the vegetative layer.

© The Author 2026.
Published by ARDA.

Keywords: Building energy simulation, Envelope retrofitting, Thermal comfort, Performance consolidation, Hot-dry climate, University buildings

1. Introduction

The building sector accounts for nearly 40 percent of the total world final energy consumption (FEC). Heating and cooling represent the majority of all building end uses in both hot and cool climate zones [1]. Public school buildings in Iraq, which include some of the largest energy consuming building types and have operated primarily with pre-1980 uninsulated walls and roofs and with individual room air conditioned units since their construction, suffer from extreme cooling demands and poor indoor thermal comfort [2, 3]. The Faculty of Arts Building (B) at Al-Qadisiyah University in Al-Diwaniyah is an example of such a structure. It was built about 54 years ago and has no wall or roof insulation and single pane glazing that has a thermal transmittance (U-value) of $5.70 \text{ W/m}^2\cdot\text{K}$. Building envelope retrofitting is consistently identified as one of the most cost-effective pathways to reducing energy demand in existing buildings without disrupting occupancy [4]. However, selecting the optimal combination of retrofit interventions from a large candidate pool is a multi-criteria decision-making (MCDM) problem that simulation alone cannot resolve. The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) provides a systematic and computationally transparent framework for ranking alternatives by their simultaneous proximity to the positive ideal solution and distance from the negative ideal solution [5].

TOPSIS has been applied to building retrofit selection by Aram et al. [5], who ranked energy-efficiency measures in residential buildings, and Marzouk et al. [6], who optimized strategies for mosque buildings. This paper presents a parametric energy simulation study of seven envelope retrofit categories applied to Building (B), followed by a combined optimal scenario (S9) based on ASHRAE Standard 55-2017 [7], ISO 7730:2005 [8] and ASHRAE Guideline 14-2014 [9]. All 28 simulations were conducted in DesignBuilder v7 / EnergyPlus v22 [10], [11]. TOPSIS then ranked the best-performing scenario from each category and the combined scenario using energy saving, thermal comfort, discomfort-hour, energy reduction, and cost-efficiency criteria.

The study contributes evidence on envelope interventions in the hot-dry climate of southern Iraq, a region under-represented in the international building energy literature [2], [3]. To the authors' knowledge, this is the first study in Iraq to validate an educational building energy model against simultaneously collected, quality-controlled on-site sensor data alongside metered utility records, providing an empirical foundation that transcends the prototype and virtual-building limitations identified in prior Iraqi retrofitting studies [2], [3].

2. Case study

The case study is Faculty of Arts Building (B) at Al-Qadisiyah University, Al-Diwaniyah, Iraq (31.99°N , 44.93°E). As shown in Figure 1, the building is a three-story rectangular block measuring $57.35 \text{ m} \times 14.4 \text{ m}$ with a total height of approximately 10.9 m and a gross floor area (GFA) of $2,474 \text{ m}^2$. The ground floor houses the Arabic Language Department (floor-to-ceiling height: 3.9 m), the first floor houses the Geography Department (3.5 m), and the second floor houses the Community Department (3.5 m). The building faces east-southeast and was constructed approximately 54 years ago.

The existing wall construction consists of 2 cm interior plaster, 25 cm solid fired-clay brick, and 2 cm exterior cement plaster, yielding a calculated U-value of $1.70 \text{ W/m}^2\cdot\text{K}$ with no insulation layer or air gap [3]. The roof is a flat reinforced concrete (RC) slab covered with $80 \times 80 \text{ cm}$ concrete tiles. The solar heat gain coefficient (SHGC) of the existing single-pane 6 mm clear aluminum-framed windows is 0.82 with a U-value of $5.70 \text{ W/m}^2\cdot\text{K}$. The window-to-wall ratio (WWR) is 0.379 on the side façades and 0.19 on the front and rear, giving a building-average WWR of 0.34. The three-story floor plans are presented in Figure 2.



Figure 1. Faculty of Arts Building (B), Al-Qadisiyah University, Al-Diwaniyah, Iraq: existing condition (on-site photographs showing uninsulated façades, split-unit AC condensers, and the decorative concrete screen panels)

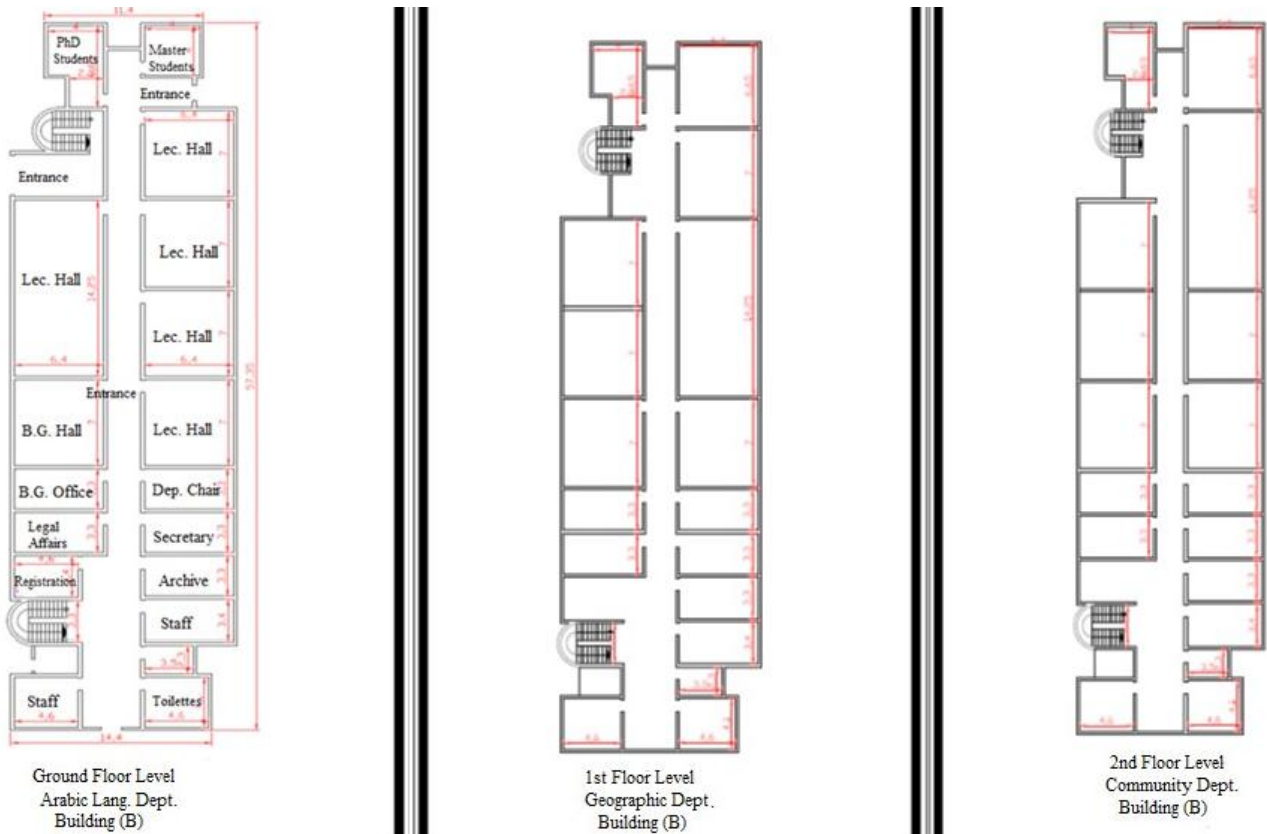


Figure 2. Building (B) floor plans: ground floor — Arabic Language Dept. (GFA: 826 m²), 1st floor — Geography Dept. (824 m²), 2nd floor — Community Dept. (824 m²)



Figure 3. Revit three-dimensional model of Building-B: south-east elevation (left), east façade (center), side façade detail (right)

The building is cooled entirely by standalone split-unit AC systems mounted on all façades, with no centralized heating, ventilation and air conditioning (HVAC) or mechanical ventilation. The building has lighting installed in the form of Fluorescent and Halogen light fixtures. The Building operates on a 10 hour daily operating cycle from Sunday to Thursday from 8:00 AM – 6:00 PM, which equates to around 220 work days per annum. Utility Records for Electricity usage indicate that the building uses approximately 330,030 kilowatt hours of electricity per year. Summer month averages are at their highest point of use at about 40,708 kW/month and lowest point of use during winter at approximately 8,070 kW/month. For the entire duration of the summer months, on site Diesel Generators provide approximately 50% of the Buildings total Power requirements, resulting in estimated costs of \$33,273,169 IQD/year [3].

3. Methodology

The Simulation Model has been created with DesignBuilder V7 [10] utilizing the Three Architectural Floor Plans that have been received from the University Construction Unit to validate against the Autodesk Revit 3D Model Produced For This Study (Figure 3). EnergyPlus V22 [11], a software product of the U.S. Department Of Energy (US DOE) provided the computational engine. Historical climate data for Al- Diwaniyah were obtained from the Meteoblue Historical Archive Weather File [12]. As shown in Figure 4, peak monthly maximum temperatures reach 47 °C in July and mean daily minima of 7 °C in January, characteristic of the BWh hot-desert classification. Thermal comfort was evaluated using the Fanger Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) model per ISO 7730 [8] and ASHRAE Standard 55 [7].

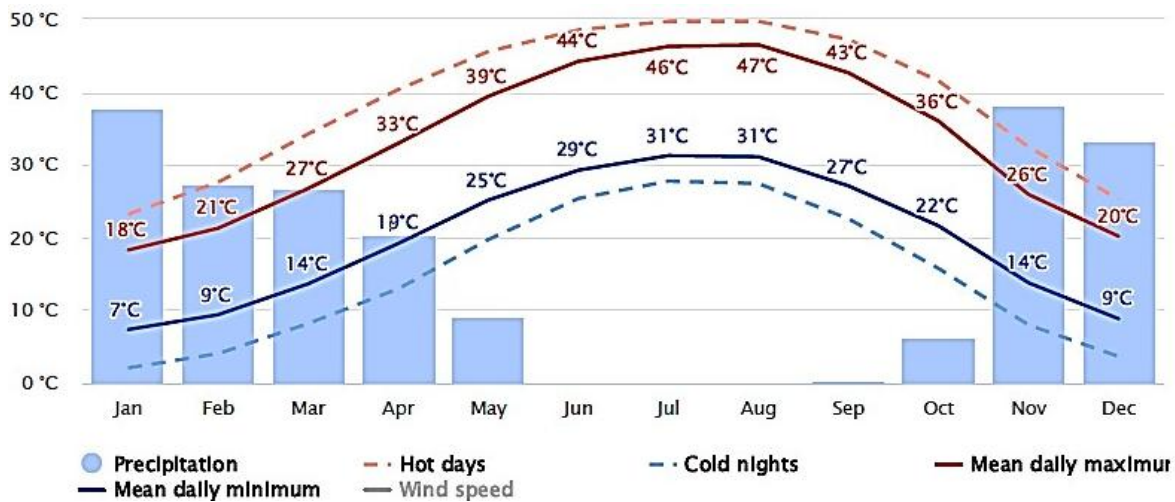


Figure 4. Monthly temperature ranges and precipitation for Al-Diwaniyah, Iraq (Meteoblue archive [12]): hot-desert (BWh) profile with peak daily maxima of 47 °C in July

The base model was calibrated against the building's metered utility records prior to running any retrofit scenario. Two standard ASHRAE Guideline 14 [9] calibration metrics were computed: the coefficient of variation of the root mean square error (CVRMSE) and the mean bias error (MBE), defined respectively as:

$$CVRMSE = \frac{\sqrt{\frac{\sum_{i=1}^{N_i} (M_i - S_i)^2 / N_i}{\frac{1}{N_i} \sum_{i=1}^{N_i} M_i}}}{1} \quad (1)$$

$$MBE = \frac{\sum_{i=1}^{N_i} (M_i - S_i)}{\sum_{i=1}^{N_i} M_i} \quad (2)$$

Where M_i is the metered monthly energy consumption, S_i is the simulated value for month i , and N_i is the total number of monthly data points ($N_i = 12$). ASHRAE Guideline 14 [9] identifies acceptable limits as follows: $CVRMSE \leq 30\%$ and $|MBE| \leq 10\%$ for monthly calibration. Using equations (1) and (2), we get $CVRMSE = 5.79\%$, and $MBE = -1.48\%$. Both are clearly below the allowable values. A baseline model is developed using EnergyPlus that indicates annual consumption at 306,421 kwh/yr. Metered data shows an estimated total

consumption of about 330,030 kwh/yr. The difference of 7.1% is due to the fact that this does not account for the energy consumed by a diesel generator which is included in the electric output from EnergyPlus [11, 12]. The performance data collected during the metering of this building's indoor environment to validate the calibrated model were provided with data collected through a multi-month environmental monitoring program that sampled across all three floors of this building from September 2024 to October 2025. There were ten sensors installed on the same day, but at different times, for use in sampling air temperature and humidity levels across all of the building's 10 thermal zones. The sensors were mounted at 1.1 meters above the finished floor level, which is equivalent to the seated occupant height referenced in ISO 7730 [8, 13] for assessing thermal comfort. Each sensor consisted of an ESP32 microprocessor (Espressif Systems, dual-core Xtensa LX6 processor running at 240 MHz) that operated independently of its two attached sensors [14]. These sensors operated as a redundant or cross check pair of silicon-based solid state devices, one of which was a Silicon Laboratories Si7021 device (accuracy rating of ± 0.4 °C, ± 3 % RH; I2C interface) designated as the reference sensor [15, 16], while the other was a TSIC 206 high accuracy temperature integrated circuit (accuracy rating of ± 0.3 °C over the range 0 – 60 °C; ZAC wire digital output) designated as the secondary cross check [17]. During every hour that the sensor logged data, the ESP32 firmware would compare the temperature values recorded from both of these sensors. If there were greater than a 0.5 °C difference between them, then those records would be identified as suspect and rejected from further analysis. Time synchronization between the ten-sensor network was accomplished using NTP based on UTC + 3 (Asia/Baghdad). The maximum clock drift between any two devices in the network was 6 minutes. The total number of hours included in the full dataset was 89,337. After filtering out suspected errors through automation, the overall valid record retention rate of all zones for all days was over 97%, providing confidence that this dataset could serve as a reliable basis for validating the results of calibration analyses.

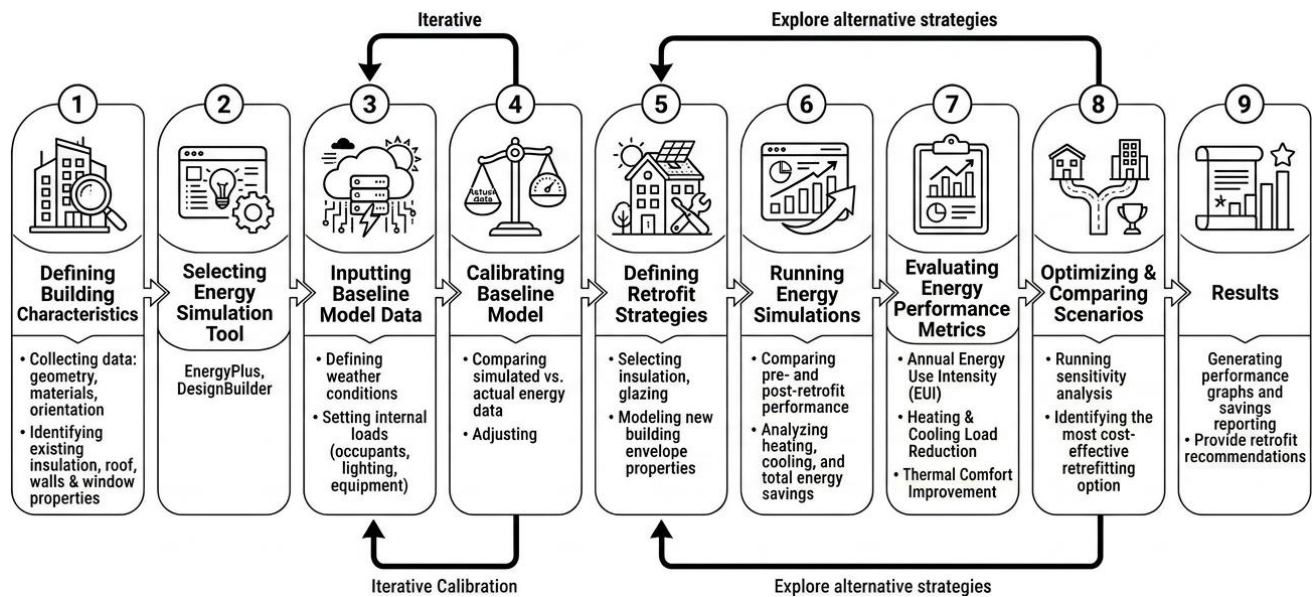


Figure 5. Simulation procedure flow chart: sequential parametric methodology that begins with the building geometry definition and ends with calibration, retrofit simulation, and evaluation of TOPSIS

In order to identify the potential for energy savings from retrofitting an existing building with low-cost envelope upgrades, seven envelope retrofit categories were analyzed sequentially, one at a time using a parametric approach as described by [4] of this research. For each envelope retrofit category, there were numerous materials used to create the envelope upgrade that were tested relative to the previously established baseline; the single most efficient material was selected to be included in the final optimal combination (S9). A description of the methodology used to select materials for inclusion into the final scenario is provided in figure 5. The winning candidates for each of the seven categories listed above are:

- S1 -- base case: existing building – calibrated reference scenario;

- S2 -- Walls: insulated plasterboard dry-lining with a polyisocyanurate (pir) foam insulation core (50mm thick), thermal conductance = 0.022 w/m.k [4];
- S3 -- solar coating: low emissivity spectrally selective coating saint gobain cool lite extreme triple silver (shgc = 0.23, U-value = 1.0 w/m².k) [13];
- S4 -- draft proofing: sealants made from Silicone, applied around all AC conduit penetration points and Window frame perimeter locations [14];
- S5 -- Roof: green Roof covering installed over the waterproof membrane and drain layers [2];
- S6 -- Window glazing: triple-glazed argon filled glass unit (U-value <= 1.0 w/m².k, shgc = 0.20–0.27) [4];
- S7 -- exterior shading device: horizontal aluminum louvers (blade depth 200-300 mm) and vertical aluminum fins (angle 45°) [15];
- S8 -- interior shading device: roller shade with solar screen material (closed during 08:00–18:00) [15];
- S9 -- optimal combination: all seven category winners applied simultaneously

All retrofit options had the Installation costs estimated based upon market unit rates for materials and skilled labor in Iraq and surface finishing. All materials that are not manufactured domestically will be imported via regional distribution channels of the Gulf States (UAE, Turkey, Jordan) with an estimated import premium of 15-25% above international benchmark rates [16]. Labor rates were determined by the prevailing trade rates for installing skilled tradesmen in Al-Diwaniyah province.

Each option was financially assessed using the Return on Investment formula defined within the research framework [16]:

$$ROI = [(Total Annual Savings \times n) - Investment Cost] / Investment Cost \times 100\% \quad (3)$$

Where 'n' is a lifecycle period (25 years adopted within this study). Total annual savings include two components: (i) electricity grid savings at institutional tariff rate of 0.04 \$/kwh; and (ii) diesel generator fuel savings estimated as 0.08\$/kwh-equivalent for supply fraction of 50% to generate blended saving rate of 0.06\$/kwh. The exchange rate used is 1\$=1310 IQD (average of 2025) [16].

TOPSIS [5] was applied to rank six retrofit scenarios (S2–S6 and S9) using five criteria: (C1) annual energy saving in kWh/yr ($W_1 = 0.30$); (C2) reduction in mean annual PPD in percentage points ($W_2 = 0.25$); (C3) reduction in annual discomfort hours as a percentage of the base-model total ($W_3 = 0.15$); (C4) percentage energy reduction ($W_4 = 0.15$); and (C5) cost-efficiency index — annual total savings divided by total investment cost ($W_5 = 0.15$). C5 is a benefit criterion (higher is better). This extended five-criterion formulation adds economic value relative to the four-criterion baseline, following the multi-criteria framework of Aram et al. [5] and Marzouk et al. [6]. S7 external shading and S8 internal shading had no complete energy data therefore both will be assessed based upon the comfort criteria for each.

Weights were applied to each criterion through expert judgement as part of our previous research, as follows: The weights for the two energy performance criteria (C1 & C4) totaled .45 as they reflect the main reason for attempting to reduce electricity usage. The weights for the two thermal comfort criteria (C2 & C3) also totaled .40 since this is an occupation-focused motive. Finally, the weight for the economic cost-efficiency (C5) was .15 as it represents budgetary constraints, but we wish to avoid allowing subsidized tariffs to influence the ordering of options within a highly subsidized environment.

4. Results and discussion

The Base Model recorded a mean annual Fanger PMV of +0.52 (warm) [8]. At its highest value during the year; the peak summer PMV was +1.73 in August when the PPD had reached 66.4%, over three times greater than the 20 % ASHRAE Standard 55 [7] limit. The annual number of Discomfort Hours totaled 1841 hours or roughly 83.7 % of the Total Occupied Hours per Year. As well as accounting for 69.9% of the total annual electrical usage (a total of 214,340 kWh/year from 306,421 kwh/year), the fact that Cooling Electrical usage represents

most of the building's Energy Usage confirms that the Uninsulated Thermal Envelope is the primary reason why there is such a large energy demand [3]. The extreme difference between Summer & Winter Load can be illustrated by comparing the Monthly Electricity Consumption Ratio of Peak to Low use (40,708 kwh / 8,070 kwh = 5.04). This extreme difference reflects an extreme imbalance in the need for Heating vs. Cooling Loads due to the characteristics of the BWh Climate.

Table 1 summarizes the annual energy and comfort data of all nine scenarios. Each of the seven single measures produces a reduction in annual discomfort hours as compared with the reference scenario. In terms of both electricity consumption and discomfort hours, the green roof (S5) provides the greatest impact among the single measures. For example, it leads to an overall electricity savings of 8.8 % (i.e., 27,072 kWh/yr), and a reduction of 28.4% in total annual discomfort hours (from 1841 to 1318 h). These are due primarily to the direct evaporative-cooling effects produced by transpiring vegetation that intercepts incoming solar radiation and uses this for plant metabolic activities; during these processes it will release moisture into the atmosphere. Consequently, peak roof surface temperatures will be suppressed. Peak roof surface temperature in Al-Diwaniyah was shown to reach values of approximately 65–70 °C in July. Therefore, the shading effect provided by the green roof's leafy canopy will be most effective in suppressing the heat fluxes onto the building envelope at times when high levels of solar irradiance prevail [2], [4]. The mean annual PMV under the green roof scenario shifts to -0.06, essentially thermally neutral, representing the best single-scenario comfort outcome.

Table 1. Annual energy and thermal comfort results: all scenarios vs. base model (S1)

Scenario	Energy (kWh/yr)	Redn. vs. S1	Discomfort (hrs/yr)	PPD (%)
S1 — Base model	306,421	—	1,841	40.0
S2 — PIR Plasterboard	297,740	-2.8%	1,550	38.95
S3 — COOL-LITE XTREME	320,702	+4.7%	1,677	40.99
S4 — Silicone sealant	305,488	-0.3%	1,741	38.76
S5 — Green roof	279,349	-8.8%	1,318	34.67
S6 — Triple glazing	313,266	+2.2%	1,615	40.13
S7 — Louvers + fins	—	—	1,820	—
S8 — Roller shade	—	—	1,449	—
S9 — Combined	172,604	-43.7%	1,542	19.98

The PIR plasterboard wall lining (S2) yields the lowest discomfort hours of all wall variants (1,550 hrs/yr, -15.8%) and is the most practically realizable option given the solid brick wall construction without an existing air cavity [4]. The COOL-LITE XTREME solar coating (S3) and triple glazing (S6) perform comparably on comfort grounds (PPD 40.99% and 40.13% respectively). Table 1 summarizes the annual energy and comfort data of all nine scenarios. Each of the seven single measures produces a reduction in annual discomfort hours as compared with the reference scenario. In terms of both electricity consumption and discomfort hours, the green roof (S5) provides the greatest impact among the single measures. For example, it leads to an overall electricity savings of 8.8 % (i.e., 27,072 kWh/yr), and a reduction of 28.4% in total annual discomfort hours (from 1841 to 1318 h). These are due primarily to the direct evaporative-cooling effects produced by transpiring vegetation that intercepts incoming solar radiation and uses this for plant metabolic activities; during these processes it will release moisture into the atmosphere. As a consequence, peak roof surface temperatures will be suppressed. Peak roof surface temperature in Al-Diwaniyah was shown to reach values of approximately 65–70 °C in July. Therefore, the shading effect provided by the green roof's leafy canopy will be most effective in suppressing the heat fluxes onto the building envelope at times when high levels of solar irradiance prevail [15].

Table 2 illustrates a detailed analysis of the cost of installing the systems and the financial viability data to evaluate all alternatives. All costs were assessed as per current Iraq market prices including premium costs associated with importing materials, costs related to hiring experienced labor for installation and costs

associated with completing each system's surface finishes. The blended effective saving in US Dollars/kWh is calculated using two components; 1) the subsidized grid energy pricing of \$0.04/kWh and 2) the replacement value of generator fuel (\$0.08/kWh at 50% generator dependency).

Table 2. Installation cost breakdown and financial performance (Iraqi market, 2025–2026 rates)

Scenario	Area (m ²)	Total Cost (USD)	Total Cost (IQD ×10 ³)	Ann. Saving (USD/yr)	Payback (yrs)	25yr ROI (%)
S2 — PIR Plasterboard	1579	\$36,633	47,989	\$868	42.2	-40.8%
S3 — COOL-LITE XTREME	841	\$36,163	47,374	—	—	—
S4 — Silicone sealant	2405	\$7,456	9,767	\$93	79.9	-68.7%
S5 — Green roof	826	\$65,254	85,483	\$2,707	24.1	3.7%
S6 — Triple glazing	841	\$99,238	130,002	—	—	—
S7 — Louvers + fins	841	\$27,332	35,806	—	—	—
S8 — Roller shade	841	\$13,876	18,178	—	—	—
S9 — Combined	varies	\$285,952	374,598	\$13,382	21.4	17.0%

A green roof (S5) presents the best possible financial characteristics for each individual option; therefore, it has the lowest payback time (24.1 years) and highest ROI (3.7%) over 25 years due to both high savings of energy and the large amount of additional generator fuel displaced. S2 - PIR Plasterboard Lining will have a higher pay back period (42.2 years) under subsidized tariffs, although the institutional tariff rate of 0.04 USD/kWh in Iraq is one of the most highly subsidized in the world -- at market rates in similar climate zones (0.10-0.15 USD/kWh), pay-backs for all options are approximately 2.5 to 3.5 times lower than under current conditions. Options S3-S8 do not produce electrical savings as independent options within the EnergyPlus model; nevertheless, they contribute to the comfort factor through the TOPSIS cost-effectiveness measure (C5). When viewed from an overall perspective, the total investment required for the combined option (\$285,952 / \$374.6m IQD) with a predicted 25 year ROI of 17.0 percent under present tariff conditions is a significant investment in public facilities; however, taking into consideration the annual dis-comfort burden of 1841 occupied hours in the original model -- and institutional reputations and health impacts resulting from thermal stress suffered by students and faculty members -- this option is justifiable on societal and institutional basis. The results of the combined scenarios are those that implement each of the seven selected passive strategies together. The overall energy savings associated with these results are an estimated 172,604 kWh/year, which represents a reduction of 43.7% compared to the baseline value of 306,421 kWh/year. In addition to the total energy savings associated with these results, they also represent a savings of approximately 106,744 kWh/year over the next best result in this study (which was based solely upon the use of a green roof; i.e., 279,349 kWh/year [2]). This finding indicates that there are strong synergies among the different passive strategies applied in this study. In terms of temperature, the results indicate a shift in the mean annual PMV from +0.52 in the baseline to -0.11 in the combined scenario. As such, it appears as though the indoor air temperature remains neutral throughout the year [8]. Monthly, the results show that the maximum amount of electrical energy consumed by the building occurs during the month of June (i.e., 18,926 kWh), while historically, this has occurred during either July or August. These findings are consistent with prior research suggesting that the primary function of evaporative cooling mechanisms (such as that used in conjunction with green roofs) is active primarily during early summer when vegetation is still relatively active [2].

Finally, the results clearly demonstrate that the combined scenario is capable of achieving a mean annual PPD of 19.98% [7], which represents the first time in this study that any one strategy has achieved a value greater than the 20% threshold specified by ASHRAE Standard 55 [7]. Annual discomfort hours fall from 1,841 (base) to 1,542 under S9, a reduction of 16.2% — less proportionally dramatic than the energy saving (43.7%) because some discomfort hours arise from mild winter undercooling that no summer-optimized retrofit fully eliminates.

Table 3 presents the TOPSIS five-criterion decision matrix, weighted normalized values, Euclidean distances, and closeness coefficients. All criteria are benefit-type. The extended weighting ($W_1=0.30$, $W_2=0.25$, $W_3=0.15$, $W_4=0.15$, $W_5=0.15$) adds the cost-efficiency dimension relative to the four-criterion baseline, following established MCDM practice in building retrofit studies [5], [6].

Table 3. TOPSIS five-criterion evaluation: decision matrix, closeness coefficients and rankings

Scenario	C1 Energy saved (kWh)	C2 PPD redn (pp)	C3 Discomfort redn (%)	C4 Energy redn (%)	C5 Cost efficiency	CC Rank
Combined optimal	133817	20.02	16.24%	43.67%	0.04680	0.9113 #1
Green roof (extensive vegetative)	27072	5.33	28.41%	8.83%	0.04149	0.4083 #2
PIR Plasterboard dry-lining	8681	1.05	15.81%	2.83%	0.02370	0.2665 #3
Silicone draught-proofing	933	1.24	5.43%	0.30%	0.01251	0.2101 #4
Triple glazed unit replacement	-6845	-0.13	12.28%	-2.23%	-0.00690	0.1388 #5
COOL-LITE XTREME solar coating	-14281	-0.99	8.91%	-4.66%	-0.03949	0.0268 #6

The TOPSIS results confirm the combined scenario (S9) as the unambiguous first-ranked alternative with a closeness coefficient of 0.9113, substantially ahead of all individual category scenarios. The incorporation of the cost-efficiency criterion (C5) modifies the ranking relative to a cost-blind analysis: the green roof (S5, CC = 0.4083) retains second position owing to its simultaneous energy and comfort performance, while the PIR plasterboard (S2, CC = 0.2665) ranks third, supported by its comfort advantage and moderate investment cost relative to glazing options. The silicone draught-proofing (S4, CC = 0.2101) ranks fourth — it's very low capital cost (USD 7,456) gives it a relatively favorable cost-efficiency score despite modest energy saving. Triple glazing (S6, CC = 0.1388) ranks fifth and COOL-LITE XTREME (S3, CC = 0.0268) ranks sixth, penalized by their high per-unit costs relative to individually modest energy impacts when applied as standalone interventions [13]. This shows a fundamental conclusion: the economics supporting (spectrally selective) glazing and solar coatings are most compelling when considered as a package as opposed to on their own. The data from the current study also have some important limitations that need to be taken into account when assessing the conclusions reached in the research. A major limitation is that the energy consumption modelling used in the study was undertaken using just one example building. While it represents the most common type of institutional building constructed prior to 1980 in southern Iraq, both the geometry and orientation of the building as well as its construction will limit the applicability of the quantitative results presented to this one example. In addition, because the EnergyPlus model did not include occupant behavioral responses (such as manually operating windows or fans or creating their own shade) to thermal distress, occupants may reduce their level of dissatisfaction with regard to the indoor environment through such actions; thus, while the number of hours they experience discomfort would represent an overestimation of their level of dissatisfaction, it represents a conservative estimate of that amount. Third, embodied carbon of the retrofit materials was not quantified, meaning the full environmental benefit of the strategy is underestimated by the operational analysis alone. Fourth, outdoor weather data were sourced from a reference meteorological station located 153.6 km from the building site; a locally measured weather file would further improve model precision. Fifth, the analysis was conducted under current climate conditions; the performance of the proposed strategies under projected future climate scenarios for Al-Diwaniyah — where cooling degree days are expected to increase from 5,647 to 7,463 by 2080 under the IPCC A2 scenario [1], was not evaluated within the scope of the present work and represents a priority direction for future research.

Table 4. Comparison of energy reduction achieved by this study against published passive envelope retrofit studies for educational and comparable buildings in hot-arid climates

Study	Building type	Climate	Simulation method	Energy reduction
This study	University, Iraq	BWh hot-desert	DesignBuilder/EnergyPlus + TOPSIS	43.7%
El-Darwish & Gomaa [18]	University, Egypt	Hot-arid	EnergyPlus	33.0%
Al-Saadi et al. [19]	School, Oman	Hot-humid/dry	DesignBuilder/EnergyPlus	32–43%
Singh [20]	University, India	Hot-arid	EnergyPlus	23–33%
Sharif et al. [21]	Residential, Oman	Hot-arid	HAP	43.35%

5. Conclusion

This study demonstrates that sequential parametric simulation combined with five-criterion TOPSIS multi-criteria ranking provides an effective and academically rigorous framework for selecting building envelope retrofit strategies in hot-dry climates. Applied to Faculty of Arts Building (B) at Al-Qadisiyah University, the approach yields the following principal findings:

- A combination of no single envelope intervention will suffice to allow the building to meet the thermal comfort target specified by ASHRAE standard 55 ($PPD \leq 20\%$) in this climate;
- Only the combined scenario (S9) can achieve 19.98% PPD and therefore confirm that, for educational buildings in southern Iraq, multiple envelope retrofits are needed.
- Individually, the green roof (S5), has the largest impact on energy consumption. It reduced annual electricity usage by 8.8% and annual occupied discomfort hours by 28.4%. The green roof also outperformed all other insulation-only scenarios.
- The green roof had the shortest payback period of 24.1 years at the blended effective tariff rate for an individual retrofit and therefore represented the best financial option of all individual retrofit options.
- The optimal retrofit solution for both energy consumption and thermal comfort resulted in a reduction of 43.7% in annual electricity usage (from 306,421 to 172,604 kWh/yr) and a shift in the average annual PMV value from +0.52 to -0.11.
- The total installed cost was \$285,952 (374.6 million IQD).
- The calculated payback period for the optimal retrofit solution was 21.4 years using the blended effective tariff rate.
- Using a TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) ranking system that includes cost effectiveness as one of the five criteria (C5), confirmed that the retrofit strategy identified above represents the most preferred solution (closeness coefficient = 0.9113).
- This ranking shows that while spectrally-selective coatings and triple-glazed windows represent significant opportunities for improving thermal comfort and energy use performance, they ranked below lower-cost retrofit solutions as separate individual interventions. Therefore, these two technologies have the greatest opportunity to provide additional benefits when implemented as part of a comprehensive retrofit program.
- Finally, it should be noted that the significantly discounted tariff charged to consumers for subsidized electric power in Iraq (\$0.04 per kilowatt hour) results in longer pay-back times than what could be anticipated in similar climates where tariffs approach or exceed \$0.10 per kilowatt hour.

In addition to this research, future studies could explore embodied carbon accounting, life cycle costing analyses for projected climate changes in southern Iraq [1] and experimental verification of results from the green roof study by way of an instrumented field study. The hybrid approach using both the PIR plasterboard and the green roof with the lower cost solar coating (as opposed to the higher-cost triple glazing) is another potential "cost-intermediate" solution that would be worthy of separate modeling.

Acknowledgement

The authors gratefully acknowledge the Construction Unit of Al-Qadisiyah University for providing architectural drawings, building metered utility records, and unrestricted site access throughout the fourteen-month monitoring campaign. The authors also thank Meteoblue AG for weather data access.

Declaration of competing interests

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

Funding information

The authors declare that they received no funding from any financial organization to conduct this research.

Author contribution

Waleed S. Alawsey Yaik-Wah Lim: Conceptualization, methodology design, architectural analysis, data collection, and drafting of the manuscript. TIST Aziz: Theoretical framework development, heritage identity analysis, data interpretation, and critical revision of the manuscript. All authors contributed equally to the discussion of results, refinement of arguments, and final approval of the version to be published.

References

- [1] International Energy Agency, World Energy Outlook 2023. Paris, France: International Energy Agency, 2023.
- [2] Q. Al Yasiri and M. Szabó, "Energetic and thermal comfort assessment of phase change material passively incorporated building envelope in severe hot climate: An experimental study," *Applied Energy*, vol. 314, p. 118957, 2022. <https://doi.org/10.1016/j.apenergy.2022.118957>.
- [3] Q. Al-Yasiri and M. Szabó, "Building envelope-combined phase change material and thermal insulation for energy-effective buildings during harsh summer: Simulation-based analysis," *Energy for Sustainable Development*, vol. 72, pp. 326–339, 2023, <https://doi.org/10.1016/j.esd.2023.01.003>.
- [4] M. Santamouris and D. Kolokotsa, "Passive cooling dissipation techniques for buildings and other structures: The state of the art," *Energy and Buildings*, vol. 57, pp. 74–94, 2013. <https://doi.org/10.1016/j.enbuild.2012.11.002>
- [5] S. Aram, E. Ghaffarianhoseini, and A. Ghaffarianhoseini, "Utilising TOPSIS to select retrofit measures for optimising building energy consumption," *Sustainability*, vol. 14, no. 16, p. 10105, 2022.
- [6] M. Marzouk, M. El-Maraghy, and M. Metawie, "Assessing retrofit strategies for mosque buildings using TOPSIS," *Energy Reports*, vol. 9, pp. 1397–1414, 2023, <https://doi.org/10.1016/j.egyr.2022.12.073>.
- [7] ASHRAE Standard 55 2017, Thermal Environmental Conditions for Human Occupancy. Atlanta, GA, USA: ANSI/ASHRAE, 2017.
- [8] ISO 7730:2005, Ergonomics of the Thermal Environment — Analytical Determination and Interpretation of Thermal Comfort using Calculation of the PMV and PPD Indices. Geneva, Switzerland: ISO, 2005.

-
- [9] ASHRAE Guideline 14-2014, Measurement of Energy, Demand, and Water Savings. Atlanta, GA, USA: ASHRAE, 2014.
 - [10] DesignBuilder Software Ltd, DesignBuilder v7 User Guide. Stroud, U.K.: DesignBuilder Software Ltd, 2022.
 - [11] U.S. Department of Energy, EnergyPlus Engineering Reference v22. Washington, DC, USA: U.S. Department of Energy, 2022.
 - [12] Meteoblue AG, “Weather history and climate: Al-Diwaniyah,” Meteoblue. Accessed: Jan. 1, 2026. [Online]. Available: <https://www.meteoblue.com/en/weather/historyclimate/weatherarchive/al-diwanayah>.
 - [13] Saint-Gobain Glass, “COOL-LITE XTREME solar control glass technical datasheet,” Saint-Gobain Glass. Accessed: Feb. 1, 2026. [Online]. Available: <https://www.saint-gobain-glass.com>.
 - [14] WACKER Chemie AG, Thermally Conductive Silicones, Technical Bulletin TB2007-12. Munich, Germany: WACKER, 2018.
 - [15] Whole Building Design Guide, “Sun control and shading devices,” Whole Building Design Guide. Accessed: Jan. 1, 2026. [Online]. Available: <https://www.wbdg.org/resources/sun-control-and-shading-devices>.
 - [16] A. Almomani, R. M. Almeida, R. Vicente, and E. Barreira, “Critical review on the energy retrofitting trends in residential buildings of Arab Mashreq and Maghreb countries,” *Buildings*, vol. 14, no. 2, p. 338, 2024. <https://doi.org/10.3390/buildings14020338>.
 - [17] Silicon Laboratories Inc., Si7021-A20 I²C Humidity and Temperature Sensor Data Sheet, Rev. 1.4. Austin, TX, USA: Silicon Labs, 2022.
 - [18] I. El Darwish and M. Gomaa, “Retrofitting strategy for building envelopes to achieve energy efficiency,” *Alexandria Engineering Journal*, vol. 56, no. 4, pp. 579–589, 2017. <https://doi.org/10.1016/j.aej.2017.05.011>.
 - [19] H. A. Al-Dulaimi, W. S. Alawsey, and W. F. Hassan, “The myth of homogeneity and the dynamic reality in urban spaces,” *African Journal of Applied Research*, vol. 11, no. 5, pp. 494–510, 2025, doi: 10.26437/gdmyyp24.
 - [20] M. K. Singh, “Retrofit approach to improve energy efficiency in higher educational institution buildings in hot and arid climate,” *Journal of Cleaner Production*, vol. 413, p. 137488, 2023.
 - [21] S. A. Sharif, H. Hizam, M. Z. A. Kadir, and A. S. Al-Ogaili, “Transforming a typical residential building into net zero energy residential building through energy conservation strategies in hot and arid climate,” *Energy and Buildings*, vol. 283, p. 112831, 2023.
-