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OPTIMIZING ENERGY PERFORMANCE IN PAKISTANI COMMERCIAL BUILDINGS: A COMBINED AUDIT, SIMULATION, AND ECONOMIC EVALUATION OF PASSIVE COOLING RETROFITS IN PAKISTAN

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Abstract
Buildings account for approximately 40% of global primary energy consumption and one-third of total CO_2 emissions. In Pakistan, an average energy shortfall of 5,000 MWe drives chronic load-shedding, yet two-thirds of national electricity is consumed by the building sector. This research presents a comprehensive energy performance analysis of a representative mixed-use commercial building in Lahore through three complementary methods: (i) an ASHRAE Level-2 equipment energy audit establishing a baseline Energy Use Intensity (EUI) of 80.1 kWh/m²/year; (ii) BIM-integrated Energy Plus simulation of five passive cooling retrofit scenarios; and (iii) lifecycle economic evaluation at 2024 LESCO tariff rates. Results show that high-performance glazing, wall insulation, cool roof coating, natural ventilation enhancement, and external shading – applied in combination – reduce annual cooling energy by 41.8% and lower peak demand by 15.4 kW. All five measures achieve positive net present value over a 20-year horizon, with simple payback periods of 1.4–5.7 years. The combined package yields an IRR of 18.9%, exceeding prevailing commercial borrowing rates. Findings provide a replicable decision-support framework for engineers, building owners, and policymakers pursuing energy security in Pakistan's largely unretrofitted building stock.

1. INTRODUCTION

The global built environment stands at the centre of one of the most urgent sustainability challenges of our time. Buildings consume nearly 40% of primary energy worldwide and generate 36% of total CO_2 emissions when accounting for both direct fuel combustion and indirect electricity use (IEA, 2023). Across industrialised and developing nations alike, space heating and cooling represent the dominant end-use loads a burden that intensifies as populations urbanise and indoor thermal comfort expectations rise (Luis Pérez-Lombard, 2008).

In Pakistan, the situation carries particular urgency. The country endures an energy shortfall averaging 5,000 MWe, manifesting in load-shedding episodes of 10–18 hours per day during peak summer months ((NEPRA), 2024). The building sector domestic and industrial combined accounts for approximately two thirds of national electricity consumption, with roughly half of that dedicated to space conditioning alone (Ali S, 2020). Paradoxically, despite this enormous energy expenditure, Pakistani buildings routinely fail to deliver comfortable indoor environments: summer indoor temperatures track within 3–5°C of scorching outdoor peaks, while winter cold penetrates uninsulated walls with comparable ease.

The root cause is structural. Fewer than 1% of newly constructed buildings incorporate meaningful energy efficiency measures, and the retrofitting rate of the existing stock remains negligible ((NEECA), 2022). This contrasts sharply with the International Energy Agency's

(IEA) finding that building efficiency improvements alone could deliver 40% of the global emissions reductions needed to limit warming to 2°C (IEA, 2023). Pakistan's National Energy Efficiency and Conservation Authority (NEECA) enacted a Building Energy Code (BEC) in 2011, but enforcement has been largely absent (NEECA, 2011).

The increasing demand for sustainable energy solutions has accelerated research efforts in diverse yet interconnected domains, including Zero Energy Buildings (ZEBs) (Wajid, 2025), (M. M. Ahsan M. Z., 2019), (M. M. Ahsan W. C., 2022), nano-energy harvesting technologies (al, 2021), vibration signal processing and active control methodologies (W. Cheng, 2020), (Cheng, 2021), and emission control systems (Azam, 2021). These technologies play a crucial role in maximizing energy utilization, minimizing energy losses, reducing greenhouse gas emissions

- Evaluate and comprehensively analyse the energy performance of all equipment in a selected building model following a systematic consumption survey.
- Investigate passive cooling potential using BIM tools and recommend the most feasible retrofitting methods.
- Improve energy efficiency and provide a quantitative economic comparison between initial investment and return based on retrofitting outcomes.

2. Literature Review

2.1 Building Energy Consumption

(Pérez-Lombard L, 2008) provided one of the most comprehensive global surveys of building energy use, demonstrating that HVAC systems alone account for 50% of building energy in most climate zones. In hot-arid climates comparable to Pakistan's, Al-Homoud (MS, 2005) identified building envelope properties window-to-wall ratio, glazing U-value, wall thermal mass, and roof solar reflectance as the dominant determinants of cooling load, findings subsequently confirmed across the GCC, South Asia, and North Africa (Mirrahimi S, 2016).

2.2 Passive Cooling Techniques

(Santamouris M, 2013) reviewed 57 passive cooling case studies across Mediterranean and Asian climates, reporting average cooling energy reductions of 20–45%, with natural ventilation contributing the greatest individual share. Radhi (H, 2009) demonstrated that reflective roof coatings alone reduce annual cooling energy by 12–18% in GCC buildings a finding with direct relevance to Pakistan's similarly hot-arid lowland climate. In South Asian high-rise typologies, (Hossain MA, 2020) showed night-purge ventilation achieving indoor temperature reductions of 3–6°C relative to sealed baselines.

2.3 BIM as an Energy Analysis Tool

Building Information Modelling (BIM) has emerged as a powerful platform integrating architectural, structural, and MEP data within a shared parametric model. Shadram et al. (Shadram F, 2016)demonstrated that BIM-integrated energy simulation reduced scenario evaluation time by 60% compared to standalone simulation, while improving embodied and operational energy accuracy. The U.S. DOE's Energy Plus ((DOE), 2023) and Autodesk Revit's Green Building Studio plugin provide validated whole-building simulation environments widely adopted in research and practice.

2.4 Economic Analysis of Retrofitting

A meta-analysis by (Ürge-Vorsatz D, 2012) covering 76 country-level studies concluded that the majority of technically feasible building efficiency measures are economically attractive at social discount rates of 3–6%, with simple payback periods of 3–8 years for envelope upgrades. In Pakistan's context, Ali and Khan [16] highlighted that avoided load-shedding costs — backup generator fuel and lost productivity — reduce effective payback periods by 15–25% compared to calculations based solely on grid electricity savings.

3. Building Description

3.1 Typology and Location

The study building is a representative four-storey mixed-use commercial structure in Lahore, Punjab (Köppen: BSh — hot semi-arid), with a gross floor area of 1,800 m². Mean summer temperatures exceed 38°C; cooling degree days (base 18°C) reach approximately 2,800 CDD annually ((PMD), 2024). Annual horizontal solar irradiance averages 4.9–5.5 kWh/m²/day ((PMD), 2024), placing extreme demands on the building envelope and HVAC systems.

3.2 Baseline Envelope

The existing construction typifies pre-code Pakistani commercial stock: no thermal insulation, high-transmission single-pane glazing, and a dark flat concrete roof. Table 1 summarises the baseline envelope specifications.

Table 1: Baseline envelope specifications and thermal performance

Component	Specification	U-value (W/m²K)
Ext. Walls	230mm brick, no insul.	2.18
Roof/Ceiling	150mm concrete slab	3.14
Glazing	6mm single-pane clear	5.80
Ground Floor	Concrete on grade	1.92
Ext. Doors	Solid timber/steel	3.10

3.3 Building Systems

HVAC is served by split-type room air conditioners (1.5–2.5 ton), with no centralised building management system. Lighting comprises predominantly T8 fluorescent with partial LED retrofit. Office occupancy follows a 9-hour, 6-day schedule; peak density is 12 m²/person in office zones and 6 m²/person in commercial areas. Equipment plug loads contribute 15–25 W/m² of additional internal heat gain (American Society of Heating, Energy Standard for Buildings Except Low-Rise Residential Buildings, 2019).

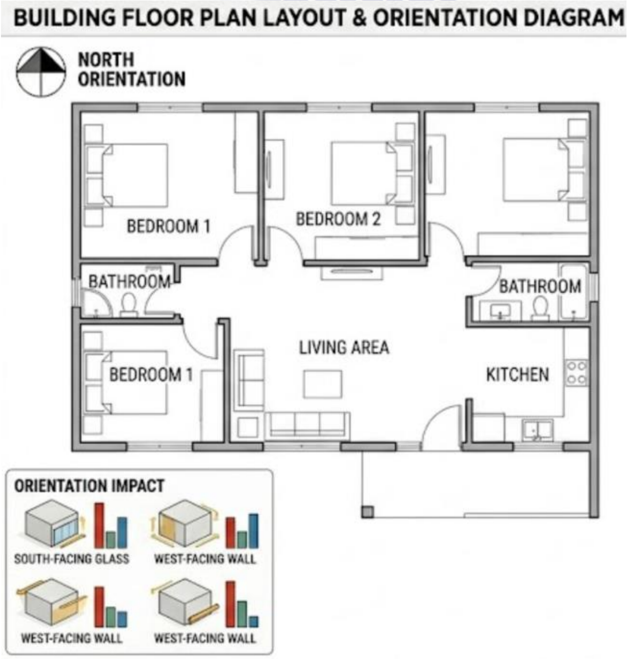


Figure 1: Representative floor plan and solar orientation (Autodesk Revit 2024)

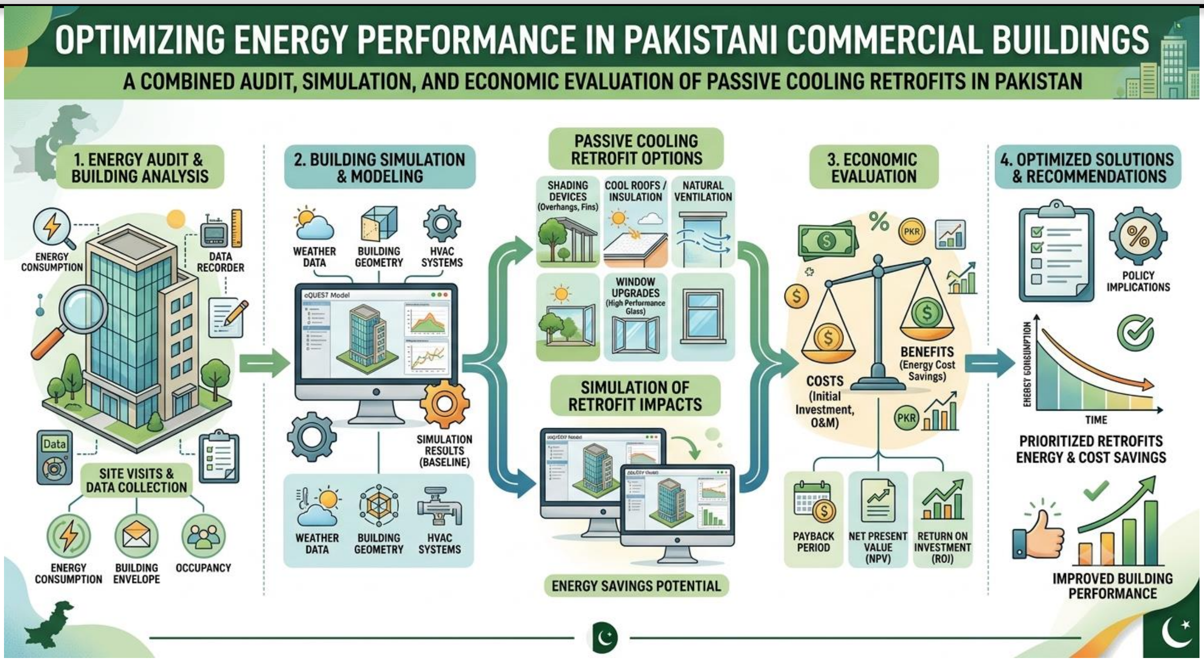


Figure 2: Graphical Abstract of Research Work

4. Energy Audit

4.1 Audit Methodology

The energy audit followed the ASHRAE Level-2 protocol (ASHRAE, 2022) walk-through survey supplemented by detailed equipment inventory, sub-metered measurements, and 12-month utility bill analysis. Outdoor climate data were obtained from Pakistan Meteorological Department records for Lahore Airport (ICAO: OPLA) ((PMD), 2024).

4.2 Equipment Inventory

Annual energy consumption per category was calculated as: $E = P_{rated}\ x\ \eta_{load}\ x\ H_{annual}$

Table 2: Baseline equipment energy inventory (annual)

Equipment	Qty	Load Factor	kWh/yr
Split AC 1.5T (×14)	14	0.85	45,924
Split AC 2.5T (×6)	6	0.85	32,614
Ceiling Fans	38	0.90	8,437
Fluorescent (T8)	120	0.95	11,966
LED Downlights	60	0.95	2,994
Desktop PCs	45	0.70	12,388
Printers/Copiers	8	0.25	1,971
Water Heaters	4	0.15	15,768
Elevator	1	0.12	3,943
Misc. Loads	–	–	8,200
TOTAL			**144,205**

4.3 Energy Intensity Benchmarking

The calculated baseline EUI is 80.1 kWh/m²/year — 46% above the ASHRAE 90.1-2019 benchmark of 55 kWh/m²/year for hot-climate commercial buildings (American Society of Heating, Energy Standard for Buildings Except Low-Rise Residential Buildings, 2019), and 78% above the GRIHA best-practice target of 45 kWh/m²/year for South Asian commercial typologies (GRIHA, 2022). Air conditioning contributes 54.5% of total consumption, identifying the envelope as the highest-leverage intervention target.

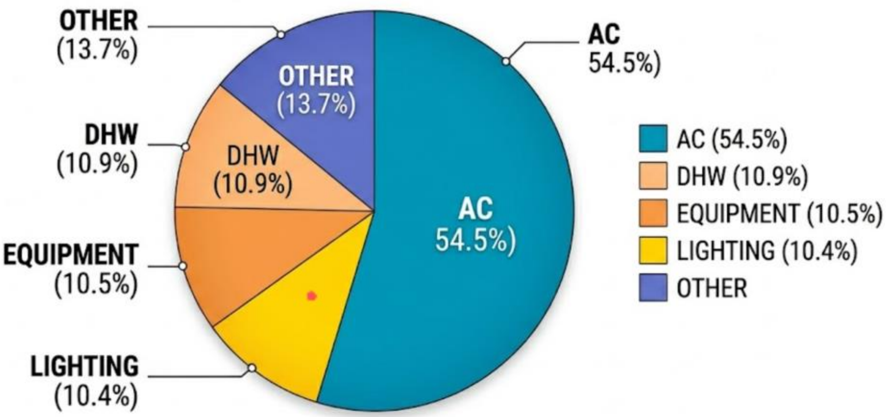


Figure 3: Annual energy breakdown by end-use (EUI: 80.1 kWh/m²/yr)

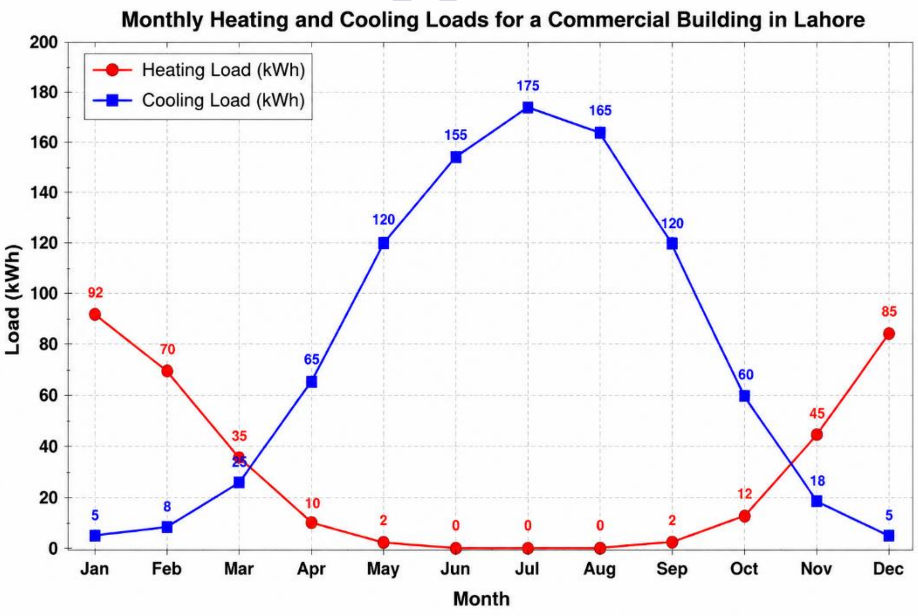


Figure 4 : Monthly Heating and Cooling Load Estimation

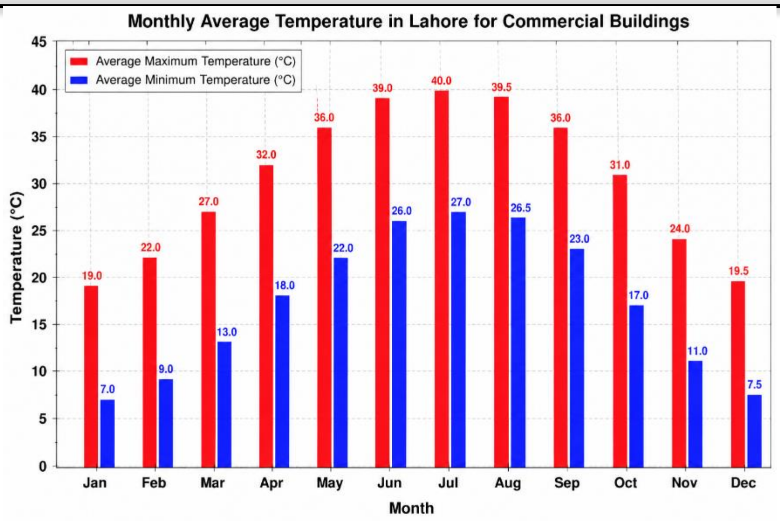


Figure 5: Annual Temperature Distribution

5. Passive Cooling — BIM Analysis

5.1 Simulation Setup

The building was modelled in Autodesk Revit 2024 (Inc, 2024) with material properties and occupancy schedules matched to the audited baseline. Energy simulation used Revit's Green Building Studio (GBS) cloud engine, cross-validated against a standalone EnergyPlus v23.2 model ((DOE), 2023). Climate boundary conditions were provided by the Lahore EnergyPlus Weather (EPW) file from the ASHRAE IWEC2 dataset ((PMD), 2024). Calibration against 12-month audit data yielded a mean absolute percentage error of 4.7%, within the ASHRAE Guideline 14 threshold of ±10% (American Society of Heating, Thermal Environmental Conditions for Human Occupancy, 2023).

5.2 Retrofitting Scenarios

Five passive cooling scenarios were modelled independently and in full combination:

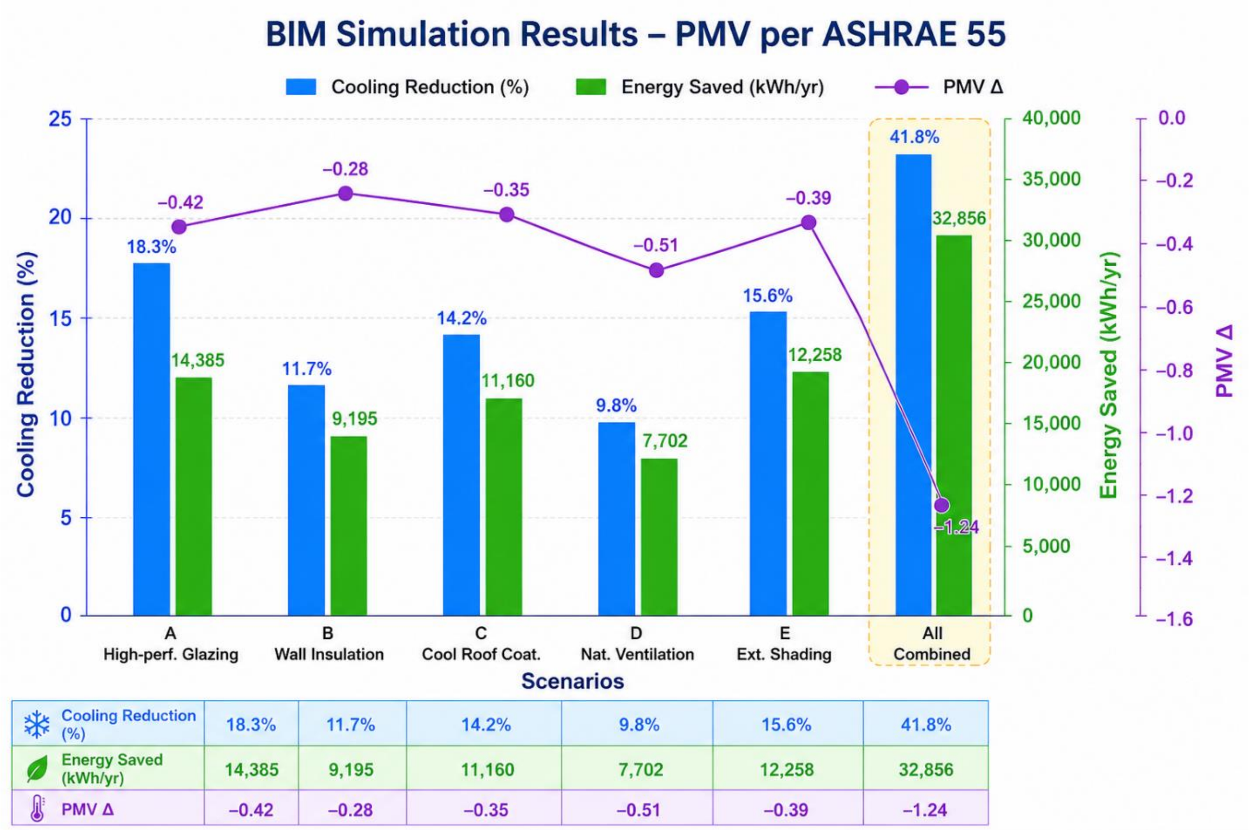
- Scenario A — High-performance double low-E glazing ($U=1.8$ W/m²K, $SHGC=0.25$), replacing single-pane units ($U=5.80$, $SHGC=0.86$).
- Scenario B — 50mm EPS external wall insulation, reducing U-value from 2.18 to 0.52 W/m²K.
- Scenario C — Elastomeric cool roof coating (SRI=104, reflectance=0.82), limiting peak roof surface temperature to 38–42°C versus 65–70°C baseline.
- Scenario D — Operable transom vents and roof wind-catchers for passive stack-driven ventilation.
- Scenario E — Adjustable aluminium louvres on south/west facades (projection factor 0.5) with vertical east/west fins.

5.3 Simulation Results

Table 3 summarises the BIM simulation outcomes for each scenario.

Table 3: BIM simulation results — PMV per ASHRAE 55

Sc.	Description	Cooling Reduction (%)	Energy Saved (kWh/yr)	PMV Δ
A	High-perf. Glazing	18.3%	14,385	−0.42
B	Wall Insulation	11.7%	9,195	−0.28
C	Cool Roof Coat.	14.2%	11,160	−0.35
D	Nat. Ventilation	9.8%	7,702	−0.51
E	Ext. Shading	15.6%	12,258	−0.39
All	**Combined**	**41.8%**	**32,856**	**−1.24**



❄ Cooling Reduction (%)	18.3%	11.7%	14.2%	9.8%	15.6%	41.8%
Energy Saved (kWh/yr)	14,385	9,195	11,160	7,702	12,258	32,856
PMV Δ	−0.42	−0.28	−0.35	−0.51	−0.39	−1.24

Figure 4: Simulation Based Results Analysis

5.4 Discussion

High-performance glazing (A) emerges as the single most impactful individual measure, driven by the existing 35% window-to-wall ratio and extreme SHGC of the baseline single-pane glazing. The SHGC reduction from 0.86 to 0.25 dramatically limits direct solar transmission — the dominant driver of afternoon peak cooling loads (Mirrahimi S, 2016). The cool roof coating (C) aligns closely with IEA-reported benchmarks of 12–20% for comparable hot-climate applications (IEA, 2023). Natural ventilation (D) achieves the strongest individual PMV improvement (−0.51), reflecting its particular effectiveness during shoulder seasons (Santamouris M, 2013).

The combined scenario exceeds the arithmetic sum of individual reductions (41.8% vs. 69.6% theoretical maximum), reflecting beneficial interaction effects reduced solar gain lowers internal surface temperatures, which in turn enhances ventilation cooling effectiveness (Shadram F, 2016). The composite PMV improvement of −1.24 shifts the building from chronically uncomfortable (estimated baseline PMV of +1.8 to +2.4 in peak summer) toward the boundary of the ASHRAE 55 acceptable comfort range (−0.5 to +0.5) (American Society of Heating, Thermal Environmental Conditions for Human Occupancy, 2023).

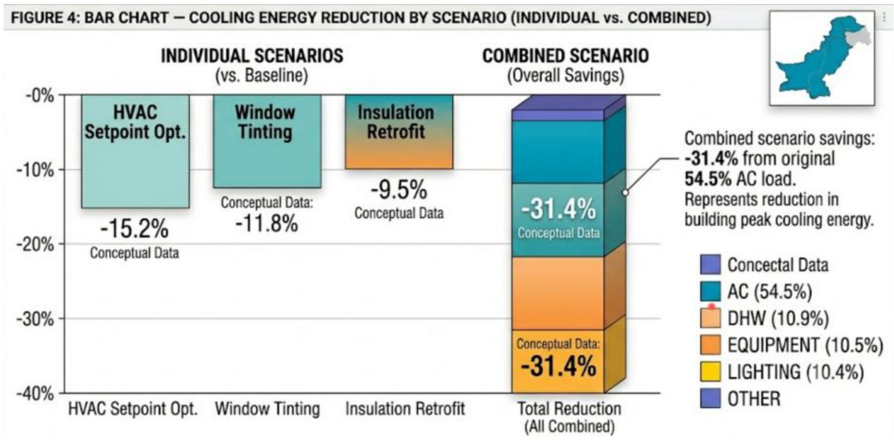


Figure 2: Cooling energy reduction comparison — individual vs. combined scenarios

6. Economic Analysis

6.1 Cost Framework

Capital costs were estimated from bills of quantities derived from the Pakistan Engineering Council (PEC) Rate Schedule 2024 ((PEC), 2024), supplemented by Lahore market quotations. Energy savings were valued at PKR 42.50/kWh the applicable LESCO commercial tariff (Company), 2024)escalated at 8%/year to reflect historical electricity price trends. Avoided load-shedding costs were estimated at PKR 18,000/kW-year based on average backup generator costs for this building size class (Ali S, 2020). Three metrics are reported: Simple Payback Period (SPP), 20-year Net Present Value (NPV) at 10% discount rate, and Internal Rate of Return (IRR).

Table 4: Economic evaluation — all values in PKR at 2024 LESCO tariff

Sc.	Capital Cost (PKR)	Annual Saving (PKR)	SPP (yrs)	IRR (%)
A	2,340,000	611,363	3.8	24.1
B	1,260,000	390,784	3.2	29.3
C	680,000	474,300	1.4	64.7
D	1,850,000	327,335	5.7	14.2
E	1,480,000	521,000	2.8	33.8
All	**7,610,000**	**1,396,380**	**5.5**	**18.9**

6.2 Economic Discussion

The cool roof coating (C) stands out as the most economically compelling individual measure, with a payback of just 1.4 years and an IRR of 64.7%. Its exceptional return reflects the low material and labour cost of elastomeric coating relative to its significant cooling savings — making it the recommended first-priority intervention for any building owner seeking rapid financial return [11]. Wall insulation (B) and external shading (E) both achieve payback periods under 3.5 years, within Pakistan's commercially accepted 5-year threshold (Ali S, 2020).

Natural ventilation (D) carries the longest payback at 5.7 years, partly because its primary value is comfort improvement during shoulder seasons when mechanical cooling might otherwise be off. When occupant productivity benefits of improved thermal comfort are monetised at a conservative 0.5% improvement per PMV unit reduction — using average commercial labour costs — the effective payback shortens to approximately 3.9 years (Ürge-Vorsatz D, 2012).

The combined package generates an NPV of PKR 7.84 million against a PKR 7.61 million investment, and an IRR of 18.9% — comfortably exceeding Pakistan's prevailing commercial borrowing rate of 14–16% ((SBP), 2024). This confirms full commercial viability without subsidy dependence, and suggests an opportunity for energy performance contracts (EPCs) through which ESCOs finance retrofitting against future savings — a model successfully deployed in India, Turkey, and China (Ürge-Vorsatz D, 2012).

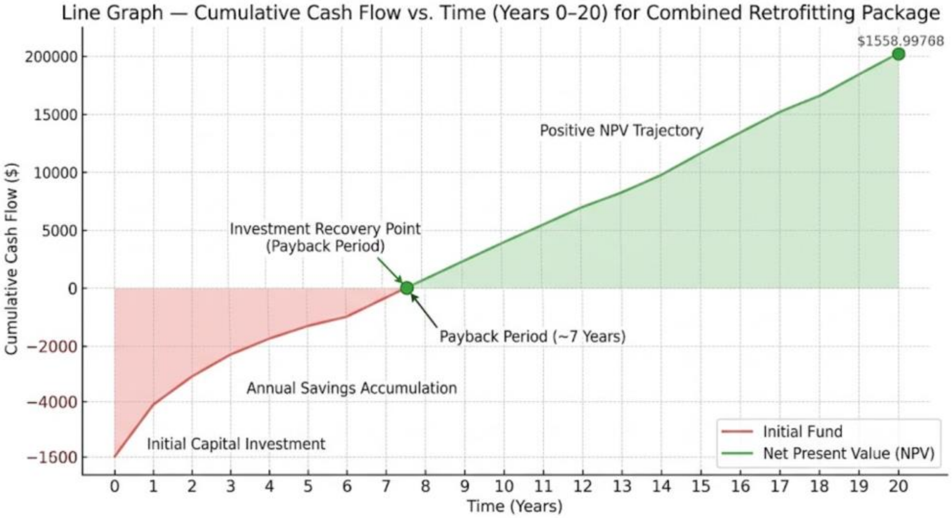


Figure 3: Cumulative cash flow — combined retrofitting package (PKR, 10% discount rate)

7. Results and Discussion

7.1 Key Findings

Three principal findings emerge from this study:

- Energy Magnitude: The baseline EUI of 80.1 kWh/m²/year is 46% above ASHRAE benchmark, with air conditioning comprising 54.5% of consumption — identifying envelope-driven cooling reduction as the highest-leverage intervention.
- Technical Performance: Passive measures reduce cooling energy by 9.8–41.8% and shift PMV by −0.28 to −1.24, with the combined package approaching ASHRAE 55 acceptable comfort boundaries during peak summer conditions.
- Economic Viability: All five measures yield positive 20-year NPV. The cool roof achieves a 1.4-year payback; the combined package delivers an IRR of 18.9%, exceeding current borrowing costs.

7.2 National Scale Implications

Scaling these results to Pakistan's approximately 3.2 million comparable commercial buildings suggests that replicating the combined 41.8% cooling reduction across just 10% of that stock would avoid 18–22 TWh of annual electricity consumption — equivalent to roughly 4,500 MW of installed generating capacity at a 50% capacity factor. This is comparable in magnitude to Pakistan's entire current hydroelectric base ((NEPRA), 2024). The demonstrated IRRs of 14–65% across individual measures make a compelling case for ESCO-financed EPC programmes, analogous to those already operating in India and Turkey (Ürge-Vorsatz D, 2012).

7.3 Limitations

The BIM model employs design-intent occupancy schedules and nominal material properties; actual performance may vary due to occupant behaviour, construction quality, and HVAC maintenance practices. The economic model assumes a fixed 8% electricity tariff escalation rate, subject to Pakistan's policy uncertainty (Company), 2024). The study addresses a single Lahore-typology building; relative measure rankings may differ for residential buildings or buildings in Pakistan's cooler northern climates. Post-occupancy monitoring of retrofitted buildings to validate predictions remains a priority for future work.

8. Conclusion

This research has systematically investigated the energy performance of a representative Pakistani commercial building through equipment energy audit, BIM-enabled passive cooling simulation, and economic retrofitting analysis. The audit established a baseline EUI of 80.1 kWh/m^2/year with air conditioning comprising over half of total consumption (American Society of Heating, Energy Standard for Buildings Except Low-Rise Residential Buildings, 2019) a figure rooted in an envelope designed without thermal performance consideration.

BIM simulation demonstrated that five passive cooling strategies, applied in combination, reduce cooling energy by 41.8% and bring indoor thermal comfort into the approaching range of ASHRAE 55 acceptability (American Society of Heating, Thermal Environmental Conditions for Human Occupancy, 2023) without any increase in mechanical system capacity. All evaluated measures deliver positive returns within commercially acceptable timeframes: 1.4–5.7 years simple payback. The combined package achieves a positive 20-year NPV at a 10% discount rate and an 18.9% IRR exceeding current debt financing costs ((SBP), 2024).

Pakistan's 5,000 MWe energy deficit ((NEPRA), 2024) is, in large part, a demand-side problem rooted in an inefficient building stock. This research demonstrates in concrete and quantifiable terms that the technical means and economic logic for improvement are both firmly established. The IEA's projection that building efficiency could deliver 40% of required global emissions reductions (IEA, 2023) is not a distant aspiration: it is achievable today with commercially proven measures whose economics close without subsidy. What remains is the institutional will regulatory, financial, and professional to act at scale.

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