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Simulation-Based Thermal Performance Assessment and Economic Evaluation of Passive Retrofitting Strategies for Energy Load Reduction in an Existing Institutional Building

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Abstract - **Buildings account for a significant portion of global energy demand and carbon emissions, with space heating and cooling being primary contributors to operational energy use. Despite growing awareness of energy conservation imperatives, the integration of energy-efficient measures in newly constructed buildings remains limited, underscoring the substantial improvement potential within the existing building stock. This study focuses on Pakistan, where persistent energy shortages and frequent load shedding necessitate immediate and practical efficiency interventions. The research evaluates the effectiveness of passive retrofitting strategies in enhancing the thermal performance of an existing institutional building. A simulation-based approach was employed using Autodesk Ecotect 2011 to assess baseline thermal loads and quantify the impact of selected retrofit measures. Key interventions, including insulation enhancement, window upgrades, optimization of window-to-wall ratio, and energy-efficient lighting, were analyzed individually and collectively to determine their influence on annual thermal load reduction. An economic assessment was also conducted to evaluate feasibility based on cost and projected energy savings. The findings demonstrate that targeted passive retrofitting can significantly reduce building thermal loads while improving indoor comfort and economic viability. By incorporating climate-responsive strategies tailored to local conditions, this study provides practical recommendations to strengthen energy performance across Pakistan's building sector and supports broader sustainable development objectives.**
Keywords: **Passive Retrofitting, Thermal Performance, Energy Efficiency, Building Simulation, Climate-Responsive Design**

I. INTRODUCTION

Rising global energy demand, the depletion of fossil fuel reserves, and the intensifying impacts of climate change have collectively shifted international focus toward energy-efficient technologies, systems, and infrastructure [1]. As a result, the promotion of renewable energy resources and the improvement of energy efficiency have become foundational components of national energy strategies and regulatory frameworks worldwide. The building sector constitutes a substantial share of global energy use, accounting for nearly half of worldwide electricity consumption and approximately one-third of total carbon emissions [2]. A significant portion of building electricity demand is attributed to space heating and cooling, which represents 25–40% of total national energy consumption in many countries [3]. Despite this considerable energy footprint, only about 1% of newly constructed buildings incorporate advanced energy-efficiency measures, highlighting the vast untapped potential for improving the performance of the existing building stock [4]. According to the International Energy Agency (IEA), enhancing building efficiency can yield substantial reductions in overall energy consumption [5].

Consequently, contemporary research prioritizes both the adoption of renewable energy systems and the enhancement of energy performance in existing buildings to mitigate emissions and curtail energy demand. Retrofitting the current building stock presents a practical and sustainable pathway for improving environmental performance within the sector. Energy retrofitting-encompassing operational improvements, structural modifications, and upgrades to energy-intensive systems-offers multiple long-term benefits, including improved indoor environmental quality, enhanced thermal comfort, reduced operational costs, and lower maintenance requirements [6].

From an environmental perspective, particularly concerning material usage and construction waste, retrofitting has proven to be more sustainable than demolition followed by reconstruction [7].

Given that a large proportion of existing buildings is expected to remain operational for the next 50 to 100 years, neglecting retrofitting initiatives would substantially undermine the objectives of green building design and climate mitigation strategies. Accordingly, extensive efforts have been directed toward developing and implementing retrofit solutions to enhance the energy performance of existing structures. Simulation-based investigations further support this approach. One study evaluating daylighting strategies in office buildings examined optimal window-to-wall ratios and glazing configurations. The findings indicated that reducing the window-to-wall ratio from 50% to 30% significantly decreased energy consumption, while optimized glazing systems reduced heating loads by up to 83% [8]. Another investigation conducted in Dubai's hot climate assessed passive cooling strategies for residential buildings. By improving natural ventilation, incorporating shading devices to limit solar heat gains, and modifying glazing characteristics, researchers achieved notable reductions in cooling loads.

Additionally, Olufolahan and Michael examined the applications of Building Information Modeling (BIM) and demonstrated, through simulation of a selected case study building, that BIM provides critical insights for optimizing building orientation, envelope design, and overall performance [9]. In Pakistan, the energy crisis remains acute, with an average shortfall of approximately 5000 MWe, resulting in frequent power outages during both summer and winter [10].

The building sector-encompassing residential and industrial facilities-accounts for nearly two-thirds of national energy consumption, with roughly half allocated to heating and cooling demands. Paradoxically, despite this high energy utilization, many buildings fail to maintain adequate indoor thermal comfort under extreme climatic conditions, revealing pronounced inefficiencies in design and operation.

Retrofitting existing buildings and promoting energy-efficient construction practices are therefore imperative. Although numerous retrofitting strategies have demonstrated measurable benefits, existing guidelines often provide generalized recommendations that may not adequately address project-specific requirements. Accordingly, this study examines the performance of passive cooling strategies using BIM-based simulation tools and identifies the most feasible retrofitting techniques for local application.

In addition to evaluating energy performance improvements, the research incorporates an economic assessment that compares initial capital investments with projected returns derived from quantitative energy savings. The analysis begins with an evaluation of baseline energy consumption, followed by the implementation of selected retrofitting measures and a detailed discussion of their respective impacts. The building sector is among the largest energy-consuming domains globally, accounting for nearly half of worldwide electricity demand and approximately one-third of total carbon emissions [11].

Although retrofitting existing buildings and promoting energy-efficient construction are widely recognized as viable solutions, current retrofitting guidelines generally provide broad recommendations that lack project-specific adaptability. This gap underscores the need for a systematic, performance-based evaluation of retrofitting strategies tailored to local climatic, technical, and economic conditions, particularly within the context of Pakistan's energy crisis.

II. METHODOLOGY

This study quantifies the impact of thermal retrofitting measures on the energy performance of a non-residential (institutional) building. A conventional, non-integrated retrofit strategy was adopted due to its comparatively lower initial capital investment, despite integrated system approaches generally offering greater long-term energy reductions but longer payback periods. The methodological framework is based on a comparative analysis between the existing building configuration (baseline case) and the building after the application of selected retrofitting measures.

A dynamic simulation study was performed using Autodesk Ecotect 2011 to evaluate thermal performance and estimate annual heating and cooling loads. The software supports comprehensive Building Information Modeling (BIM)-based analyses, including thermal behavior, daylighting, shading, acoustics, and cost assessment, making it suitable for modeling buildings with varying geometrical and operational complexities [12]. The methodology was executed in two primary stages:

Stage 1: Baseline Thermal Analysis

1. Development of a three-dimensional BIM model of the existing building.
2. Determination of annual energy consumption through detailed thermal load calculations.
3. Solar access analysis to identify envelope components responsible for maximum heat gains during summer and maximum heat losses during winter.

Stage 2: Retrofitting and Economic Evaluation

1. Implementation of selected thermal retrofitting strategies within the BIM model.
2. Recalculation of annual heating and cooling loads to quantify energy savings.
3. Cost estimation of each retrofit measure.
4. Determination of payback period based on initial investment and projected annual energy savings.

This structured approach enables a performance-based assessment of each retrofit option in terms of both energy efficiency and economic feasibility.

A. Building Details

The selected case study building is a single-story institutional facility with a total covered area of 1,360 square feet. The longitudinal axis of the building is oriented along the south–north direction, influencing solar exposure and thermal behavior. Detailed architectural and construction specifications are provided in Table I.

TABLE I BUILDING DESCRIPTION

S.No.	Parameter	Value/Description
1	Building Orientation	Longitudinal Axis Facing South-North
2	Number of stories	1
3	Total Area	1360 ft^2
4	Total Volume	16320 ft^3
5	Total Area of exposed Walls	543 ft^2
6	Total Windows Area	68 ft^2
7	Floor Height	12 ft
8	Window to Wall Ratio	12.5%
9	Indoor Design Temperature	26 ^{o}C
10	Operating Schedule	9am- 8pm
11	Occupancies	8 Persons
12	Infiltration Rate	0.25 ACH
13	Lighting level	400 lux
14	Appliances	3

B. Energy Performance Simulation Modelling

The building's energy performance was simulated using Autodesk Ecotect, a comprehensive graphical interface built around dynamic thermal and energy simulation engines. This platform enables detailed modeling of building geometry, envelope characteristics, internal gains, occupancy schedules, and HVAC configurations. Within the input design parameters, zone-specific lighting requirements and target illuminance levels were incorporated to accurately represent lighting performance. These values were entered directly into the model to define the lighting design levels in accordance with Autodesk Ecotect's simulation framework.

Because lighting operation within the building is predominantly occupancy-driven, lighting schedules were assumed to correlate closely with zone occupancy patterns. Occupancy profiles were estimated based on available energy consumption data, which served as indirect indicators of occupant presence and behavioral patterns. The HVAC system was modeled using the basic mode in Autodesk Ecotect.

This approach simplifies system representation by avoiding detailed component-level characterization, thereby reducing computational complexity. Instead, the basic mode applies an idealized load calculation methodology with fixed performance parameters defined by the modeler. Energy consumption associated with auxiliary components such as pumps and fans can be specified individually, using available building management system (BMS) data where applicable.

Although this simplified HVAC modeling approach may not provide the same level of accuracy as detailed system modeling, it ensures internal consistency across all simulated cases. Consequently, while absolute energy values may carry some uncertainty, the relative variations in energy consumption between baseline and retrofit scenarios remain reliable due to uniform HVAC model assumptions. The MP Hall building model developed in Autodesk Ecotect is illustrated in Figure 1.

C. Simulation Modelling of the Building

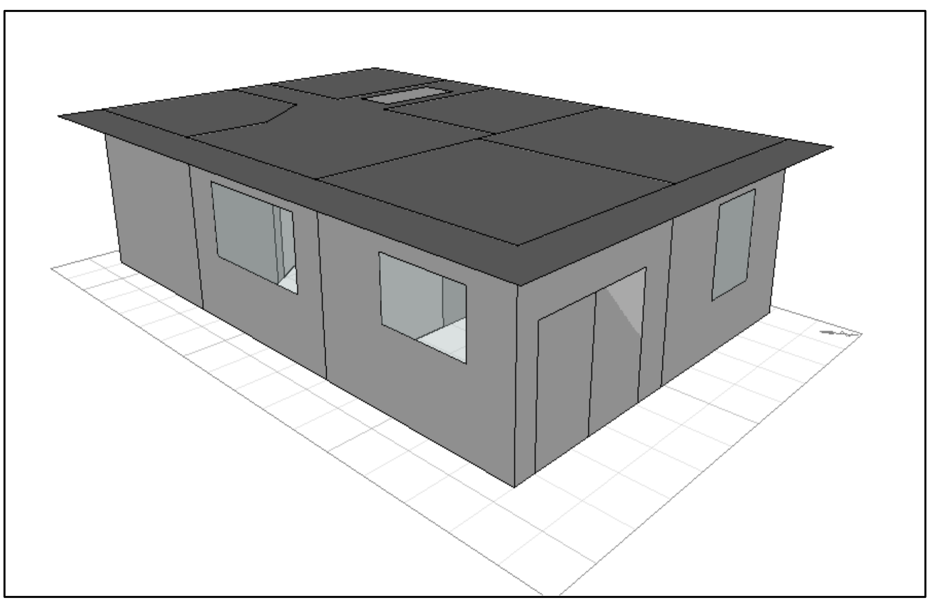

Fig.1 3D Model of the Building Designed on Autodesk Ecotect Software

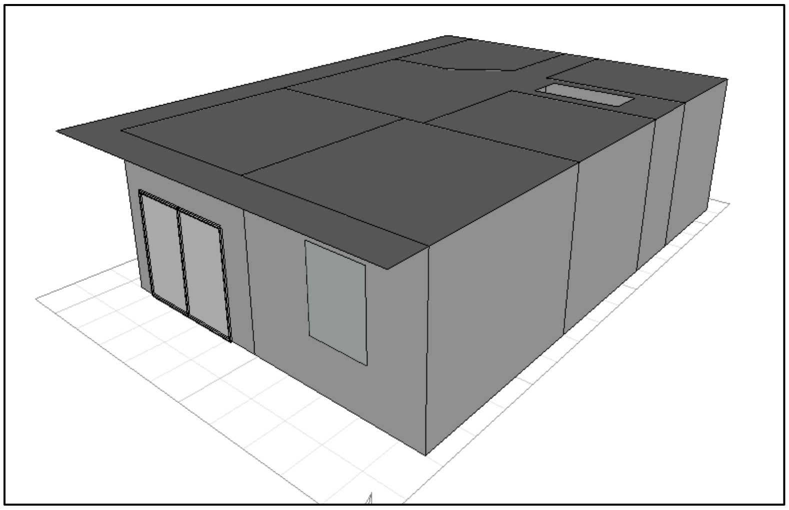

Fig.2 3D Model of the Building Designed on Autodesk Ecotect Software

D. Applying Retrofitting Techniques

Following the assessment of the building's baseline performance, a series of targeted retrofitting interventions were implemented to reduce thermal loads and improve overall energy efficiency. Each measure was selected based on its technical feasibility, cost-effectiveness, and potential impact on heating and cooling demand.

E. Optimization Measures Implemented

The retrofitting strategy included the following interventions:

1. Upgrading from single-glazed to double-glazed windows
2. Optimization of the window-to-wall ratio (WWR)
3. Installation of thermal insulation
   a. Selection of the most effective insulation material
   b. Determination of optimal insulation thickness
4. Implementation of energy-efficient lighting systems

All existing single-glazed windows were replaced with brown-tinted double-glazed units while maintaining other design parameters constant. Double glazing was selected due to its improved thermal resistance (lower U-value), reduced conductive heat transfer, and enhanced indoor thermal comfort. The window-to-wall ratio was optimized in accordance with the recommendations of the Building Energy Code of Pakistan to balance daylight penetration with minimized solar heat gains and conductive losses [13]. Envelope insulation was introduced to reduce unwanted heat transfer through walls and roofing assemblies. Both insulation material type and thickness were evaluated to determine the configuration that provided the highest thermal resistance with economic feasibility. In addition, conventional 40 W fluorescent tube lights were replaced with 25 W LED luminaires delivering equivalent luminous intensity. This substitution reduced internal heat gains from lighting while simultaneously lowering electrical energy consumption.

F. Simulation Approach

Each retrofit measure was initially simulated independently while keeping all other building parameters constant to isolate and quantify its individual impact on annual energy consumption. Subsequently, a combined simulation incorporating all selected modifications was performed. The results of these retrofitted scenarios were then systematically compared with the baseline design to evaluate cumulative energy savings and performance improvements.

III RESULTS AND DISCUSSION

A. Monthly Energy Consumption of Baseline Design (Before Using Retrofitting Technique)

TABLE II CONSUMPTION SLAB AND ENERGY CHARGES

Consumption Range (kWh)	Energy Charge (Rs/kWh)
$0 \le E \le 100$	7.7
$100 < E \le 200$	13.7
$E > 200$	19.4

Where:
E = Monthly energy consumption (kWh)

Electricity cost was calculated using the prevailing progressive tariff structure. The unit energy charges were Rs 7.7/kWh for the first 100 kWh, Rs 13.7/kWh for the next 100 kWh, and Rs 19.4/kWh for consumption exceeding 200 kWh.

TABLE III EQUIPMENT, TOTAL UNITS AND CHARGES

Equipment	Energy Consumption (kWh/day)	Cost (Rs/day)
Fans	5	35
Lighting	4	28
Pump	1.1	7.7
Air Conditioner	15	105
Refrigerator	4	28
Total	29.1	224.07

TABLE IV EQUIPMENT, TOTAL UNITS, OPERATING HOURS

Equipment	Number	Power (kW)	Hours/day	Daily Energy (kWh)	Monthly Energy (kWh)
Fans	3	0.075	15	3.375	101.25
LED	10	0.012	6	0.72	21.6
Pump	1	0.6	0.5	0.3	9
AC	2	3	4	24	720
Refrigerator	1	0.2	12	2.4	72
Total				30.795	923.85

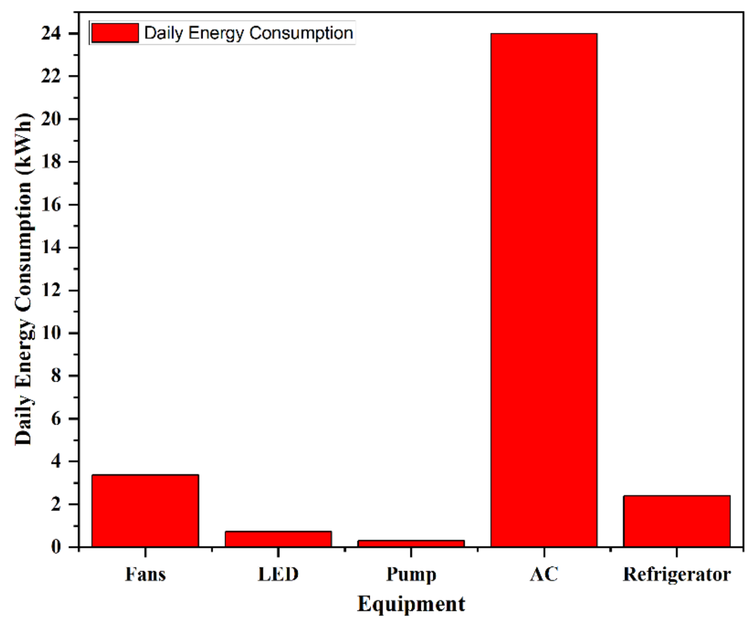

Fig.3 Daily Energy Consumption (Before Retrofitting)

B. Replacing Energy Savers with LED

Energy consumption of single LED = 7 W
Number of LED = 9
Total connected load = 9 × 7 = 63 W = 0.063 kW
Energy Consumption of total LED (for 1 hour) = 0.063 × 1 = 0.063 kWh
Energy Consumption of total LED (for 6 hours per day) = 0.063 × 6 = 0.378 kWh
Monthly Energy Consumption of total LED (31 days) = 0.378 × 31 = 11.718 kWh
Monthly Energy cost of all LED lightings = 11.718 × 7.7 = Rs 90.23
After implementing monthly savings = 293.08 − 90.23 = Rs 202.85
Cost of per LED as well as installation = Rs 350
Total cost of all LED as well as installation = 350×9 = Rs 3150
Payback period = 3150 / 202.85 = 15.53 ≈ 16 months
If tariff = 7.7 Rs/kWh, then:
Monthly LED cost = Rs 90.23
Monthly savings = Rs 202.85
Payback period ≈ 16 months

C. Replacing Old Fans with Advanced Energy Efficiency Bldc Motor Fans

Energy consumption of single BLDC motor fan = 32 W
Number of fans = 3
Connected Load Total = 32 × 3 = 96 W = 0.096 kW
Energy Consumption of total fans (for 1 hour) = 0.096 × 1 = 0.096 kWh
Energy Consumption of total fans (for 1 day, 8 hours) = 0.096 × 8 = 0.768 kWh
Monthly Energy Consumption of total fans (31 days) = 0.768 × 31 = 23.81 kWh
Monthly Energy cost of all fans = 23.81 × 7.7 = Rs 183.34
To calculate monthly savings, we must subtract the new BLDC fan cost from the old fan cost.
From your earlier data (old fans):
Old fans energy consumption per day = 3 × 0.075 × 15 = 3.375 kWh
Old fans monthly energy (31 days) = 3.375 × 31 = 104.63 kWh
Old fans monthly cost = 104.63 × 7.7 = Rs 805.65
New BLDC fans monthly cost = Rs 183.34
After implementing monthly savings would be:
Monthly savings = 805.65 − 183.34 = Rs 622.31
So, after implementing monthly savings would be Rs 622.31.
Monthly energy cost reduction = 77.24% (≈ 77%).

D. Monthly Energy Consumption of Baseline Design (After Using Retrofitting Technique)

TABLE V EQUIPMENT, TOTAL UNITS, OPERATING HOURS

Equipment	Number	Power (kW)	Operating Hours (Daily)	Daily Energy (kWh)	Monthly Energy (kWh)
Fans	3	0.075	8	1.80	55.80
LED	8	0.012	4	0.384	11.904
Pump	1	0.6	0.5	0.30	9.30
AC	1	3	4	12.00	372.00
Refrigerator	1	0.2	10	2.00	62.00
Total				16.484	511.004

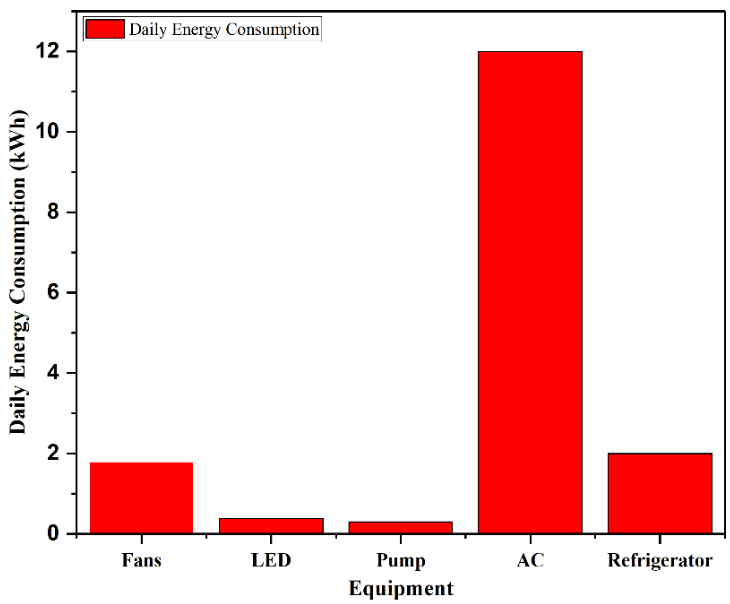

Fig.4 Daily Energy Consumption (After Retrofitting)

E. Retrofitted Simulation Results

Combined Impact of All Techniques on Heating and Cooling Loads

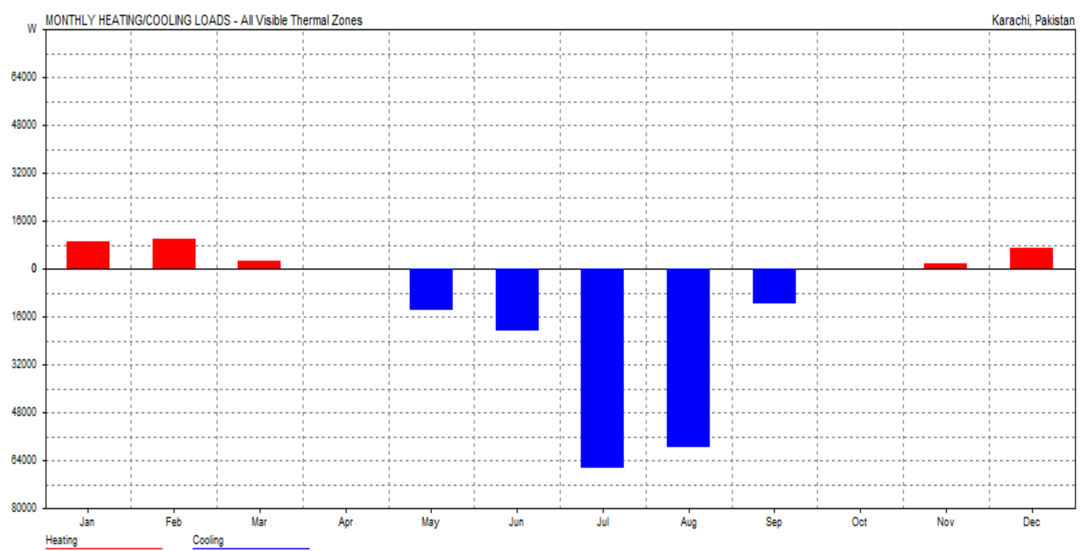

Fig.5 Monthly Heating/Cooling Loads

F. Retrofitting Techniques

Building retrofitting encompasses a range of technical interventions designed to improve energy performance, enhance occupant comfort, and reduce the environmental footprint of existing structures. These strategies are grounded in principles of thermodynamics, heat transfer, fluid mechanics, and sustainable building science. The major techniques and their theoretical foundations are outlined below.

1. *Insulation Enhancement:* Thermal insulation is one of the most effective retrofit measures for minimizing unwanted heat transfer through the building envelope. The governing principle is the reduction of heat flow via conduction, convection, and radiation. By incorporating materials with low thermal conductivity (k-value)-such as fiberglass, mineral wool, foam boards, or cellulose-the overall thermal resistance (R-value) of walls, roofs, and floors increases. This reduces heating loads in winter and cooling loads in summer, thereby lowering annual energy consumption.
2. *Air Sealing:* Uncontrolled air infiltration and exfiltration significantly contribute to energy losses. Air sealing targets leakage pathways such as cracks, joints, window frames, door perimeters, service penetrations, and duct connections. The theoretical basis lies in minimizing pressure-driven airflow and convective heat transfer across the building envelope. Techniques including caulking, weatherstripping, and sealant application improve airtightness, enhance thermal stability, and reduce the burden on HVAC systems.
3. *Window and Door Upgrades:* Fenestration systems critically influence thermal performance due to their comparatively high heat transfer coefficients. Retrofitting may involve replacing single-glazed units with double- or triple-glazed assemblies incorporating low-emissivity (low-E) coatings and insulated frames. The governing principle is to reduce conductive and radiative heat transfer (lower U-value) while optimizing the solar heat gain coefficient (SHGC). Properly designed upgrades balance daylight admission with minimized heat gains and losses, thereby achieving greater energy performance along with improved comfort levels.
4. *HVAC System Optimization:* Heating, Ventilation, and Air Conditioning (HVAC) systems account for a considerable portion of overall building energy use. Retrofitting may include equipment upgrades, duct sealing, improved insulation of piping, implementation of variable-speed drives (VSDs), programmable thermostats, and zoning controls. The theoretical framework involves improving system efficiency (COP/EER), optimizing air distribution, and reducing parasitic energy losses. Enhanced control strategies improve load matching and reduce unnecessary energy expenditure while maintaining acceptable indoor air quality.
5. *Lighting System Upgrades:* Lighting retrofits typically involve replacing incandescent or conventional fluorescent fixtures with high-efficiency LED systems. The theoretical principle is based on increasing luminous efficacy (lumens per watt) while reducing internal heat gains. LEDs provide reduced energy consumption, extended operational lifespan, reduced maintenance, and improved lighting quality. Lower internal heat gains from lighting also indirectly reduce cooling loads in conditioned spaces.
6. *Renewable Energy Integration:* The incorporation of renewable energy technologies such as photovoltaic (PV) panels and solar thermal collectors enables on-site generation of clean energy. The principle involves harnessing solar radiation to offset grid electricity demand or provide thermal energy for water heating and space conditioning. This decreases reliance on fossil fuels and lowers greenhouse gas emissions, thereby supporting long-term sustainability goals.
7. *Building Automation and Control Systems:* Modern Building Automation Systems (BAS) integrate sensing devices, actuation mechanisms, and control strategies to enable real-time optimization of building operations. The theoretical basis lies in feedback control systems and intelligent energy management. By monitoring parameters such as occupancy, temperature, humidity, and lighting levels, automated systems dynamically adjust HVAC and lighting operations to minimize energy use while maintaining indoor comfort.

Collectively, these retrofitting techniques are rooted in established principles of heat transfer, energy conservation, and environmental engineering. When strategically selected and properly implemented, they significantly improve building performance, reduce operational costs, and enhance sustainability, thereby supporting broader climate mitigation and energy security objectives.

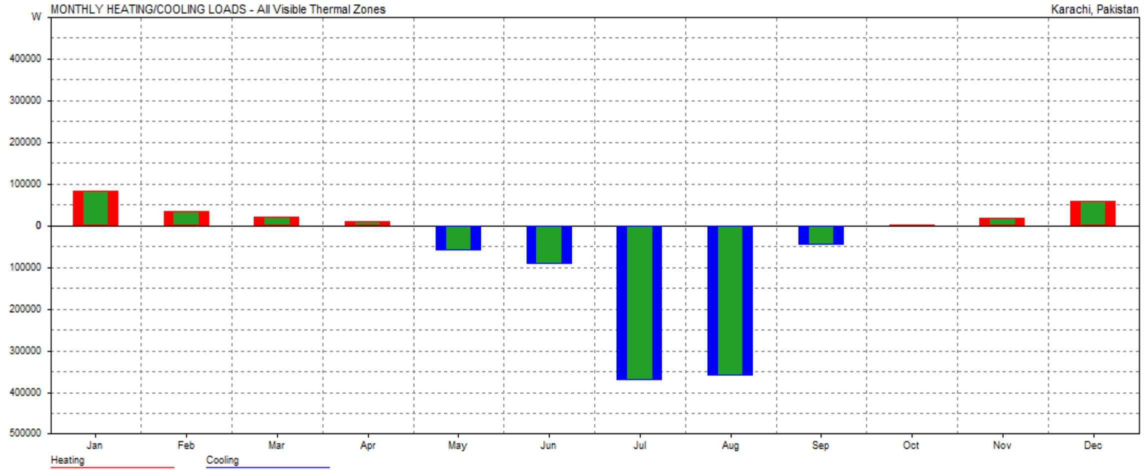

Fig.6 Monthly Heating/Cooling Loads

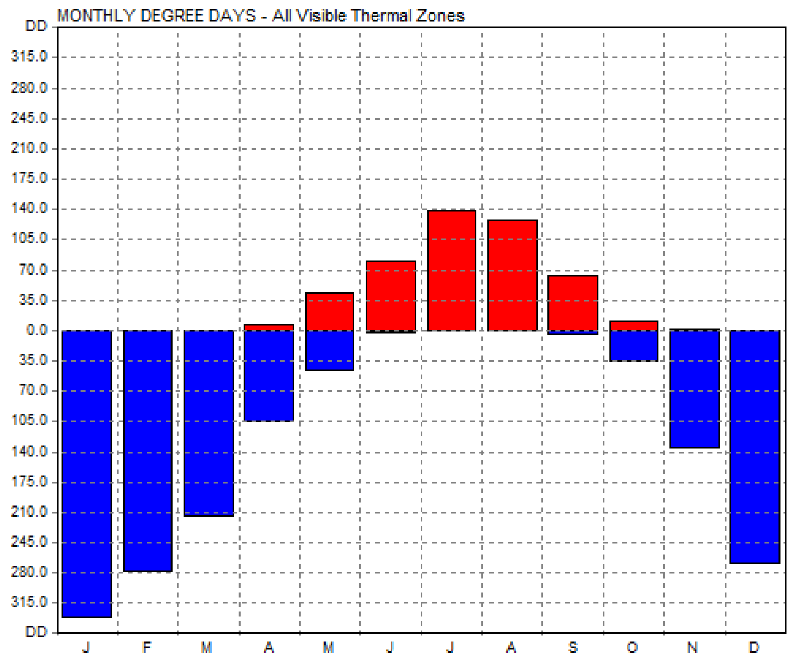

Fig.7 Monthly Degree Days

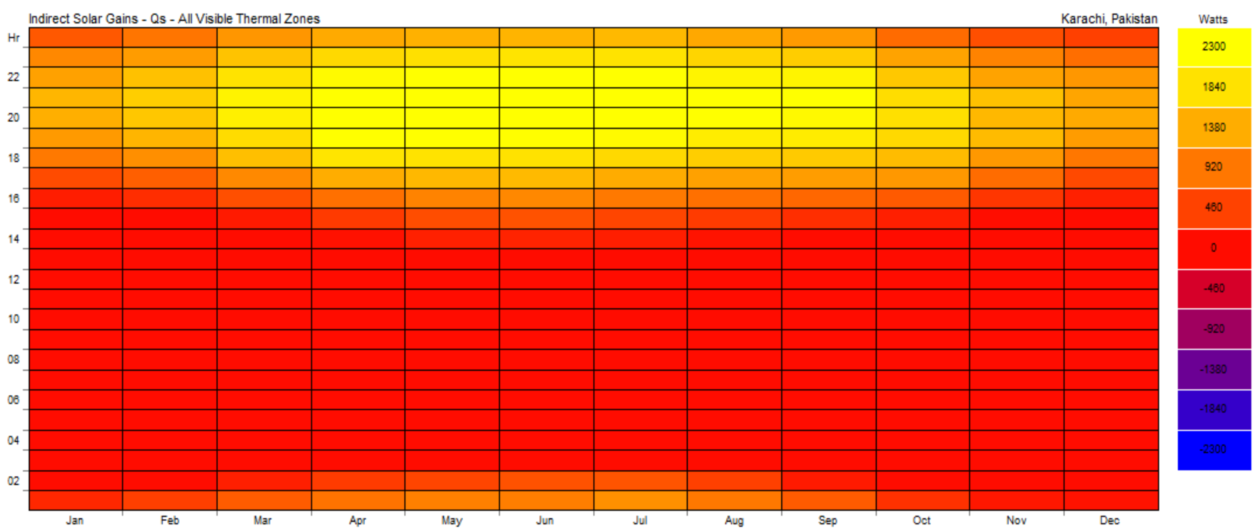

Fig.8 Indirect Solar Gains

G. Simulation Validation

To validate the accuracy of the simulation model, indoor temperature profiles were compared against measured data for the period from January to 12 December. This interval was selected because it contained the most complete and reliable weather dataset while also representing a typical operational week for the building. The figures illustrate the comparison between measured and simulated indoor temperatures for the selected office space. The recorded internal temperatures ranged between 18 °C and 26 °C during the validation period. The results indicate a strong correlation between simulated outputs and measured values, demonstrating acceptable model reliability.

A detailed assessment shows that the influence of sol–air temperature is particularly significant for the roof assembly. Due to its unobstructed exposure to solar radiation and the absence of shading devices, the roof experiences substantial solar heat gains. Moreover, the dark grey, rough-textured rooftop surface exhibits higher solar absorptivity, further increasing surface temperature and conductive heat transfer into the conditioned space. Similarly, the east- and west-facing façades demonstrate elevated sol–air temperatures compared to other orientations. This is attributed to low-angle morning and afternoon solar exposure, which increases incident radiation and consequently results in higher heat transfer rates for identical wall areas and U-values.

Overall, a satisfactory agreement is observed between measured and simulated temperature profiles. However, the model slightly overpredicts peak indoor temperatures during weekend periods when the HVAC system is inactive. This deviation is likely due to simplified assumptions in the HVAC modeling approach and thermal mass representation. Despite this minor discrepancy, the validation results confirm that the simulation model provides a reliable basis for the comparative analysis of retrofitting scenarios.

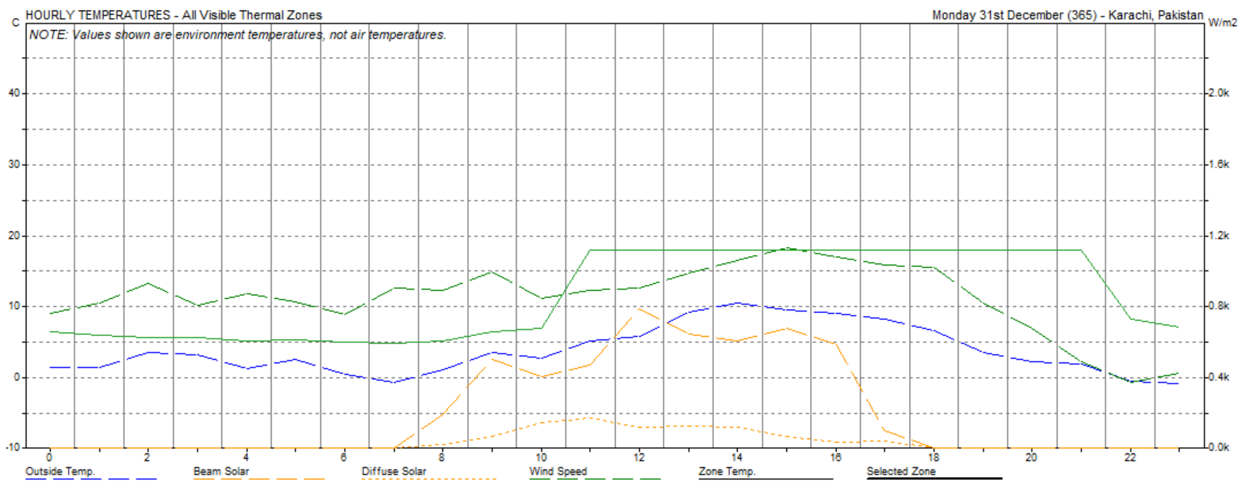

Fig.9 Graph of Hourly Temperatures

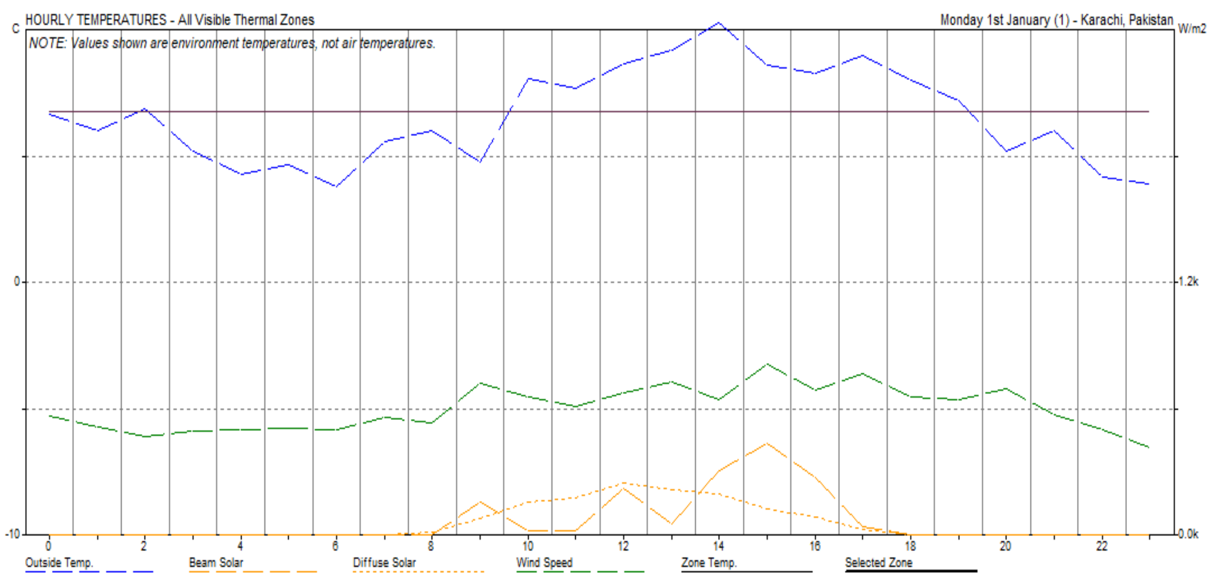

Fig.10 Graph of Hourly Temperatures

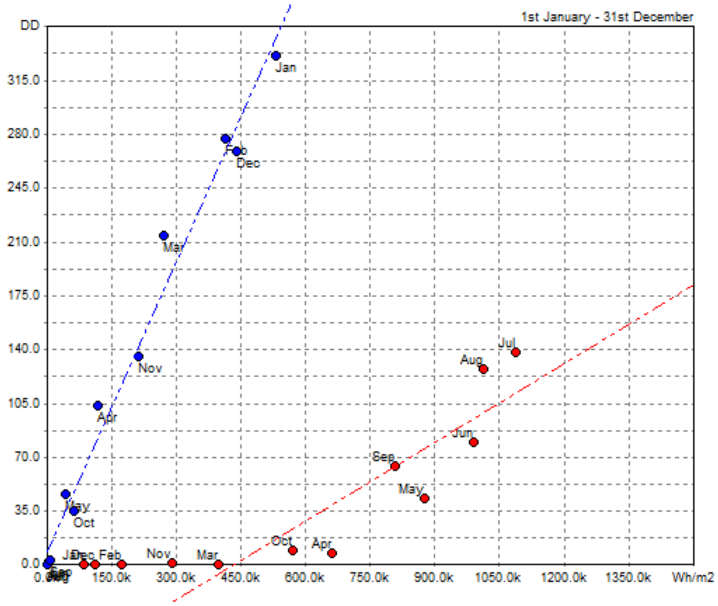

Fig.11 Monthly Energy Consumption Graph

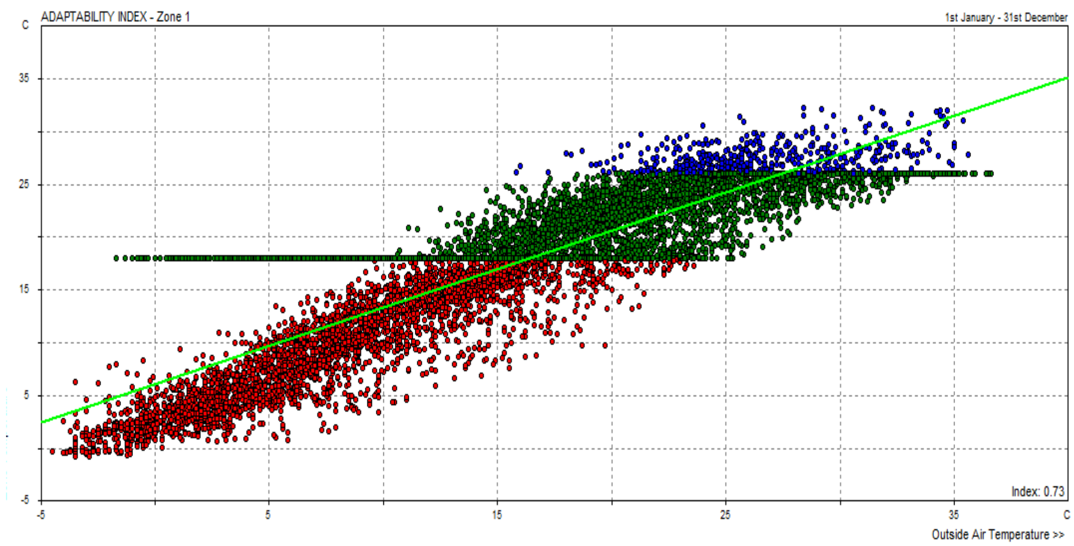

Fig.12 Adaptability Index

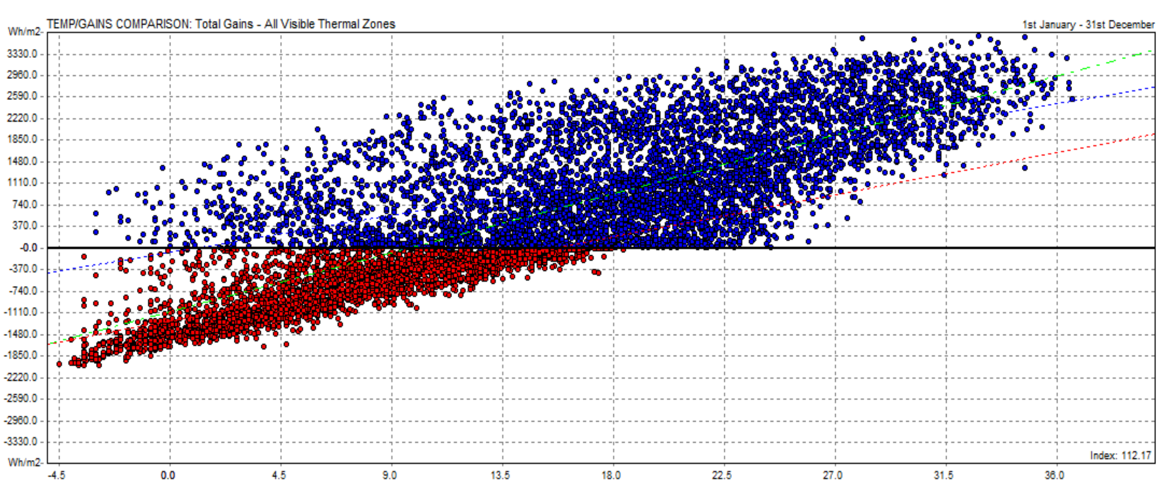

Fig.13 Temperature Gains Comparison

IV. CONCLUSION

This study evaluated the performance of selected passive cooling retrofitting techniques in an existing institutional building located in Karachi. The building's baseline thermal behavior was initially assessed through simulation using Autodesk Ecotect 2011 to quantify annual heating and cooling loads and identify envelope-related inefficiencies. Subsequently, individual and combined retrofitting measures were applied within the simulation environment to determine their impact on annual thermal load reduction. An economic assessment was also conducted to examine the feasibility of each intervention by comparing projected energy savings with the required initial investment.

The analysis yields the following key conclusions:

1. Insulation upgrades proved to be the most effective individual retrofitting measure, achieving a 17% reduction in annual thermal load. Among the materials evaluated, cellulose insulation with an optimum thickness of 4 inches demonstrated the highest feasibility in terms of performance and cost-effectiveness.
2. Window replacement, specifically substituting single-glazed units with double-glazed assemblies, resulted in a 4.16% reduction in thermal load, ranking as the second most impactful intervention. Optimization of the window-to-wall ratio and the implementation of energy-efficient lighting contributed additional reductions of 1.03% and 1.07%, respectively.
3. When all retrofitting strategies were applied collectively, the building achieved a cumulative annual thermal load reduction of up to 17%, demonstrating the effectiveness of an integrated passive retrofit approach.

Overall, the results confirm that targeted passive retrofitting strategies can significantly enhance the thermal performance and energy efficiency of existing institutional buildings in Karachi's climatic context, while remaining economically viable.

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