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Reducing Residential Energy Demand through Optimal Roof Insulation Practices: Insights from Lahore, Pakistan

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Abstract
This research quantifies the impact of roof thermal insulation in reducing residential energy demand in Lahore, Pakistan. Using Autodesk Revit BIM software, energy analysis was conducted on a contemporary two-story residential building, testing various insulation materials to determine their effectiveness in reducing cooling demands during summer. The influence of insulation thickness was also evaluated. Results indicated that applying 2-inch-thick insulation could reduce building cooling load demand by approximately 25%. The study concludes that significant energy savings can be achieved if the Pakistani government actively promotes the application of insulation materials in both existing and new residential buildings.

Keywords: Cooling Load, Energy Consumption, Insulation Materials, Roof Insulation, R-value, Sustainable Design.

Introduction
Building's energy demand is constantly increasing in Pakistan, mainly during the summer season, due to increased indoor cooling loads as outdoor temperature is very high even at nighttime. According to Pakistan economic survey, 2021-22, total electricity consumption in 2021 and 2022 for different sectors are as following: household consumption 49.1 & 47%, industry consumption 26.3 & 28 %, Agriculture consumption 8.9 & 9%, Commercial 7.4 & 7%, other consumptions are 8.3% and 8% respectively as shown in the figure 1(Government of Pakistan, Finance Division, 2022). Energy crises are more due to a high population growth rate that is 1.95 %. In Pakistan, about 64.2 % of the energy demand is currently supplied by the fossil fuels oil and gas, 29 % is supplied by hydropower, and 5.8 % by nuclear power (Wikipedia contributors, n.d.). By burning nonrenewable energy sources, that is, fossil fuels, greenhouse gas (GHG's) emissions have been boosted within the last 30 years, and these emissions have been identified as the major cause of Climate change in the atmosphere.
The building envelope plays a crucial role in ensuring a comfortable indoor

environment, particularly in terms of thermal comfort. However, its current design often fails to fulfill this purpose effectively. The envelope significantly influences the amount of energy needed to maintain desirable indoor temperatures. Due to the limited use of natural ventilation today, occupants frequently rely on mechanical systems such as air conditioners to achieve thermal comfort. These systems are major contributors to electricity consumption and greenhouse gas emissions. Therefore, there is a pressing need for sustainable passive design strategies that can create comfortable indoor conditions while minimizing energy use, especially for cooling. A fundamental principle in designing energy-efficient buildings is heat avoidance—reducing heat gain from high outdoor temperatures and direct solar radiation. This study focuses on the impact of roof insulation and conducts a detailed cooling load analysis to determine the most suitable insulation materials and their optimal thicknesses for Lahore's climate.

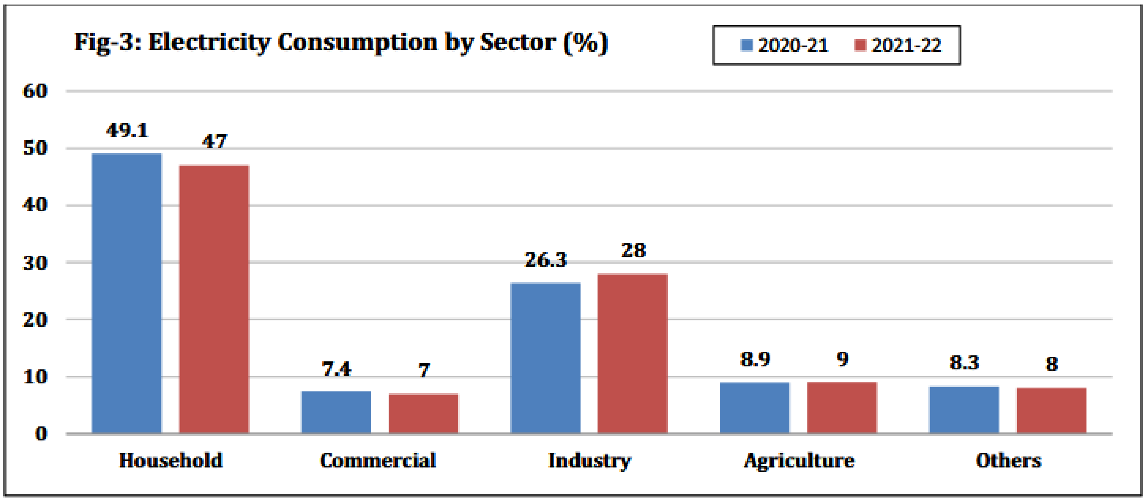

Figure 1. Shares of sectors in electricity consumption
Source: Economic Survey of Pakistan 2021–2022

Literature Review

Pakistan faces a severe energy crisis characterized by frequent electricity shortages and widening gaps between energy supply and demand (F. S. & Masood, 2012). According to the WAPDA Annual Report 2012–2013, the population is now facing a 5000 MW electrical supply shortfall—the harshest power crisis in the country's history. In this context, sustainable and passive design techniques emerge as viable alternatives to reduce building-related energy consumption. Passive design—particularly design strategies that respond to the sun's position—can play a meaningful role in mitigating Pakistan's electricity shortfall.

With the advancement of materials and technology, the global trend is shifting towards Zero Energy Buildings (ZEBs), which rely on passive energy strategies for optimal energy efficiency. Insulation is among the most effective of these strategies, especially when applied to the building envelope. Unfortunately, in Pakistan, the building industry still lacks widespread integration of passive design principles. However, vernacular architecture in cities like Lahore demonstrates that passive strategies—such as appropriate building orientation, spatial planning, shading devices, landscaping, and thermal insulation—can significantly contribute to thermal comfort and energy savings.

In Lahore's semi-arid climate, characterized by extreme summer temperatures, cooling demand dominates energy use. Studies reveal that incorporating thermal insulation into building envelopes can reduce this demand by up to 30% (M. & Arif, 2013). A recent simulation study by Mujahid (2023) using Autodesk Revit demonstrated that the modifications in residential building envelope can reduce the electrical energy demand by 37%. This is a substantial energy saving, especially considering the high proportion of electricity used for cooling in residential buildings.

Collaborative research by the Government of Pakistan, ENERCON, UN-Habitat, and the Capital Development Authority also evaluated various insulation materials in Islamabad during extreme summer conditions. The findings revealed that all tested materials improved indoor temperatures, with some lowering temperatures below 34°C compared to control houses without insulation (Government of Pakistan, 2010).

International research supports these findings. In the U.S., a study using eQuest software analyzed two climate zones—Detroit and Miami—and found that internal gains from lighting, appliances, and occupants contributed about 43.7% of the total cooling load. While insulation yielded marginal savings in hotter climates like Miami, even minimal insulation was necessary for thermal comfort (Kim & Moon, 2009). Similar research in North Cyprus demonstrated that thermally insulated external walls were three times more effective in reducing energy consumption than non-insulated walls (Emadi, n.d.).

A Saudi Arabian study examined various building envelope elements—roof and wall insulation, glazing, and thermal mass—and concluded that total energy savings of 22% to 39% could be achieved, depending on the region. Furthermore, the economic analysis showed that the initial investment in insulation was easily offset by long-term savings in electricity costs (Alaidroos, 2015).

More recently, Khan et al. (2022) conducted research in Karachi and found that the combination of insulation and reflective roof coatings resulted in up to 35% cooling energy savings in urban dwellings (Khan, Qazi, & Raza, 2022). Similarly, Aslam et al. (2023) explored the thermal performance of eco-friendly insulation materials such as recycled jute and hempcrete and confirmed their potential as low-cost, sustainable alternatives in Pakistan's hot climate (Aslam, Yousaf, & Shahid, 2023). The International Energy Agency (IEA) 2023 report also underscores those buildings in South Asia, including Pakistan, can cut energy demand by up to 40% through passive envelope upgrades, particularly insulation, optimized glazing, and shading strategies (International Energy Agency, 2023).

Climate of Lahore

Lahore lies in the hot semi-arid (Köppen BSh) zone, bordering on a humid subtropical climate, and endures extremely hot, dry summers from May through early July—average daily highs routinely exceed 40 °C, with record peaks up to 50.4 °C—followed by a pronounced monsoon from late June to September that delivers most of the city's annual 577–636 mm of rainfall in heavy, often convective storms. Winters are brief and mild, with January lows near 7 °C and frequent overnight fog, while sunshine is abundant year-round—Lahore averages more than 3,700 sunny hours annually and sees peak solar irradiance of around 7.5 kWh/m²/day in June—factors that together drive high diurnal temperature swings and steep cooling demands on residential roofs (weatherspark.com).

Methodology

To evaluate strategies for reducing energy consumption in residential buildings in Lahore, a representative prototypical house was selected for analysis. The chosen model is a detached single-family residence, which reflects the most common housing type in the region. Enhancing the energy efficiency of this housing category has the potential to significantly lower the overall energy demand of Pakistan's residential sector.For the simulation and analysis, Autodesk Revit 2014 was employed. One of the key advantages of using Revit's MEP module is its integration of the Radiant Time Series (RTS) method for calculating cooling loads, which is based on the heat balance approach recommended by ASHRAE.

Data for modelling the building was sourced from three primary avenues:

1.Reviews of architectural plans approved by the Lahore Development Authority (LDA) and the Bahria Town Housing Authority,

2.Site visits to ongoing residential construction projects,

3.Interviews with professionals, including architects, engineers, property owners, and contractors.

The residential building under study is a double-storey structure with an overall height of 26 feet. The building has a rectangular footprint, measuring 30 feet in width and 60 feet in depth, resulting in a gross floor area of 2,160 square feet. The gross external wall area amounts to approximately 1,636 square feet, of which 20.54% is occupied by windows, fitted with uncoated single glazing—a common but thermally inefficient choice in hot climates. The external walls are constructed using a traditional layered system comprising 1/8-inch exterior plaster, followed by a 9-inch thick burnt brick wall, and finished with 1/8-inch interior plaster. The roof assembly consists of a 6-inch reinforced concrete (RCC) slab, coated with two layers of hot bitumen, overlaid with a polythene sheet, followed by a 3-inch mud layer, and topped with 1½-inch brick tiles—a configuration intended to provide thermal mass and weather protection. The flooring system features ½-inch thick ceramic tiles, underlain by a 1½-inch thick plain cement concrete (PCC) layer. Beneath the PCC, there is a 4-inch gravel layer, followed by 4 inches of sand, all resting on compacted earth. This multilayered floor design provides structural integrity and helps moderate ground heat transfer into the building.

Each room in the house was individually modelled to ensure accurate simulation of internal loads. According to ASHRAE standards, sensible and latent heat gains were assumed to be 245 BTU/hr and 145 BTU/hr, respectively. Both lighting and equipment loads were set at 0.50 W/ft^2. Weather-related external loads, a critical input for accurate cooling demand estimation, were incorporated using an internet-based climate mapping service.

The building envelope's thermal performance was characterized by the following R-values (thermal resistance):

- ☐Roof: 1.815 (h·ft^2·°F)/BTU
- ☐Walls: 2.474 (h·ft^2·°F)/BTU
- ☐Floors: 4.970 (h·ft^2·°F)/BTU

An air infiltration rate of 0.3 air changes per hour (ACH) was also factored into the model. The base case building is simulated for different types of insulation materials for the roof, as roofs are more exposed to sunlight as compared with other building components. A series of parametric simulations was conducted for

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materials with different R-values to find out their effectiveness.

Results and Discussions

The software simulation results were analyzed in terms of the effect of insulation materials and the thickness on the indoor cooling demand of the building.

Comparison Of Different Insulation Materials

A variety of insulation materials are available in the market. To identify the most effective and suitable option for roof insulation, a comparative analysis of different materials was conducted, with the results presented in Table 1. The evaluation indicates that extruded polystyrene performs the best in terms of insulation effectiveness, while polyethylene ranks the lowest. Although polyurethane also shows high thermal performance, it is typically applied as spray foam, which results in significant greenhouse gas emissions during installation, making it less environmentally friendly.

Expanded polystyrene offers a similar reduction in cooling demand to polyurethane but has a porous, open-cell structure. This allows it to absorb moisture over time, which can degrade its performance. In contrast, extruded polystyrene has a closed-cell structure, making it water-resistant and more durable. It is suitable for use on both roofs and walls. A cost comparison of these insulation materials is also provided in the table. As expected, a substantial portion of the electrical energy is consumed by air-conditioning systems for indoor cooling. The calculated peak cooling load for the modelled building is 188,229 BTU/hr as shown in figure 2.

Table 1: Effect Of Insulation Material On Cooling Demand Of The Building

Name of the Insulation Material	Cooling Load Demand (BTU/hr.)	Percentage (Reducing in cooling load)
Roof with no thermal Insulation	188,229	--------
Roof with polyethylene Insulation	166,254	11.67 %
Roof with Extruded Polystyrene Insulation	141,264	24.95 %
Roof with Expanded polystyrene Insulation	140,417	25.40 %
Roof with Polyurethane Insulation	141,887	24.62 %

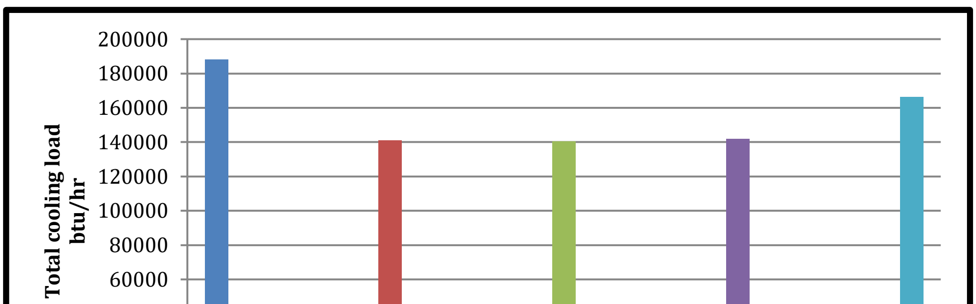

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Figure 2. Reduction In Building Cooling Load Demand By Different Insulation Materials

Table 2: List of different insulation materials (Diamond Jumbolon, n.d.), (Industrial Enterprises Insulation Experts, n.d.), (Mujahid, 2023)

Insulation Material	Density lb/ft3 (kg/m3)	R-value Ft2.0F.h/(Btu. in)	Cost Rs. per sq.ft
Diamond Jumbolon Board (Extruded polystyrene)	1.99-2.37 (32-38)	R-5.021	45 per inch
Industrial Enterprises Thermopore Blue (Expanded Polystyrene)	2.185 (35)	R-5.85	20 per inch
Industrial Enterprises Thermopore White (Expanded Polystyrene)	2.185 (35)	R-5.4	19.17 per inch
Industrial Enterprises Thermoboard (Expanded Polystyrene)	2.185 (35)	R-5.15	24 per inch
Style Styrofoam Styroboard (Expanded Polystyrene)	1.99 (32)	R-5.55	30 per inch
Style Styrofoam sheets (Expanded Polystyrene)	1.99 (32)	R-5.55	19.17 per inch
Diamond Jumbolon-Rolls (Polyethylene)	1.87 (30)	R-4.83	39 per inch
Industrial Enterprises Thermospray / Diamond Jumbolon Spray foam (Polyurethane Spray foam)	1.99 (32)	R-5.55	55/45 per inch

Effect of Insulation Material Thickness on Cooling Demand of Building

The analysis of insulation thickness using Extruded Polystyrene on the roof of a residential building is presented in both tabular and graphical formats. Since thermal resistance (R-value) is the inverse of thermal conductance (U-value), increasing the thickness of insulation does not result in a directly proportional reduction in cooling load. For example, a 1-inch-thick layer of insulation reduces the cooling load by approximately 17%, but doubling the thickness to 2 inches does not yield a 34% reduction; instead, it results in a 22.5% decrease. Furthermore, from 4.5 inches to 5 inches, the reduction in cooling load remains nearly constant,

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indicating diminishing returns with increased thickness. Figure 3 is a demonstration of this effect.

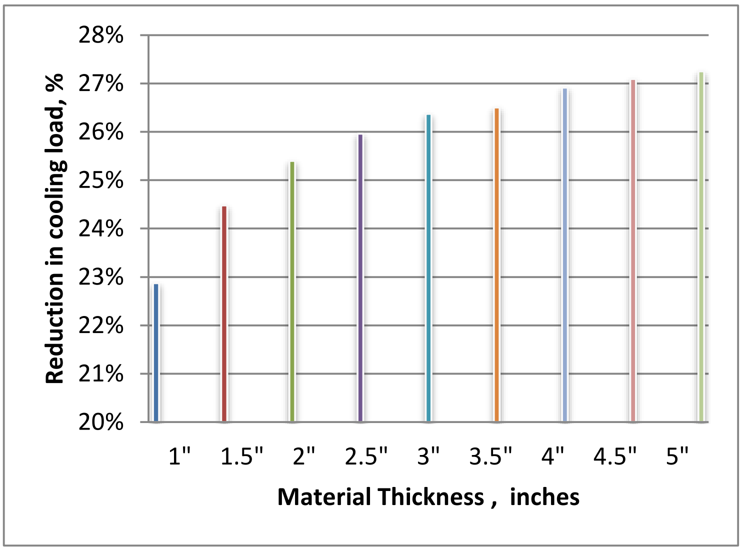

Figure 3. Effect Of Material's Thickness On Cooling Load Demand

Table 4: Effect of Insulation material thickness on cooling demand of the building

Insulation Thickness (inches)	Material	Peak Cooling load (Btu/hr)	Percentage (Reducing in cooling load)
No insulation		188,229	--------
1		145,173	22.87 %
1.5		142,141	24.48%
2		140,417	25.40%
2.5		139,354	25.96%
3		138,589	26.37%
3.5		138,321	26.5%
4		137,580	26.91%
4.5		137,226	27.09%
5		136,936	27.25%

Conclusions

The reduction of energy demand in residential buildings in Lahore has been explored through optimization of the building envelope, with a particular focus on roof insulation. This study examined the impact of four different insulation materials on indoor temperatures by determining the associated cooling loads. The analysis was conducted using Autodesk Revit 2014 simulation software.

The results indicate that buildings with uninsulated (prototypical) roofs exhibit significantly higher cooling loads compared to those with insulated roofs. Each insulation material demonstrated varying levels of thermal resistance (R-values), leading to different levels of effectiveness in reducing indoor temperatures. The simulation revealed that using insulation materials with a 2-inch thickness can reduce cooling loads by up to 25%.

Among the materials tested, expanded polystyrene (Thermopore Blue), with an R-value of 5.85 ft²·°F·h/(Btu·in), was found to be the most effective. In contrast, polyethylene, with an R-value of 4.83 ft²·°F·h/(Btu·in), was the least effective. Polyurethane spray foam insulation reduced cooling load by approximately 24.62%, but its application releases a considerable amount of greenhouse gases, making it less environmentally friendly. Extruded polystyrene demonstrated similar performance to polyurethane in terms of energy savings but with fewer environmental drawbacks, making it more suitable for roof applications.

The study concludes that significant reductions in building-level energy consumption—and broader national energy savings—can be achieved if the Government of Pakistan actively promotes the use of effective insulation materials in residential construction and retrofitting initiatives.

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