Analysis of the Impact of Insulation on Residential Building Energy Performance

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Abstract

In Pakistan, the domestic sector accounts for 45.9% of total energy consumption, ranking it among the top three energy-consuming sectors in the country. Several studies have been conducted to assess the efficiency of incorporating various sustainability measures into existing buildings using simulation tools. The purpose of this study was to conduct a cost-benefit analysis of adding insulation in residential structures in Peshawar to reduce energy consumption for cooling and heating the building. These analyses were performed with the help of eQUEST software. The study found that proper insulation outstandingly decreases gain of heat in the summer season and loss of heat in the winter season. Loss of heat and gain were calculated for the insulation of different thicknesses to select the best one. An insulation of 75 mm thickness using R-value outstandingly decreased demands of cooling and heating. The insulation layer of thickness 75 mm was observed to decrease demand of cooling and heating by 40.8% and 43.3%, respectively. Furthermore, it was observed that annually 204,189 PKR could be saved. The analysis of the investment and return showed that the breakeven point can be achieved in nine years.

Keywords: Cost-benefit Analysis; eQuest Software; Cooling Load; Heating Load.

Introduction

Energy consumption by the building sector is one of the major loads on the energy resources of many developing nations, including Pakistan, where the residential sector constitutes a substantial share of the country's overall energy use (Rauf et al., 2015; Ahmad et al., 2014; Ahmad et al., 2014). It is observed from the latest data that the domestic sectors in Pakistan uses 48 % natural resources of total energy, prove the major contributor to the overall energy need of the country (Awan, 2020). As the population increases day by day and urbanization accelerates rapidly, due to which consumption of energy increases, more straining the national grid and boost the importance of environmental linked to the production of energy from the new sources, typically from fossil fuels (Omer, 2009). Correspondingly, the implementation of energy saving in residential

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house has become increasingly crucial to meet the demands of rising energy while stimulate the sustainability (Rafique & Rehman, 2017; Ali et al., 2020). Insulation is one of the best method to enhance the energy efficiency in residential houses in order to minimize the heating and cooling demands (Chua et al., 2013). Insulation is the best method to reduce heat transfer between the interior and exterior of a building, helping to keep a consistent indoor temperature throughout the year (Lee & Lim, 2016). In the areas of the extreme climatic conditions, e.g., Peshawar, Pakistan, where temperatures change outstandingly between winter and summer, insulation is best in minimizing dependence on artificial cooling and heating systems. This, in turn, lowers overall energy consumption and associated costs (Hasan, 2020).

Various studies have been conducted recently by using experimental simulation designs in order to explored the significance of integrating insulation in buildings. It is observed from these that efficient insulation reduces demand of energy for cooling in hot regions and heating in colder climates (Guo et al., 2012). To maintain optimum installation and reasonable thickness and selection of insulation type in order to maximize the saving of energy while maintaining proper installation and optimum cost is the part of research (Dabaieh et al., 2015). While the advantages of energy-saving in insulation are well-established, the economic viability and return on investment (ROI) of such measures are usually overlooked, especially in developing countries like Pakistan, where the initial costs can create a restriction to global acquiring (Song et al., 2015). Optimization of Thermal Insulation Thickness Pertaining to Embodied Energy and Environmental Impacts analyzes the influence of energy emission factors and future climate change scenarios on optimal insulation thickness, emphasizing the importance of considering environmental impacts alongside energy efficiency (Gaarder et al., 2023). Multi-Objective Optimization of Insulation Thickness with Respect to On-Site Renewable Energy Generation in Residential Buildings investigates optimizing insulation thickness in conjunction with integrating renewable energy systems to improve energy efficiency and reduce life cycle costs, using simulation models for residential buildings in Athens, Greece (Papadopoulos et al., 2024). Energy Efficiency of Residential Buildings Using Thermal Insulation in Northern Iran examines the impact of thermal insulation on energy consumption in residential buildings in northern Iran, aiming to optimize energy use in regions with climatic conditions similar to Peshawar (Amani, 2025). Cost Benefit Analysis of Applying Thermal Insulation Alternatives to Saudi Residential Buildings explores the law of diminishing returns when improving the conservation level of residential buildings through thermal insulation, providing insights into the economic feasibility of various insulation alternatives in hot-arid climates (Al-Tamimi, 2021).

This main aim of this study is to address the gaps by providing a comprehensive cost-benefit analysis of insulation in residential houses in Peshawar, Pakistan. This research study is performed by using eQUEST, a user-friendly building energy simulation software, to evaluate the effects of different insulation thicknesses on heating and cooling energy loads in houses. The main objective of the given study is to find the thickness of optimal insulation that assault the balance between savings of energy and costs of installation, presuming a guide for resident and managing director in order to reduce consumption of energy. Furthermore, the study inspects the economic feasibility of such an investing by determining the potential energy savings, the required initial cost, and the payback period for installation of insulation. The results obtained from this study are contribute to the knowledge base on the measure of energy efficiency in Pakistani residential housings and provide practical awareness into the role of insulation in reducing use of household energy. By providing both technical and financial measures, this research work seeks to provide a significant evaluation that can help policymakers, design of buildings, and residents make informed decisions about the strategies of energy conservation. Finally, the aim is to encourage sustainable building practices that not only reduces the environmental impact of consumptions of energy but also facilitate the residents with long-term financial benefits, contributing Pakistan's broader energy sustainability objectives.

The current research lies in conducting a comprehensive cost-benefit analysis of insulation in residential buildings in Peshawar, Pakistan, a region with extreme climatic conditions. While previous studies have focused primarily on energy savings from insulation, the study integrates both technical and economic perspectives by analyzing the optimal insulation thickness, initial investment costs, payback period, and return on investment (ROI). eQUEST software is used to simulate different insulation scenarios to determine the most efficient and cost-effective solution for energy savings. This research provides practical recommendations for homeowners, policymakers, and building designers, contributing to sustainable energy consumption in Pakistan's residential sector. Compared to the above studies, the proposed work uniquely integrates both energy efficiency and economic viability to identify the most cost-effective insulation thickness for residential buildings in Peshawar, Pakistan. Unlike previous research that primarily focused on either energy savings or material properties, the study provides a holistic assessment, considering regional climate-specific factors influencing insulation performance, optimal thickness determination to balance energy savings and costs, payback period analysis to evaluate financial feasibility, practical insights for stakeholders (homeowners, policymakers, and construction professionals) to make informed decisions. By bridging these gaps, this research contributes significantly to the sustainable energy practices in Pakistan's residential sector.

Methodology

This study investigates the potential for savings of energy by using insulation in a residential building in Peshawar, Pakistan. The main objective of the study is to determine the energy efficiency in building's energy consumption and point out the solution of most cost-effective insulation in order to minimize both heating and cooling demands. The methodology consolidate the modeling of energy, simulation software, and parametric analysis to inspect the impact of different insulation thicknesses on the efficiency of building's energy.

Assumption

The energy prices are assumed to remain constant throughout the analysis, based on the latest available data at the time of the study.

Description of the Residential Building

The residential building selected for this study is located in Danish Abad, Akbar Town, Peshawar. This two-story structure, with a footprint of approximately 1,600 square feet, is oriented towards the northwest and is situated in a hot climate zone. The building consists of five distinct zones per floor: the TV lounge, bedrooms, guest rooms, kitchen, and corridors. This layout and its energy usage patterns are integrated into the eQUEST simulation. The models developed for ground floor and first floor in eQUEST are shown in Figure 1 (a-b).

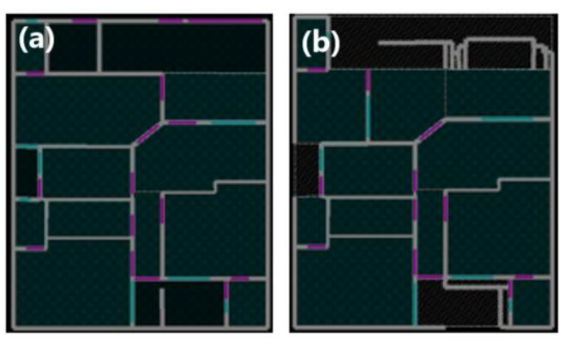


Figure 1: 2D models for (a) ground floor and (b) first floor of building from eQUEST.

Collection of Data and Analysis

Collection of data for the study involved gathering detailed information on both the indoor and outdoor conditions affecting energy consumption.

Outdoor Weather Conditions

The weather data for Peshawar, sourced from the DOE-2 website, is used to create a simulation of local environmental conditions. Although the weather data available is from 2017, the stability of Peshawar's climate over the last two decades ensured its reliability for the analysis.

Indoor Thermal Conditions

Each floor of the building is divided into zones, with specific temperature settings and occupancy data for each zone (e.g., bedrooms, TV lounge, kitchen). This allowed for an accurate representation of the building's internal environment.

Building Layout and Civil Structure

The building's layout is modeled using AutoCAD files, which are imported directly into eQUEST. This approach ensured accurate zone patterns and material specifications. The alternative method of manually drawing the building structure in eQUEST is avoided due to its complexity and potential for error.

Energy Audit

A comprehensive energy audit is conducted to assess the building's current energy use. This included evaluating the design, building envelope, orientation, energy sources (electricity and gas), and the number of operating hours of key appliances.

Building Envelope and Construction Materials

The building's envelope consists of a 7.5-by-10-inch concrete slab roof and 10-inch-thick walls with no existing insulation as shown in Figure 2. The structure features typical residential components such as kitchens, bedrooms, and TV lounges, as well as a car porch and a terrace on the upper floor. Windows and doors are made of wood and glass, and the floors are finished with marble tiles. The research primarily focuses on adding insulation to the roof and exterior walls, which currently lack any insulating material. The 3D model of residential building developed in eQUEST is shown in Figure 2 (a, b).

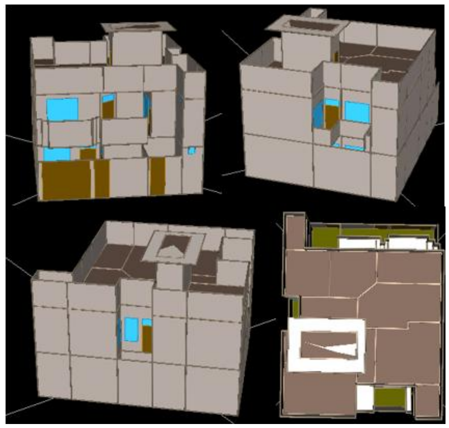


Figure 2: 3D building of residential building from eQUEST.

Energy Intake and Utility Sources

The building's energy needs are primarily met through electricity supplied by the Peshawar Electric Supply Company (PESCO), with gas from Sui Northern Gas Pipelines Limited (SNGPL) used for cooking and hot water production. Both energy sources are incorporated into the eQUEST simulation to model the building's energy consumption accurately.

While the building currently has a single air-conditioned zone (the TV lounge), the simulation in eQUEST included eleven additional HVAC zones to examine the impact of insulation on energy consumption across the entire building, as shown in Figure 3. These zones are conditioned using a split AC system, with air conditioning, heating, and ventilation powered by electricity. The impact of adding insulation to various zones is assessed by comparing the results of simulations with and without insulation. The conditioned and unconditioned zones, along with their areas in square feet, are also shown in Table 1 and Table 2.

eQUEST Simulation Setup

The energy modeling process began with the eQUEST schematic design wizard, which prompted input on the building type, seasons, and dimensional data. The process included:

Importing AutoCAD Files

The building's civil structure is imported into eQUEST using an AutoCAD file, ensuring accuracy in representing the building's geometry and zone layouts.

Defining the Building Shell

Using the building's dimensions, zone patterns, and construction materials, the building's shell is established in eQUEST.

Inputting Operational and HVAC Details

The system's operational schedule, HVAC configurations, and the location of active areas are inputted for each zone to create a comprehensive energy model.

Table 1: Thermal zoning for the building's ground floor.

S. No.	Zones	Area (sq-ft)	Zone type
1	G. Bed room 1	236.8	Conditioned
2	G. Bed room 2	220.8	Conditioned
3	G. Stairs	140.7	Unconditioned
4	G. Storage	76.7	Unconditioned
5	Guest Room	239.9	Conditioned
6	G. Kitchen	112	Conditioned
7	G. Back and Side space	139.3	Unconditioned
8	G. Car Porch	322.8	Unconditioned
9	G. Corridor	59.2	Conditioned
10	G. Tv lounge	196.8	Conditioned
11	G. Washrooms	124.4	Unconditioned

Table 2: Thermal zoning for the building's first floor.

Sr. No	Zones	Area (ft^2)	Type of zone
1	F. Bed room 1	236.8	Conditioned
2	F. Bed room 2	220.8	Conditioned
3	F. Stairs	76.7	Unconditioned
4	F. Balconies	139.3	Unconditioned
5	F. Guest room	121	Conditioned
6	F. Kitchen	112	Conditioned
7	F. Terrace	237.3	Unconditioned
8	F. Washrooms	124.4	Unconditioned
9	F. Corridor	59.2	Conditioned
10	F. TV lounge	196.8	Conditioned

Building Schedules and Operation

The operational schedule for the building is relatively simple, with typical residential usage patterns. Bedrooms are used predominantly during night time, while the kitchen and TV lounge are frequently occupied during the day. These occupancy patterns are incorporated into the eQUEST model to accurately represent the building's actual energy usage.

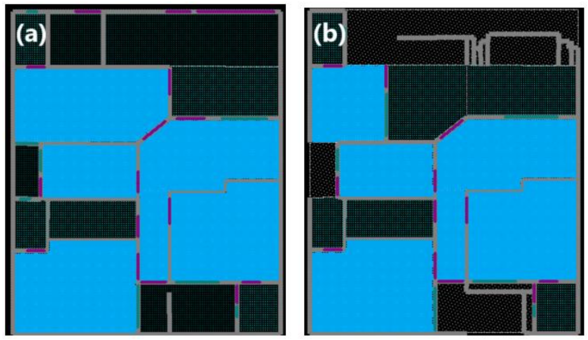


Figure 3: Zoning pattern of (a) ground floor and (b) first floor with blue color conditioned and rest are unconditioned.

Utility and Economic Data

To evaluate the financial feasibility of insulation, the study included detailed data on utility rates. Electricity and gas consumption rates are obtained from PESCO and SNGPL, and these figures are integrated into the eQUEST model to estimate the cost savings from insulation. Additionally, the cost of insulation materials and installation is factored in to calculate the potential return on investment.

Parametric Runs

A key feature of eQUEST, parametric runs, is utilized to simulate different insulation thicknesses and assess their effects on energy savings. These runs enabled the researcher to examine the impact of varying insulation values on the building's energy performance, generating comparative data for insulation thicknesses from minimal to optimal levels. The simulation results are then analyzed to identify the insulation thickness that offered the highest energy savings at the most cost-effective price.

Insulation Variations and Analysis

To evaluate the impact of insulation on the building's energy performance, various insulation thicknesses and Resistance (R) values are modeled in eQUEST. The cost of each insulation material per square foot is also incorporated into the analysis. The study continued to increase the insulation thickness in the model until further increases showed diminishing returns in energy savings. This process helped identify the optimal insulation thickness for maximum efficiency and cost-effectiveness.

Results and Discussion

Actual Electricity Consumption of Building (kWh)

The building's gas and electricity consumption are illustrated in Figure 4, which shows the annual energy usage for a single-family home. Additionally, Figure 5 presents the annual percentage breakdown of the building's total electrical consumption. The results indicate that 62% of the total energy consumption is attributed to various equipment, such as water pumps, mobile phone chargers, laptops, washing machines, irons, and kitchen appliances (e.g., microwave, juicer). Lighting and HVAC systems each account for 18% of the total energy consumption. The HVAC system's contribution to the overall electrical consumption is minimal due to its limited use, as only one section of the building is air-conditioned. The demand for cooling is highest between April and July, corresponding with the region's typically high temperatures. As shown in Figure 5, gas consumption also peaks at the beginning and end of the year, reflecting an increase in need for hot water in colder months. Table 3 presents detailed data for the consumption of electricity and gas, showing that the building consumed 4,988 kWh of electricity annually, while gas usage amounted to 69.45 M Btu. The average U.S. household consumes approximately 10,715 kWh of electricity per year, equating to about 893 kWh per month. In contrast, the subject home uses 4,988 kWh annually, which is less than half the U.S. average. This discrepancy may be attributed to differences in regional climates, home sizes, appliance usage, and energy efficiency practices (Li et al., 2023).

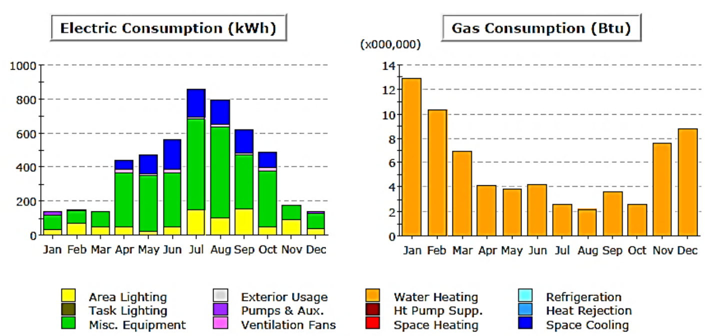


Figure 4: Building electricity and gas consumption based on eQUEST simulation results.

Comparison of Actual Utility Bills with eQUEST software results

Upon completing the eQUEST software simulations, the results are compared with actual data of utility bills for electricity (kWh) and gas (kBtu), as illustrated in Figure 6 and Figure 7. A 10% tolerance is allowed in the calibration process. The comparison between the simulated data and actual utility bills reveals a close alignment, indicating that the eQUEST model provides a reliable estimation of energy consumption.

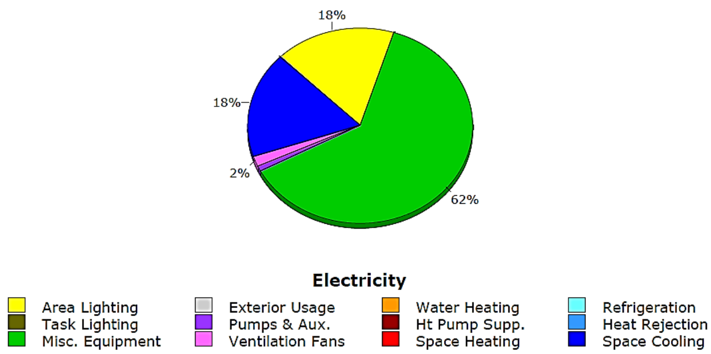
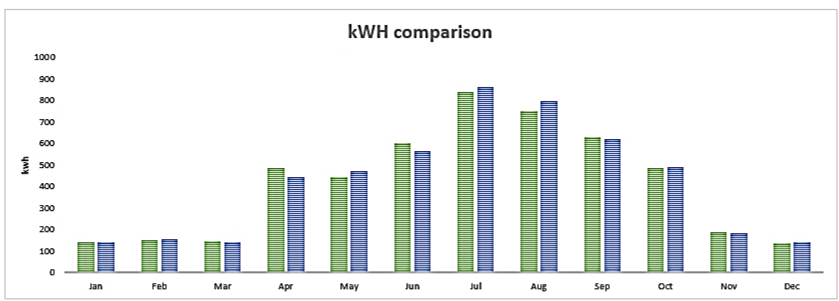
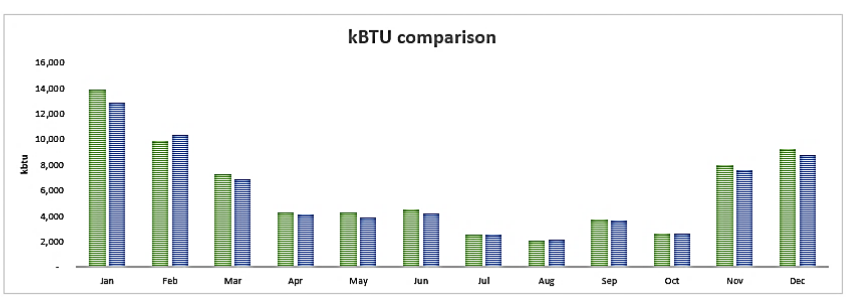


Figure 5: Pie chart of actual consumption of electricity from eQUEST software simulation.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	
Actual kWh Average	140	148	146	482	444	601	839	748	630	482	188	135	4983	
eQuest kWh	140.6472	152.0986	139.4172	443.5038	468.6848	564.3419	858.7358	795.2318	618.5432	488.5657	179.6276	139.1617	4989	
% Deviation	-0.46%	-2.77%	4.51%	7.99%	-5.56%	6.10%	-2.35%	-6.31%	1.82%	-1.36%	4.45%	-3.08%	-0.11%	**100.1%**

Figure 6: Consumption comparison of actual gas and electricity with eQUEST in kWh.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	
Actual kBTU Average	13909	9829	7233	4228	4228	4488	2559	2040	3709	2633	7938	9236	72031	
eQuest kBTU	12868	10332	6883	4081	3846	4165	2559	2140	3634	2600	7602	8740	69450	
% Deviation	7.49%	-5.12%	4.84%	3.49%	9.04%	7.20%	0.01%	-4.90%	2.03%	1.27%	4.23%	5.37%	3.58%	**96.4%**

Figure 7 Consumption comparison of actual gas and electricity with eQUEST in KBtu.

***Table 3:** Consumption of actual electricity and gas of the building from eQUEST software simulation result.*

Electric Consumption (WH)													
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Total
Space Cool			0.1	61.2	105	161	165	146	135	94.4			886.7
Heat Reject													
Refrigeration													
Space Heat													
Heat Supp.													
Hot Water			0	12.1	12.6	12.1	12.6	12.6	12.1	12.5			86.7
Pumps and Aux.	20	6.1	0.1								1.6	14.7	42.3
Ext. Usage	87	78	86.6	319	329	318	532	531	318	329	83.3	86.9	3098
Masc. Equip.													
Task Lights													
Area Lights	34	68	52.7	51	22.6	52.2	149	105	153	52.7	94.7	37.6	673.2
Total	141	152	139	444	469	564	659	795	619	401	180	139	4901
Gas Consumption (BTU x000,000)													
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Total
Space Cool													
Heat Reject													
Referation													
Space Heat													
Heat Supp.													
Hot Water	12	8.33	6	4	3.85	4.16	2.56	2.14	3.63	2.6	7.6	0.74	69.45
Pumps and Aux.													
Ext. Usage													
Masc. Equip.													
Task Lights													
Area Lights													
Total	12	8.33	6	4	3.85	4.16	2.56	2.14	3.63	2.6	7.6	0.74	69.45

Configuring the HVAC System

The HVAC system is integrated into the relevant conditioned zones of the building in the eQUEST model to determine heating and cooling loads and evaluate the impact of insulation before its application. The total energy consumption for the modeled building is obtained post-simulation. Table 4 and Figure 8 and Figure 9 illustrate the energy consumption after the HVAC system is installed. Heating and cooling loads, as well as energy consumption for ventilation, are represented in these figures. The results show that heating and cooling loads together account for 76% of the building’s total annual energy use, with heating constituting 42% and cooling 34%. The remaining 5% is used by ventilation fans. In total, the HVAC system represents 81% of the consumption of building's energy, with various other appliances and lighting making up the remaining portion. The annual energy consumption for the building after the HVAC system installation is 20,560 kWh, with 8,560 kWh used for cooling, 7,060 kWh for heating, and 970 kWh for ventilation fans. Lighting consumed 870 kWh, whereas other equipment consumed 3,100 kWh. The building's post-HVAC installation energy profile shows a substantial increase in total energy consumption, with HVAC systems comprising a significantly higher percentage of energy use compared to typical residential and commercial buildings. This deviation suggests that the HVAC system's integration has dramatically altered the building's energy dynamics, potentially due to factors such as system inefficiencies, over-sizing, or increased usage patterns (Strongylis et al., 2021).

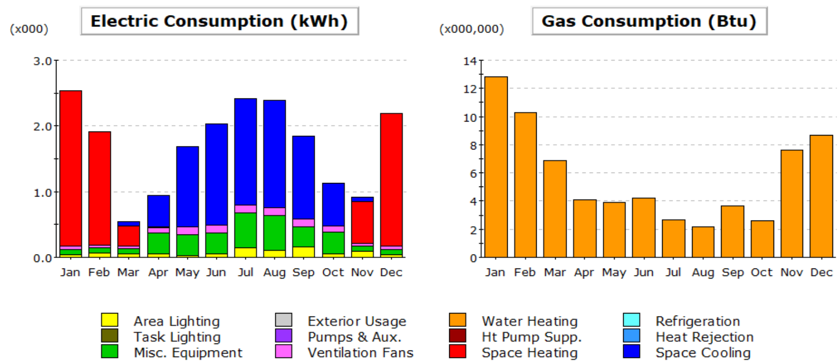


Figure 8: Consumption of electricity and gas of the building from eQUEST simulation results after the integrations of HVAC system.

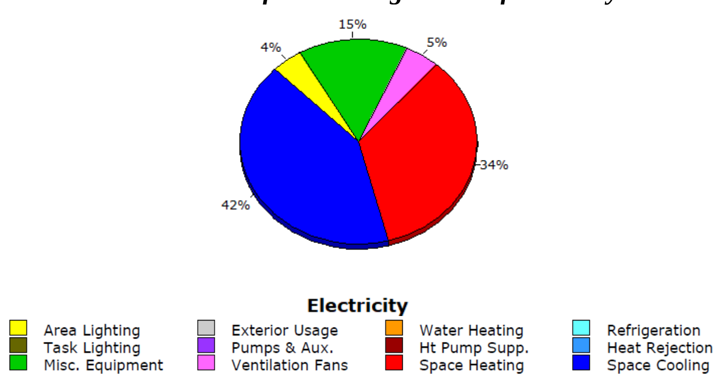


Figure 9: Pie chart for the percentage consumption of electricity obtained from eQUEST software simulation after the integrations of HVAC system.

Insulation and Parametric Analysis

In the current study, several insulation scenarios are simulated to assess their impact on energy consumption. These scenarios included full insulation, partial insulation, and insulation applied only to specific parts of the building, such as the roof or exterior walls. The results for each case are discussed in the following sections.

Table 4: Percentage consumption of electricity and gas obtained from eQUEST software simulation after the integrations of HVAC system in KWh.

Electric Consumption (KWH)													
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Total
Space Cool			0.07	0.48	1.23	1.55	1.62	1.64	1.26	0.64	0.07		8.56
Heat Reject													
Refrigeration													
Space Heat	2.37	1.73	0.30	0.01						0	0.62	2.02	7.06
HP Supp.													
Hot Water													
Vent Fans	0.05	0.04	0.03	0.08	0.11	0.12	0.12	0.12	0.11	0.10	0.04	0.04	0.97
Pumps and Aux.													
Ext. Usage													
Misc. Equip.	0.09	0.08	0.09	0.32	0.33	0.32	0.53	0.53	0.32	0.33	0.08	0.09	3.10
Task Lights													
Area Lights	0.03	0.07	0.05	0.05	0.02	0.05	0.05	0.15	0.11	0.15	0.05	0.04	0.82
Total	2.54	1.92	0.55	0.94	1.69	2.04	2.42	2.39	1.84	1.13	0.92	2.13	20.56
Gas Consumption (BTU x000,000)													
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Total
Space Cool													
Heat Reject													
Refrigeration													
Space Heat													
HP Supp.													
Hot Water	12.80	10.29	6.89	4.11	3.90	4.23	2.65	2.20	3.68	2.63	7.59	8.59	69.48
Vent Fans													
Pumps and Aux.													
Ext. Usage													
Misc. Equip.													
Task Lights													
Area Lights													
Total	12.80	10.29	6.89	4.11	3.90	4.23	2.65	2.20	3.68	2.63	7.59	8.59	69.48

Complete Insulation

Complete insulation includes minimizing loss of heat through the roof, exterior walls, and interior walls. The outcomes of 12 parametric simulations exploring the impact of various insulation thicknesses show that these thicknesses had a direct effect on the building's energy consumption, as shown in Table 5. The initial electrical energy consumption of the building is 20,560 kWh. After applying a 25 mm layer of insulation, energy consumption dropped by 4,024 kWh, and the trend continued with increased insulation thickness. At 200 mm, energy consumption decreased to 12,369 kWh, representing a 40% reduction. However, the savings began to level off after 75 mm of insulation, as shown in Figure 10**.** Beyond 75 mm, the energy savings remained relatively unchanged. Table 6 presents the costs and savings associated with varying insulation thicknesses. Insulating the building with 75 mm of insulation resulted in annual savings of Rs. 204,189, with an investment of Rs. 1,740,786. This scenario achieved a 6,522-kWh reduction in energy usage, with a payback period of 9 years. The ROI for this insulation thickness is calculated in Figure 11**,** which shows a longer payback period as insulation thickness increases beyond 75 mm, making it less practical due to the rising cost and longer recoupment time. After full insulation is applied to the building, including the roof, walls, and interior, energy usage for heating and cooling decreased. Figure 12 and Figure 13**,** along with Table 7, compare energy usage before and after full insulation. The share of energy used for heating and cooling reduced from 42% to 36%, while energy consumption for auxiliary systems, like lighting and exhaust fans, saw a slight increase.

Table 5: Consumption of energy of the building with complete insulation at varying thicknesses from eQUEST software simulation annually.

Annual Energy Use		Ambient Lights	Task Lights	Misc. Equip.	Space Heat	Space Cool	Heat Reject	Pumps & Aux.	Vent Fans	Dom Hot Water	Exterior Usage	Total
0	Basic Design	873	0	3098	7056	8559	0	0	975	0	0	20560
1	0+25 mm	873	0	3098	5158	6418	0	0	989	0	0	16536
2	0+30 mm	873	0	3098	4974	6198	0	0	991	0	0	16134
3	0+38 mm	873	0	3098	4720	5907	0	0	995	0	0	15593
4	0+50 mm	873	0	3098	4414	5547	0	0	997	0	0	14929
5	0+75 mm	873	0	3098	4000	5068	0	0	1000	0	0	14038
6	0+100 mm	873	0	3098	3733	4751	0	0	1002	0	0	13457
7	0+125 mm	873	0	3098	3548	4539	0	0	1003	0	0	13061
8	0+130 mm	873	0	3098	3519	4503	0	0	1004	0	0	12997
9	0+138 mm	873	0	3098	3474	4444	0	0	1004	0	0	12893
10	0+150 mm	873	0	3098	3414	4373	0	0	1005	0	0	12763
11	0+175 mm	873	0	3098	3311	4255	0	0	1005	0	0	12542
12	0+200 mm	873	0	3098	3232	4261	0	0	1006	0	0	12369

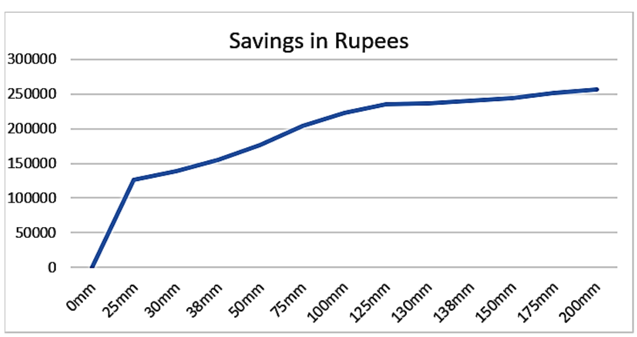


Figure 10: Graph of savings in Pakistani rupees by changing insulation thickness for the insulation of complete building.

Table 6: Insulation thickness, cost, savings, ROI and R-value for the insulation of complete building.

Insulation Size (mm)	Rate/sq. ft.	Insulation Invest.	Utility Bills/year (Rs)	Saving (Rs)	Utility Bills/Year	Savings (KWH)	Return in Years
0			644803	0	20560	0	0
25	60	696315	518810	125993	16534	4024	6
30	65	754341	506234	138569	16134	4426	5
38	70	812368	489251	155552	15593	4967	5
50	95	1102499	468484	176319	14929	5631	6
75	150	1740788	440614	204189	14038	6522	9
100	190	2204998	422426	222377	13457	7103	10
125	250	2901313	410019	234784	13061	7499	12
130	255	2959339	408016	236787	12997	7563	12
138	260	3017365	404755	240048	12893	7667	13
150	285	3307496	400698	244105	12763	7797	14
175	340	3945785	393785	251018	12542	8018	16
200	380	4409995	388358	256445	12369	8191	17

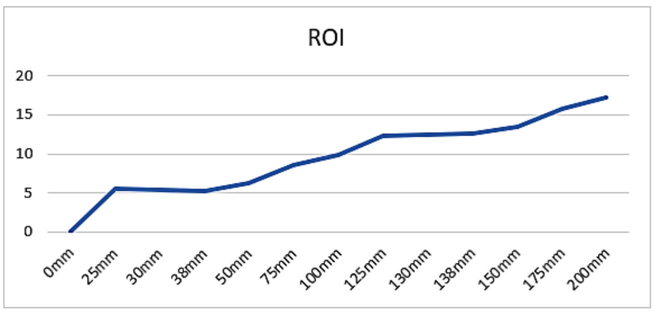


Figure 11: Graph showing return on investment for various insulation thicknesses in full building insulation.

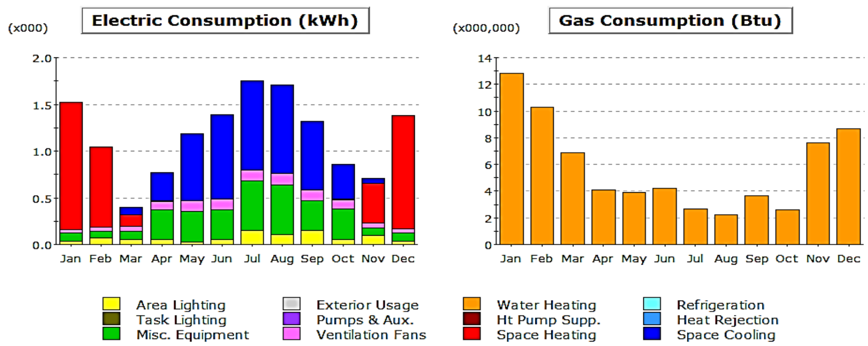


Figure 12: Electricity and gas usage in a building based on eQUEST simulation results after applying 75mm Insulation.

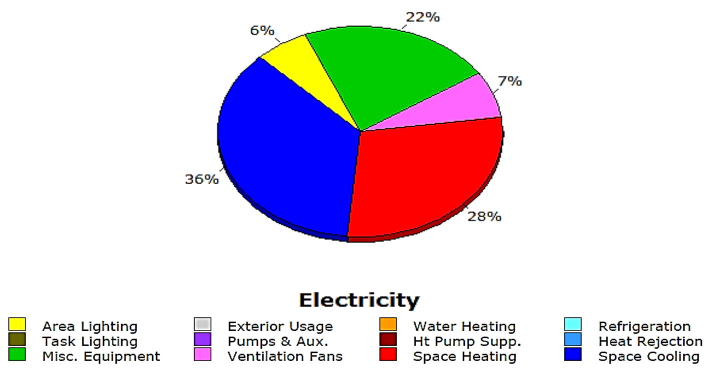


Figure 13: Pie chart for the percentage consumption of electricity using eQUEST software simulation after insulation of full building with 75.0 mm thickness.

Table 7: Consumption of electricity in kWh for the building after applying 75mm insulation based on eQUEST simulation results.

Electric Consumption (KWH x000)													
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	0.08	0.31	0.72	0.90	0.95	0.95	0.73	0.38	0.05		5.07
Heat Reject													
Refrigeration													
Space Heat	1.30	0.86	0.12	0.01						0.00	0.43	1.22	4.00
HP Supp.													
Hot Water													
Vent Fans	0.04	0.04	0.06	0.09	0.11	0.12	0.12	0.12	0.11	0.10	0.05	0.04	1.09
Pumps and Aux.													
Ext. Usage													
Misc. Equip.	0.09	0.08	0.09	0.32	0.33	0.32	0.53	0.53	0.32	0.33	0.08	0.09	3.10
Task Lights													
Area Lights	0.03	0.07	0.05	0.05	0.02	0.05	0.15	0.11	0.15	0.05	0.09	0.04	0.87
Total	1.52	1.04	0.40	0.77	1.19	1.39	1.75	1.70	1.31	0.86	0.71	1.38	14.04

The Roof and Exterior Walls Insulation

To reduce the insulation budget, a scenario is considered where only the roof and exterior walls are insulated, excluding the interior walls. This approach resulted in a lower initial investment, as shown in Table 8**,** and a slight decrease in energy efficiency due to the lack of interior wall insulation. The results for varying insulation thicknesses are summarized in Table 9**,** with energy consumption at 50 mm insulation thickness at 14,038 kWh and at 75 mm insulation thickness at 14,666 kWh. A 75 mm thickness is found to be optimal, with a payback period of 8 years compared to 9 years for fully insulating the building. Figure 14 demonstrates the relationship between insulation thickness and energy savings. As insulation thickness increased, the savings in kilowatt-hours decreased. Figure 15 shows the ROI for this scenario, indicating that the return-on-investment increases as the insulation thickness grows, but at a slower rate than in the full insulation case.

Table 8: Insulation thickness, cost, energy savings, ROI and R-value for the insulation of roofs and exterior walls.

Insulation Size (mm)	Rate/sq. ft.	Insulation Invest.	Utility Bills/year (Rs)	Saving (Rs)	Utility Bills/Year	Savings (KWH)	Return in Years
0			644803	0	20560	0	0
25	60	574941	531951	112852	16951	3609	5
30	65	622853	520575	124228	16587	3973	5
38	70	670765	504959	139844	16088	4472	5
50	95	910323	486779	158024	15507	5053	6
75	150	1437853	460455	184348	14666	5894	8
100	190	1820647	443654	201149	14129	6431	9
125	250	2395588	431626	213177	13745	6815	11
130	255	2443499	430059	214744	13695	6865	11
138	260	2491411	426892	217911	13594	6966	11
150	285	2730970	422932	221871	13467	7093	12
175	340	2257999	416149	228654	13251	7309	14
200	380	3641293	410782	234021	13079	7481	16

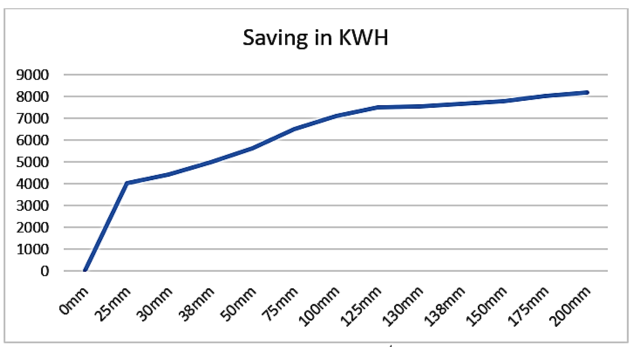


Figure 14: Savings of energy in kWh from various insulation options for roofs and exterior walls.

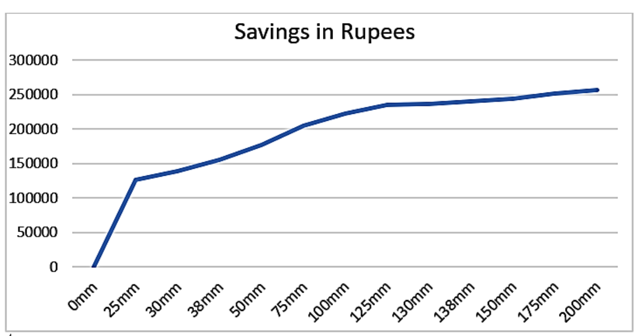


Figure 15: Cost savings in Pakistani rupees for various insulation thicknesses in roofs and exterior walls.

Table 9: Consumption of energy of a building with insulation of roof and exterior wall at variable thicknesses based on eQUEST software simulation annually.

Annual nergy Use (KWH)		Ambient Lights	Task Lights	Misc. Equip.	Space Heat	Space Cool	Heat Reject	Pumps & Aux.	Vent Fans	Dom Hot Water	Exterior Usage	Total
0	Basic Design	873	0	3098	7056	8559	0	0	975	0	0	20560
1	0+25 mm	873	0	3098	5352	6640	0	0	987	0	0	16951
2	0+30 mm	873	0	3098	5183	6444	0	0	989	0	0	16587
3	0+38 mm	873	0	3098	4947	6179	0	0	992	0	0	16088
4	0+50 mm	873	0	3098	4675	5865	0	0	995	0	0	15507
5	0+75 mm	873	0	3098	4285	5409	0	0	1000	0	0	14666
6	0+100 mm	873	0	3098	4039	5116	0	0	1003	0	0	141129
7	0+125 mm	873	0	3098	3862	4905	0	0	1006	0	0	13745
8	0+130 mm	873	0	3098	3835	4882	0	0	1007	0	0	13695
9	0+138 mm	873	0	3098	3792	4823	0	0	1008	0	0	13594
10	0+150 mm	873	0	3098	3734	4753	0	0	1009	0	0	13467
11	0+175 mm	873	0	3098	3633	4636	0	0	1011	0	0	13251
12	0+200 mm	873	0	3098	3555	4542	0	0	1012	0	0	13079

Insulation of Only the Roof

In another scenario, only the roof is insulated. This option had the lowest cost but also the least energy savings. The ROI is lower compared to the full and partial insulation cases. The roof insulation alone has the lowest ROI is that while it helps reduce heat gain and loss through the roof, significant thermal losses still occur through uninsulated walls, limiting overall energy savings. The ROI for 25 mm insulation is 9 years, for 50 mm it is 8 years, and for 75 mm it is 7 years. The total cost for 75 mm roof insulation is Rs. 646,260, with an estimated annual savings of Rs. 97,136. Figure 16 present the savings and ROI for roof-only insulation. As expected, the savings remained relatively low compared to the other insulation scenarios, making it a less effective solution in terms of long-term energy efficiency. Roof-only insulation is chosen as one of the scenarios because, in many climates, the roof is a major source of heat gain and loss, significantly influencing indoor temperatures and cooling/heating loads (Rashid et al., 2024). Additionally, this scenario is selected based on practical considerations, as roof insulation is often the easiest and most cost-effective retrofit option compared to wall or floor insulation, which may require more extensive modifications.

Potential Barrier to Implement Insulation in existing building

The initial investment required for insulation materials, labor, and retrofitting can be a significant barrier, especially for homeowners with limited budgets. While insulation leads to long-term energy savings, the payback period varies depending on the material used, climate conditions, and energy costs. Access to high-quality insulation materials may be limited in certain regions, affecting both pricing and feasibility. Sustainable and energy-efficient materials, such as aerogels or phase-change materials, may not be widely available or may come at a premium cost. Retrofitting insulation in older buildings can be challenging due to structural constraints, particularly if the existing walls, roofs, or floors are not designed for additional insulation layers. Compliance with local building codes and regulations may impose restrictions on the types and thicknesses of insulation that can be used, requiring modifications to initial designs.

Discussion on Environmental Benefits of Insulation

1. Reduction in Carbon Emissions**:** Insulation significantly decreases the need for heating and cooling**,** leading to lower energy consumption and, consequently, reduced fossil fuel dependency in power generation. Studies indicate that well-insulated buildings can reduce CO_2 emissions by up to 40%**,** depending on climate conditions and insulation type.
2. Improved Energy Efficiency**:** By minimizing heat loss in winter and heat gain in summer**,** insulation enhances the overall efficiency of HVAC systems**,** reducing energy waste. A well-insulated building requires less electricity and natural gas, directly contributing to a lower carbon footprint**.**
3. Sustainability and Material Choices**:** The use of eco-friendly insulation materials, such as recycled cellulose, sheep's wool, or aerogel-based solutions, can further improve sustainability. Some modern insulation materials have negative carbon footprints, meaning they offset more emissions than they produce during manufacturing.

Comparison with Studies in Hot-Arid and Hot-Humid Climates

HVAC Energy Consumption in Hot-Arid Climates

A study focusing on energy efficiency and thermal comfort in arid climates demonstrated that implementing specific passive design strategies led to a reduction in electricity consumption for cooling by up to 64.7% during summer months (AHMAD, 2021). Another investigation into building energy consumption patterns in hot-arid regions revealed that central and split air conditioning systems are more energy-efficient than window units, potentially reducing energy consumption by approximately 48% (Sheikha, 2024).

HVAC Energy Consumption in Hot-Humid Climates

In tropical countries characterized by hot and humid conditions, studies have shown that a significant portion of electricity, approximately 50-60%, is consumed for cooling and ventilation purposes (Chen et al., 2017). Research on sustainable active cooling strategies in hot and humid climates indicates that optimizing HVAC systems can lead to substantial energy savings while maintaining thermal comfort and indoor air quality (Simpeh et al., 2022). The findings from these studies align with our observations, where HVAC systems account for a substantial portion of total energy consumption, especially in climates with extreme temperature and humidity levels. This comparison underscores the critical need for implementing energy-efficient HVAC solutions and passive design strategies tailored to specific climatic conditions to achieve optimal energy performance.

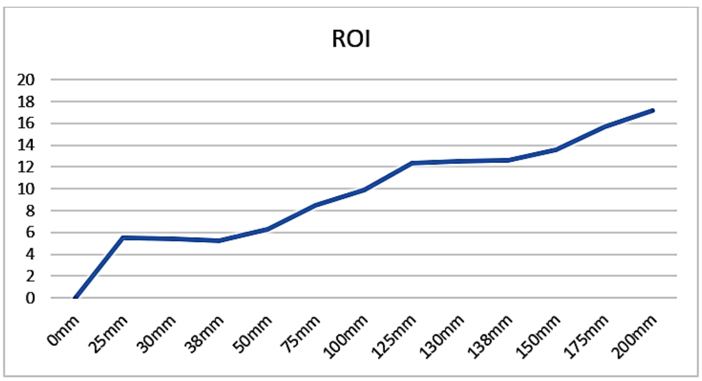


Figure 16: Graph illustrating return on investment for varying insulation thicknesses in roofs.

Conclusion

This study aimed to evaluate the effect of insulation on the energy usage of a standard residential building in Peshawar for the 2021–2022 period. The building sector plays a major role in global energy consumption, with residential buildings in Pakistan representing 45.9% of the nation's overall energy demand. The study highlights a notable disparity between the simulated and actual energy consumption of the chosen building. In the 2021–2022 period, the use of actual energy of the building is 20,560 kWh, while the simulation with 75 mm of insulation (full insulation) demonstrated a reduction to 14,038 kWh annually. The insulation of only the roof and exterior walls, roof-only insulation, and top-roof insulation, also showed significant reductions in energy consumption, except for the top-roof-only insulation scenario, which is less effective. The findings indicate that there is more than a 35% potential reduction in energy use across various building systems and loads, highlighting a substantial opportunity for energy savings. These reductions can largely be achieved through strategic changes in insulation practices, reinforcing the need for stronger energy policies promoting building insulation. The study underscores the importance of insulation as an effective means of improving energy efficiency and reducing residential energy consumption in Peshawar and similar regions.

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