

**RETROFIT STRATEGIES TO INTEGRATE THERMAL
INSULATION FOR ENERGY EFFICIENCY IN THE
RESIDENTIAL BUILDINGS OF SAUDI ARABIA**

BY

HASSAN HASSAN UMAR

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This thesis, written by **HASSAN HASSAN UMAR** under the direction of his thesis advisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN ARCHITECTURE**.



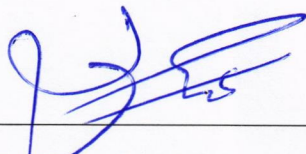
Prof. Omar S. Asfour

(Advisor)



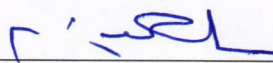
Prof. Muhammad Asif

(Member)



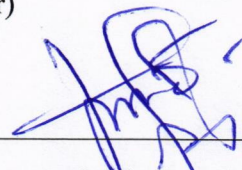
Dr. Omar Al-Mahdy

Department Chairman



Prof. Suliman S. Al-Homidan

Dean of Graduate Studies



Dr. Mohammed Alhaji Mohammed

(Member)

Date



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I dedicated this Master's thesis work to my family and my advisor.

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LIST OF ABBREVIATIONS

C_{ES} :	Cost of Energy Saved
C_{ETP} :	Cost of Residential Electricity Tariff in Saudi Arabia
CoP:	Coefficient of Performance
ECI:	Energy Cost Index
EIFS:	Exterior Insulation and Finish Systems
EPS:	Expanded Polystyrene
ES:	Energy Saved
EUI:	Energy Use Index
$Ins.TC$:	Total Cost of Strategies in Each Scenario
IECC:	International Energy Conservation Code
PP:	Payback Period
R1:	External Roof Insulation
R2:	Internal Roof Insulation
SASO:	Saudi Arabia Standard Organization
SBC:	Saudi Building Code
SEEC:	Saudi Energy Efficiency Center
SEEP:	Saudi Energy Efficiency Program
W1:	External Wall Insulation
W2:	Internal Wall Insulation
WWR:	Window-to-Wall Ratio
XPS:	Extruded Polystyrene

ABSTRACT

Full Name: Hassan Hassan Umar

Thesis Title: Retrofit Strategies to Integrate Thermal Insulation for Energy Efficiency in
The Residential Buildings of Saudi Arabia

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In hot-climate countries, such as Saudi Arabia, where air conditioning accounts for most electricity consumption, thermal insulation retrofitting establishes a major approach for enhancing energy efficiency and reducing carbon emissions. Approximately 70% of residential buildings in Saudi Arabia lack thermal insulation, leading to cooling demands that contribute to over 47% of the nation's electricity consumption. These challenges highlight that existing buildings require additional improvements in energy efficiency. Therefore, this study aims to identify effective thermal insulation retrofit strategies for walls and roofs in typical Saudi residential buildings to evaluate their impact on energy efficiency, economic benefits, and environmental effects.

A mixed-methods approach was adopted, integrating expert interviews and energy simulations using DesignBuilder software. Twenty-four retrofit scenarios, including internal and external insulation for walls and roofs, window glazing, and HVAC upgrades, were analyzed. Multi-criteria decision analysis using the TOPSIS method ranked the scenarios based on energy savings, payback periods, and material lifespan. Economic and environmental analyses further quantified their viability.

The results revealed energy savings ranging from 12% to 75%, with comprehensive strategies achieving carbon emissions reductions exceeding 74%. Scenario S8, combining roof insulation with an HVAC upgrade, ranked highest with a closeness to the ideal solution (C_i) of 0.92, offering 65.5% energy savings and a payback period of 8.6 years. Expert interviews further emphasized the importance of material availability, cost considerations, and practical challenges during implementation.

This research highlights the significant opportunity that thermal insulation retrofitting presents for improving energy efficiency and reducing the environmental impact of Saudi Arabian residential structures. The findings help policymakers, architects, and homeowners in achieving informed decisions that reflect national and international sustainability goals by offering actionable insights and real-world recommendations.

ملخص الرسالة

الاسم الكامل: حسن حسن عمر

عنوان الرسالة: إستراتيجيات التعديل التحديثي لدمج العزل الحراري لكفاءة الطاقة في المباني السكنية في المملكة العربية السعودية المجال

التخصص: الهندسة المعمارية

تاريخ الدرجة العلمية: ديسمبر 2024

في البلدان ذات المناخ الحار، مثل المملكة العربية السعودية، حيث يمثل تكييف الهواء معظم استهلاك الكهرباء، فإن إعادة تجهيز العزل الحراري يؤسس نهجاً رئيسياً لتعزيز كفاءة الطاقة وتقليل انبعاثات الكربون. يفتقر ما يقرب من 70% من المباني السكنية في المملكة العربية السعودية إلى العزل الحراري، مما يؤدي إلى متطلبات التبريد التي تساهم في أكثر من 47% من استهلاك الكهرباء في البلاد. تسلط هذه التحديات الضوء على أن المباني القائمة تتطلب تحسينات إضافية في كفاءة الطاقة. لذلك، تهدف هذه الدراسة إلى تحديد استراتيجيات فعالة لتعديل العزل الحراري للجدران والأسطح في المباني السكنية السعودية النموذجية لتقييم تأثيرها على كفاءة الطاقة والفوائد الاقتصادية والآثار البيئية.

تم استخدام DesignBuilder. تم اعتماد نهج متعدد الأساليب يدمج بين مقابلات الخبراء ومحاكاة الطاقة باستخدام برنامج تحليل أربعة وعشرين سيناريو للتعديل التحديثي، بما في ذلك العزل الداخلي والخارجي للجدران والأسقف، وزجاج النوافذ، وتحديثات التدفئة والتهوية وتكييف الهواء. وقد صنف تحليل القرارات متعدد المعايير باستخدام طريقة السيناريوهات بناءً على وفورات الطاقة وفترات الاسترداد والعمر الافتراضي للمواد. كما أجرت TOPSIS التحليلات الاقتصادية والبيئية مزيدياً من التحاليل الاقتصادية والبيئية لتحديد مدى جدواها.

كشفت النتائج عن وفورات في الطاقة تتراوح بين 12% و75%، مع استراتيجيات شاملة تحقق تخفيضات في الذي يجمع بين عزل السقف وتحديث نظام التدفئة والتهوية، 8% انبعاثات الكربون تتجاوز 74%. احتل السيناريو

بنسبة 0.92، مما يوفر وفورات في الطاقة بنسبة (Ci) وتكييف الهواء، المرتبة الأعلى مع تقارب مع الحل المثالي وفترة استرداد تبلغ 8.6 سنوات. كما أكدت مقابلات الخبراء على أهمية توافر المواد واعتبارات التكلفة 65.5% والتحديات العملية أثناء التنفيذ.

يسلط هذا البحث الضوء على الفرصة الكبيرة التي يوفرها تحديث العزل الحراري لتحسين كفاءة الطاقة وتقليل الأثر البيئي للمباني السكنية في المملكة العربية السعودية. وتساعد النتائج صانعي السياسات والمهندسين المعماريين وأصحاب المنازل في اتخاذ قرارات مستنيرة تعكس أهداف الاستدامة الوطنية والدولية من خلال تقديم رؤى قابلة للتنفيذ وتوصيات واقعية.

CHAPTER 1

INTRODUCTION

1.1 Background

During the period from 1990 to 2019, global final energy consumption experienced a growth of 38%, with non-residential buildings demonstrating a 54% increase and residential buildings showing a 32% increase, while global CO₂ emissions from buildings exhibited a 50% increase (IPCC Climate Change, 2022). Operational buildings consume 55% of worldwide electricity, with residential buildings contributing 22% (Hossain et al., 2021). To reduce these environmental implications, the building sector has led energy and carbon emission reduction efforts (Fahmy et al., 2020), particularly in hot climates where temperatures can extremely reach high levels (Ibrahim et al., 2021). Considering climate and energy use for thermal comfort is essential in such climates. Significantly, reducing energy use improves thermal comfort (Fouseki et al., 2020).

The trend of renovating or redesigning existing buildings has recently grown in popularity (Cheng et al., 2020; Dritsos, 2022). This correlates with the growing understanding that cities must mitigate climate change and achieve sustainable development goals as urban populations rise globally (Sharma et al., 2022). However, this process requires considering multiple design variables which can be difficult (Ferrara et al., 2015) and requires a significant amount of time which necessitates the adoption of a more synchronized, fast, and effective method.

To expedite the decision-making process in retrofitting, several research have examined how retrofit strategies affect building energy performance using diverse

techniques/approaches like data-driven methods (often known as black-box or grey-box models) (Fan et al., 2021; Pasichnyi et al., 2019) which employ statistical techniques to find relationships among building input and output variables, without requiring a complete understanding of the actual behavior of the buildings (Grillone et al., 2020), optimization approach (Ascione, Bianco, Mauro, et al., 2019; Hashempour et al., 2020), or a hybrid of both strategies (Ali et al., 2020; Grillone et al., 2020).

Saudi Arabia has significantly increased energy consumption attributed to the expansion of its population, urbanization, and economic growth (Al Harbi & Csala, 2019; Salam & Khan, 2018). Saudi Arabia's residential buildings use 50% of the building sector's and 80% of the nation's electric power (Al Harbi & Csala, 2019; Alshamrani et al., 2022; Felimban et al., 2019). Furthermore, Figure 1 shows that about 47.25% of countrywide electricity consumption comes from the residential sector (General Authority for statistics, 2023).

Survey analysis of General Authority for statistics (2019b), Saudi homeowners exhibited varying energy consumption patterns across different regions. The average annual energy use index (EUI) for conditioned housing areas stands at 249.5 kWh/yr.m². Notably, this EUI ranges from 184.2 kWh/yr.m² in Hail to 314 kWh/yr.m² in Madinah. The anticipated yearly energy expenses for households in Saudi Arabia amount to an incredible 52,869,842,123 Saudi Riyals (equivalent to 1.410 billion USD). Furthermore, the Energy Cost Index (ECI) for ventilated housing areas is 70.3 Saudi Riyal/year.m² (approximately 18.75 USD/year.m²). Fortunately, the cost of electricity remains generally affordable for Saudis, contingent upon their income.

Moreover, the survey findings reveal that 34% of Saudi inhabitants allocate 5-10% of their yearly budget to energy expenses. Additionally, 22% spend less than 5%, 23% allocate 11-

15%, and 21% dedicate over 16% of their budget to energy costs (General Authority for statistics, 2019a). These figures show how energy use affects Saudi households financially and emphasize the need to manage energy expenses in the context of the nation's socioeconomic environment.

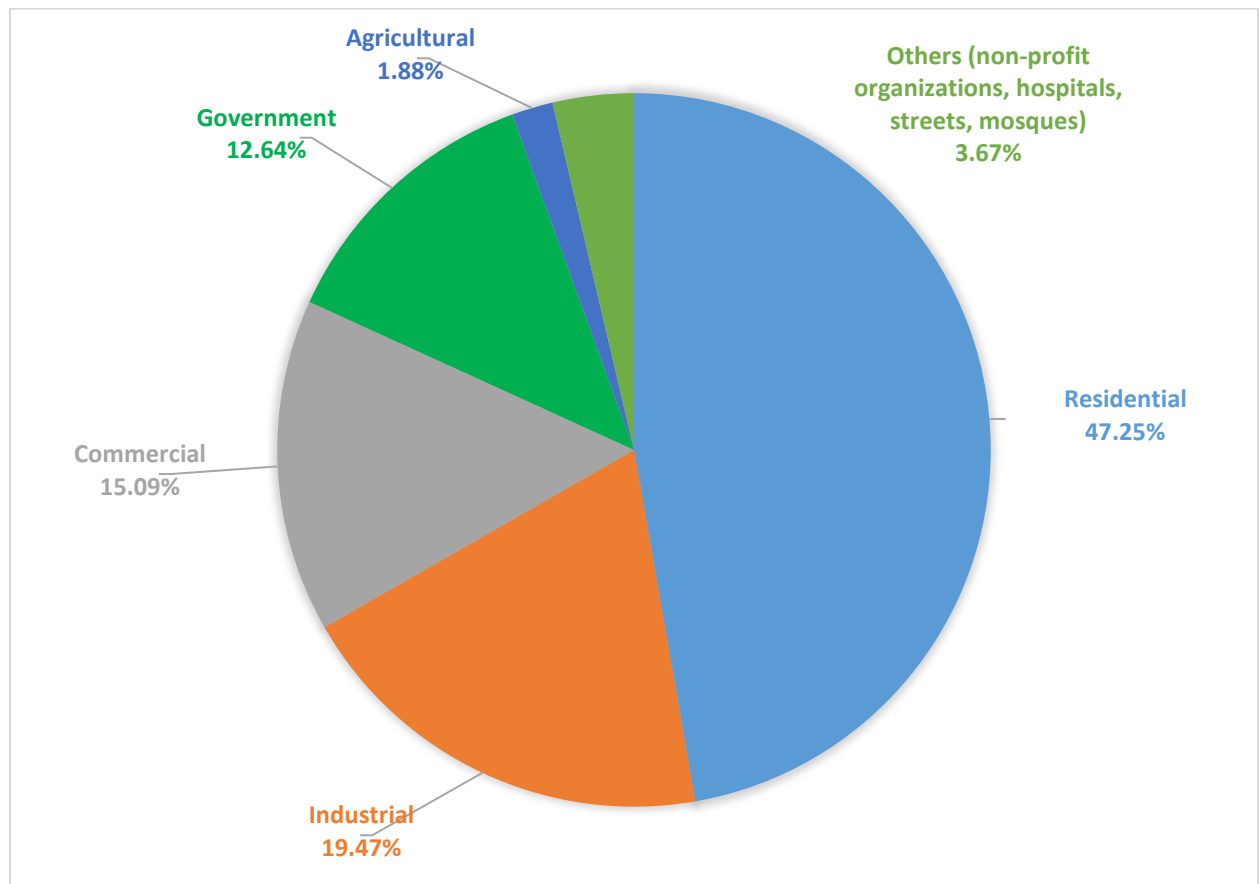


Figure 1: Sector-wise Saudi electric consumption.

Source: (General Authority for statistics, 2023)

In Saudi Arabia, residential buildings are major consumers of electricity, some are often inadequately insulated while some lack insulation entirely. A substantial number of residential buildings (at least 70%) have inadequate thermal insulation (Al-Qahtani & Elgizawi, 2020; SEEC, 2022). Particularly, there are variations among different regions within the Kingdom of Saudi Arabia (KSA). For instance, the eastern region displays the

highest proportion of houses equipped with insulation, standing at 34.48%. While the Asir region reports the lowest at 4.8% (General Authority for statistics, 2019a). This difference is associated with the challenging weather conditions in the eastern region and a prevalent energy-conscious culture influenced by prominent oil, petrochemical, and related industries. Conversely, the Asir region, marked by its mild climate and fewer impactful industries, shows lower insulation rates, a common trend in remote areas of Saudi Arabia.

The lack/inadequacy of insulation in residential buildings contributes to elevated energy usage for cooling needs (Taleb & Sharples, 2011), along with corresponding financial expenses and environmental consequences (Alaboud & Gadi, 2020). Al Kanani et al. (2017) estimated that residential buildings' air conditioning systems use 70% of electricity for interior cooling. This highlights the critical need for reducing domestic energy use. Furthermore, residential energy consumption is the main element in all operational zones of Saudi Arabia, with high temperatures being a key factor that influences electricity consumption in residential areas across the country (Mikayilov et al., 2020). Thermal insulation of walls, glazing, and roofing reduces energy consumption most in hot-arid conditions (Ozel, 2011). Implementing effective building envelope thermal insulation reduces hot air-conditioning system size and energy use, prolonging thermal comfort (Al-Homoud, 2004).

Understanding the importance of energy efficiency, the Saudi Arabian government has already taken some serious steps toward stipulating initiatives and energy policy requirements to promote thermal insulation in buildings and improve energy efficiency with an emphasis on residential buildings. The order is thus a strategic commitment that allows the fostering of sustainable development, greenhouse gas emissions reduction, and

energy consumption optimization in all sectors. Among these programs are the enforcement and regular revisions of appliances used in homes (including air conditioners) minimum energy performance requirements (MEPs) since 2001 by the Saudi Arabia Standards Organization (SASO) (SASO, 2012, 2013, 2014a, 2018). In 2010, authorities founded the Saudi Energy Efficiency Center (SEEC) to realize an improvement in energy efficiency in both consumption and production. SEEC's basic main goal is to save the natural resources of KSA and increase the level of the economic and social well-being of the country's inhabitants up to 2030 (SEEC, 2024). The projects aim to lower the cost of energy in 80 percent of the population's cities (Arab News, 2020).

Furthermore, in 2012, The Saudi Energy Efficiency Program (SEEP) was established under SEEC through the Council of Ministers to enhance energy efficiency in various sectors, such as industry, construction, and land transportation. With 12 teams from government agencies, it developed 80 initiatives focusing on demand-side efficiency during 2001–2018. SEEP has established global benchmarks for energy efficiency across various aspects of the construction sector, including thermal insulation, lighting systems, air-conditioning, and household appliances. It enforces adherence to these standards through systems applicable to both imported and locally produced commodities. Additionally, the program collaborates with organizations to streamline and enhance energy efficiency codes, extending its initiatives to new government buildings and implementing projects aimed at enhancing energy efficiency in existing structures (SEEP, 2018).

The Saudi Building Code (SBC) safeguards the needs of safety, durability, and sustainability of structures (SBC, 2024a). The code was developed through two main components: Firstly, the requirements, symbolized by the acronym (KBS), encompass the

minimum engineering standards essential for design, construction, operation, and maintenance. These standards are meticulously formulated to align with the existing requirements and regulations in the Kingdom. Secondly, the requirements, denoted by the acronym (SBC), include detailed design specifications and construction methods (SBC, 2024b). And it is regularly updated (SBC, 2024a). This regulatory framework for the building sector in Saudi Arabia is essential for ensuring the integrity and durability of projects.

In 2007, the Saudi Energy Conservation Code (SECC) was established, drawing inspiration from the International Energy Conservation Code (IECC). The SECC encompasses building codes applicable to both commercial structures (non-low-rise) (SBC 601) and residential buildings (low-buildings) (SBC 602). It explains the requirements and standards for enhancing energy efficiency in buildings, emphasizing aspects such as thermal insulation (Arab News, 2020; SEC, 2024). It became obligatory for government buildings in 2009, and in 2010, thermal insulation standards were extended to include all new constructions (SASO, 2014b). In 2014, the government required all buildings to have thermal insulation in their walls and roof. This requirement serves as a prerequisite for obtaining building permits (Alayed et al., 2021). Despite these rules, energy efficiency in Saudi Arabian buildings is not sufficient due to the existing inefficient buildings, which form most of the building stock (Alrashed & Asif, 2014b; Imran Khan et al., 2024; Krarti et al., 2017; Shenashen et al., 2016).

However, Saudi Arabia's building thermal insulation market is driven by energy-saving awareness, government policies promoting sustainable construction, and the desire to minimize carbon emissions, and it is projected to reach 437,612.95 (thousand USD) by

2029, growing 7.0% compound annual growth rate (CAGR) (MWR, 2024). Moreover, 6Wresearch (2022), reported that the market for Saudi building thermal insulation is projected to expand to a CAGR of 5.5% through 2022-2028, aligning with the nation's broader goals outlined in VISION 2030 for a diversified and sustainable economy. In 2021, the residential sector dominated Saudi Arabia's building thermal insulation market revenue.

Furthermore, over the past few years, Saudi residential electricity consumption has undergone a shift. While an increase in housing units was conventionally associated with rapid growth and household electricity use, recent trends have indicated differently. For instance, over the period between 2007 and 2018, while the consumption of electricity in households increased by 45%, a sharp growth of 73% was recorded in the growth of housing units because of a significant increase in the population of the whole country (Krarti et al., 2020). Nevertheless, since 2016, electricity consumption growth, including in residential buildings, has markedly slowed down. This deceleration can be attributed to governmental initiatives aimed at reforming the power sector and optimizing markets for electricity, resulting in increased consumer electricity prices and improved measures for energy efficiency that have reduced demand. Notably, despite this trend, housing demand remains robust, particularly among younger demographics, prompting the Ministry of Housing's initiative in early 2020 to develop 200 million square meters of new residential projects across the nation (Humidan, 2020).

According to the housing survey of (General Authority for statistics, 2019b), Saudi families occupied 3,591,098 homes, accommodating an estimated 21,420,372 people resulting in an average household number of 6 occupants. Figure 2 illustrates the percentage of Saudi Arabian residential unit type distribution. Understanding housing demand trends and

demographics is necessary for policy planning and sustainable development of residential infrastructure, despite changes in energy consumption dynamics.

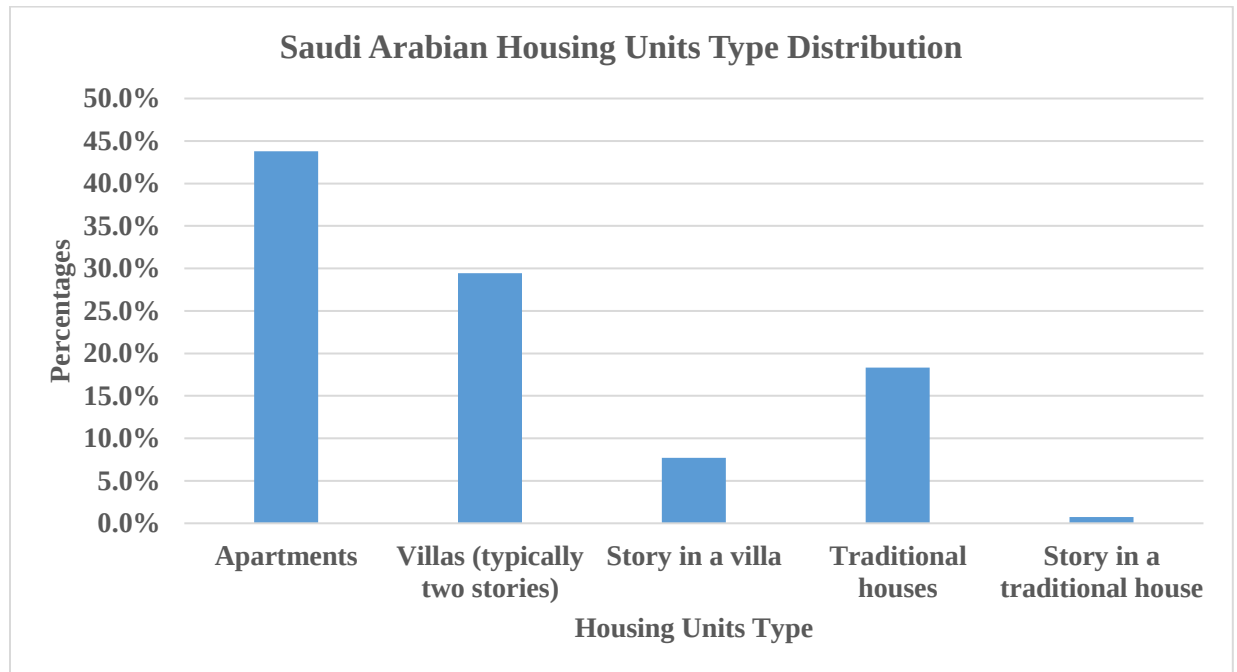


Figure 2: The Saudi Arabian housing unit type distribution

Source: (Al-Homoud & Krarti, 2021)

From the above-mentioned studies, we conclude that residential buildings in Saudi Arabia appear to be central in the context of energy consumption, requiring that energy be conserved and requiring the necessity of retrofitting them with thermal insulation to reduce energy use and thus save efficiency. Because residential structures are large parts of the built environment, energy use inside them is intricately connected with the well-being and comfort of a population and a family. The choice of residential buildings for this study is because they are different in terms of features and energy use patterns from non-residential buildings (Al-Tamimi, 2022). Other than this, occupancy patterns, which are a key component in the process efficiency of retrofit strategies, are different for residential as compared with non-residential, hence also prompting them to receive special attention.

These unique characteristics of residential buildings justify the focus on thermal insulation retrofit strategies for energy efficiency in the residential building envelope of Saudi Arabia.

1.2 Research Problem Statement

The residential building insulation in Saudi Arabia is lacking or inadequate contributing to about 70% of electricity consumption energy due to the use of air conditioning systems. This fact seems very critical for areas like Dhahran which are hot most of the time. Over the past few years, Saudi Arabian research has focused on thermal insulation in building envelopes to improve energy efficiency in residential buildings (Table 1). However, most of the studies focused on the efficiency and increasing thickness of insulating materials in roof and walls to reduce thermal loads and enhance the insulation thickness which is not practical in the line of retrofitting existing buildings because it will require the demolition of the building envelope. Furthermore, few of these studies examined such strategies' cost-effectiveness and payback period. In addition, choosing the best insulation materials may not be best for the environment which may increase carbon emissions, which have not been fully studied. Additionally, reducing energy demand through insulation retrofits can also decrease the dependence on fossil fuels for electricity generation, contributing to greenhouse gas emissions.

Therefore, this study aims to identify practical strategies for integrating thermal insulation into existing residential buildings and evaluate their effectiveness by targeting walls and roof using Dhahran climatic conditions. This study will consider the energy efficiency, payback period, and carbon emission reduction gained through the optimization of these building envelope strategies.

1.3 Aim and Objectives

This research aims to identify the most effective retrofit techniques of wall and roof thermal insulation for improving energy efficiency in typical residential buildings of Saudi Arabia.

To achieve this aim, the study has set the following objectives:

- I. Identify thermal insulation integration strategies into the existing residential buildings envelope in Saudi Arabia.
- II. Evaluate the impact of these different retrofit strategies on energy consumption with reference to the hot climatic conditions of Saudi Arabia.
- III. Assess the economic analysis and carbon emissions reduction of these strategies and determine the most effective ones.

1.4 Significance of the study

The research helps global energy efficiency discussions, especially in hot areas. It tries to reduce residential building environmental impact through sustainable retrofit options. Actionable knowledge helps architects, builders, and construction professionals embrace energy-efficient retrofit procedures. The study encourages homeowners to make informed decisions that improve living conditions and save energy expenses by providing affordable retrofit choices. Providing empirical data and analysis, the research advances academic understanding and encourages additional research in relevant subjects. It also helps in enhancing energy conservation and improving energy efficiency in the Kingdom which is part of the Vision 2030 of Saudi Arabia under the program, known as the Saudi Energy Efficiency Centre (SEEC) Program, which aims to enhance efficiency in three key sectors

that collectively contribute to more than 90% of the country's energy consumption: buildings, transportation, and industry (Saudi Energy Efficiency Center, 2018).

1.5 Methodology

The study methodology comprises of four phases. The first phase is Model Development and Validation. This phase focuses on creating and refining the typical model case using DesignBuilder software, which will be used to address the research objectives outlined in this thesis. This phase typically involves the two steps including development of the building case which has two sections which are case study selection (explains the justification for using the DesignBuilder software and selecting the villa house as a case study) and characteristics creation of the case study model which (explains appropriate climatic data used for the location and building characteristics). The second step is calibration and validation, which involves ensuring that the appropriate input information on envelope construction materials and other relevant parameters are provided to the DesignBuilder software. Then conduct a simulation analysis on a prototypical villa and compare it with a building of similar typology supported by validated data.

The second phase is the Criteria Development for Selecting Thermal Insulation Materials which involves interviewing the building construction experts in Saudi Arabia to gather their views on identifying thermal insulation materials that are applicable, available, durable, and practical. It also explored the insulation techniques used in residential retrofits, factors influencing material selection, such as cost and availability, and the challenges encountered during the retrofitting process. The third phase is the Analysis of Retrofit Impacts on Energy Consumption which involves the exploration of the identified retrofit

strategies for both wall and roof and identifying design options that maximize energy efficiency by minimizing the total energy needs for cooling.

The final phase is the Analysis of the Economic Benefits and Environmental Effects, it involves conducting an economic analysis by calculating the payback period of each strategy and finding design options or strategies that have the highest payback period. Furthermore, an analysis of the environmental impact will be conducted using the DesignBuilder software to determine the reduction impacts of each strategy on the total carbon emissions of the building and finally identify a strategy that has the highest impact on the CO₂ emissions reduction. Finally, it determined the most effective strategies using a multi-criteria approach using Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS).

1.6 Limitations of the Study

The study investigates effective thermal insulation retrofit strategies' impact on energy efficiency in relation to residential buildings in Saudi Arabia. The thesis covers the economic benefits and environmental impact by determining the payback period and carbon emission saving of the different strategies employed, shedding light on the urgency of the reduction of energy and carbon especially in hot climatic conditions. As much as the study covers lots of ground, some limitations require consideration. The study is concerned primarily with residential buildings; hence the results may not be directly generalizable to the case of non-residential buildings. The study is geographically confined to the specifics of climatic conditions in Dhahran, Saudi Arabia; hence it may not be generalized to those regions with different climate patterns. Furthermore, the reliance on DesignBuilder to model the energy performance introduces certain limitations. While the software excels in

architectural modeling and energy simulations, it has constraints in handling complex thermal bridging facts like mentioned by the experts, which may have impact on the energy performance.

1.7 Structure of the Thesis

The thesis is structured into five chapters, each with distinct content. The upcoming overview briefly outlines the contents of each chapter. The study's aim and objectives are outlined in Section 1.3 under the introduction chapter.

Chapter 1 provides a background on the study which includes, the environmental impact of buildings; the increased trend of retrofitting existing buildings in connection to urban sustainability; discusses retrofit strategies by emphasizing their usefulness in design variable management; the significant increase of energy consumption, the inadequacy of thermal insulation, and the need for retrofit in Saudi Arabia residential sector; government initiatives for energy efficiency; Saudi building codes and regulations and the governmental decision to make it mandatory in buildings; housing demand and initiatives; and justification for focusing on thermal insulation retrofit strategies for residential building and their unique characteristics compared to non-residential ones. Subsequently, it delineates the problem statement; the study's aim and objectives; the significance of the study; and briefly summarizes the methodological steps.

Chapter 2 discusses building retrofit and energy efficiency, highlighting the global energy problem and the role of buildings, the need for energy-efficient building design, and the concept of retrofit. It emphasizes the significance of building envelope design, thermal insulation of various envelope elements, and recent Saudi regulations on thermal

insulation. The chapter also addresses the necessity of retrofitting residential buildings in Saudi Arabia, detailing energy challenges, residential building types, their current thermal insulation status, potential retrofit strategies, and existing challenges. Lastly, it reviews previous studies to identify research gaps, establishing the context for this study's contribution to energy efficiency in residential buildings.

Chapter 3 commences by providing a summary of the four methodological phases employed in conducting this research (as depicted in Figure 4). It will also analyze the results of the validation process (within the calibration and validation section of the methodology). Subsequently, a comprehensive description of the research methodologies employed in each phase is provided.

Chapter 4 shows the interviewees' feedback regarding the thermal insulation techniques used in residential retrofits, factors influencing their choice of the thermal insulation materials such as cost and availability of materials, and the challenges encountered during the retrofitting, then discuss the study findings obtained from the application of various retrofit strategies on energy consumption, carbon emissions reduction and the economic benefits (payback periods). Ultimately, it analyzes the findings of the study and explains their importance. Additionally, it will analyze the implications of the results and their contribution to the current knowledge base.

Chapter 5 is the final chapter which will provide an organized summary of the study's findings, while also considering the objectives and procedural measures outlined in Chapters 1 and 3. Furthermore, it will analyze the implications of these conclusions. Furthermore, it will delineate the limitations of the study, specifically about the employed strategies. Ultimately, it will present suggestions for further projects.

CHAPTER 2

LITERATURE REVIEW

This chapter explores building retrofit and energy efficiency by introducing the global energy problem and the role of buildings, the need to design new energy-efficient buildings, the concept of retrofit, and its role in energy efficiency. It then examines thermal insulation and building retrofitting while emphasizing the importance of building envelope design, the role of thermal insulation of the different envelope elements, thermal insulators, the Saudi Building Code, and recent regulations regarding thermal insulation. The chapter also addresses the need for residential building retrofit in Saudi Arabia, discussing the energy challenges in Saudi Arabia, the role of residential buildings, the type of residential buildings and their thermal insulation status, potential thermal insulation retrofit strategies, and the existing challenges. Finally, it reviews previous studies to identify the current research gap, setting the context for this study's contribution to energy efficiency in residential buildings.

2.1 Building Retrofit and Energy Efficiency

Growing energy demand and the related environmental effects including greenhouse gas emissions and resource depletion highlight the worldwide energy challenge. Considering around 55% of the energy consumed worldwide comes from operational buildings, with residential buildings contributing 22% (Hossain et al., 2021). Between 1990 and 2019, global final energy consumption experienced a growth of 38%, with non-residential buildings demonstrating a 54% increase and residential buildings showing a 32% increase, while global CO₂ emissions from buildings showed a 50% increase (IPCC Climate Change,

2022). The growing awareness of the environmental effects of energy use has prompted initiatives to reduce consumption, especially in hot countries where high temperatures require energy-intensive cooling techniques (Ibrahim et al., 2021).

Designing retrofit strategies has become clear as a feasible way to solve environmental problems and improve energy savings. Retrofits enable improvements in the thermal performance of existing building components including walls, windows, roof, and HVAC systems. Retrofitting is especially crucial for buildings that were not originally intended with energy efficiency in mind (Ahmed et al., 2022; Felimban et al., 2023). These kinds of strategies not only save energy use but also increase thermal comfort (Fouseki et al., 2020). Retrofitting provides an alternative to reach sustainable development objectives in the framework of climate change and increasing urban populations (Sharma et al., 2022). Studies on several retrofit strategies, data-driven approaches, optimization methods, and hybrid technologies, have shown how well they improve building energy performance (Ali et al., 2020; Ascione, Bianco, Mauro, et al., 2019; Fan et al., 2021; Grillone et al., 2020; Hashempour et al., 2020; Pasichnyi et al., 2019). However, these statistical techniques are used to expedite the decision-process in order to find relationships among building input and output variables, without requiring a complete understanding of the actual behavior of the buildings (Grillone et al., 2020).

Improving energy efficiency and reducing energy usage depends much on retrofitting existing buildings. Retrofitting strategies have shown great promise for energy savings in Saudi Arabia. For instance, incorporating a mere 2 cm layer of polyurethane on the external walls of residential buildings can result in a significant 27% reduction in the demand for cooling (Alaboud & Gadi, 2020). Highlighting that wall insulation can enhance building

energy efficiency and decrease energy consumption. Similarly, retrofitting commercial buildings with energy-efficient technologies can reduce annual energy use by 27% (Ahmed et al., 2022). Comprehensive retrofit programs can help the residential sector's annual electricity consumption reduce by 50% in Saudi Arabia (Krarti et al., 2020). Therefore, adopting energy-efficient technologies and conducting comprehensive retrofit projects will help the nation significant social, environmental, and financial benefits, thereby supporting the objectives of Saudi Vision 2030.

2.2 Thermal Insulation and Building Retrofitting

Walls, ceilings, windows, and flooring all help to define the building envelope, separating the interior from the outside temperature. It profoundly affects building general sustainability, indoor thermal comfort, and energy economy. Heat transmission, thermal bridging, air permeability, and moisture control have to all be considered in the building envelope design. Efficient envelope design minimizes indoor temperature, reduces energy loss, and reduces dependence on active cooling or heating systems (Kumar et al., 2021). High solar radiation and temperatures in hot climates such as Saudi Arabia require the utilization of enhanced thermal insulation materials and reflecting coatings to improve the envelope's performance.

A building's surface area consists mostly of walls, which hence determine its thermal load. Effectively insulated walls help reduce heat transmission, so preserving cooler summer temperatures and warmer winters. To improve wall insulation, one often uses cavity wall insulation, insulated concrete forms (ICFs), and external thermal insulation composite systems (ETICS). For instance, according to Latha et al. (2023), wall construction plays a crucial role in controlling heat absorption within buildings, particularly in hot climates such

as those found in Egypt and the Middle East. In addition, research conducted by Rakhshan & Friess (2017) indicated that improving wall insulation to reach a U-value of 0.3 W/(m²K), coupled with enhancing air conditioning systems to attain a Coefficient of Performance (CoP) of 2.7, resulted in a 40% drop in summer peak energy consumption and a 32% decrease in CO₂ production. Typically, the walls of residential buildings are constructed using individual bricks, which may be red blocks, cement blocks, autoclaved aerated concrete (burkani blocks, or Siporex). These bricks are then covered on both sides with a 2 cm layer of cement mortar as a finishing touch (Felimban, 2024).

In 2021, block factories in Saudi Arabia were mandated to comply with specific thermal properties outlined in the updated Saudi Building Code (SBC) to enhance energy efficiency in building envelopes. Cement blocks with unfilled holes exhibit a K-value of 0.976 W/mK, an R-value of 0.204918 m²K/W, and a U-value of 4.880 W/m²K, indicating relatively low thermal performance. In comparison, red blocks with unfilled holes show improved thermal resistance with a K-value of 0.382 W/mK, an R-value of 0.52356 m²K/W, and a U-value of 1.910 W/m²K. Hollow concrete blocks (arkani) demonstrate the lowest U-value at 0.555556 W/m²K and a K-value of 0.36 W/mK, reflecting higher thermal efficiency. Autoclaved aerated concrete (Siporex) outperforms traditional materials with a K-value of 0.156 W/mK, an R-value of 1.282051 m²K/W, and a U-value of 0.780 W/m²K, making it a highly effective option for energy-efficient wall systems (Felimban, 2024).

Roof accounts for most of the heat gain in structures, particularly in areas that have high solar intensity. Combining reflecting or radiant barrier materials with roof insulation will help significantly reduce indoor temperatures. In hot climates, technologies including insulated roof panels, cool and green roofs have demonstrated effectiveness. Because of

their cost-effectiveness and energy savings, cool roofing technologies, including coatings with great solar reflectance, are becoming increasingly popular in Saudi Arabia. According to a comparative study by Rawat & Singh (2022), cool roof technology demonstrates significant energy-saving potential across various climate zones. The research revealed that the average energy conservation effect of cool roofs ranges from 15% to 35.7% in different climatic conditions, including Temperate, Tropical, Composite, Hot, and Warm-Humid regions.

Windows facilitates significant energy flow between indoor and outdoor spaces. While permitting natural light penetration, advanced glazing systems including spectrally selective films, low-emissivity coatings, and double or triple glazing enhance thermal insulation characteristics (Hart et al., 2019; Mohamed et al., 2023). Similarly, reducing direct solar heat gain, shading devices including automated blinds, louvers, and overhangs improve window performance even further. These innovations also save a lot of energy; for instance, thin-glass triple-pane glazing can save up to 7% energy in cooling-dominated areas like Houston, Texas (Hart et al., 2019), while aerogel glazing on southern facades can lower annual energy usage by 26.3% (Mohamed et al., 2023).

In February 2022, the Saudi Building Code (SBC) National Committee reduced energy efficiency requirements in response to feedback from construction companies and hesitancy to issue new residential building permits. The evolution of SBC energy requirements highlights progressive upgrades in construction standards to improve building energy performance, with specific reference to changes in U-values, solar heat gain coefficients (SHGC), and system efficiencies.

The updates to wall construction U-values, initially set at 0.342 W/m²K as of July 1, 2021, were revised to 0.403 W/m²K on August 23, 2021, and further increased to 0.611 W/m²K by February 21, 2022, with an application deadline by the end of 2023. Roof construction U-values also shifted from 0.202 W/m²K to 0.272 W/m²K by the second update and remained consistent thereafter. Ground and floor construction U-values, however, retained a uniform value of 0.49 W/m²K across all revisions (Felimban et al., 2023).

Window glazing specifications, including U-values of 2.66 W/m²K and an SHGC of 0.25, remained unchanged, as well as the maximum window-to-wall ratio (WWR) of 25%. Air infiltration rates, maintained at 4 ACH (Air Changes per Hour at 50 Pascals), and HVAC system efficiency, specified as a Coefficient of Performance (CoP) of 4, remained constant throughout the updates (Felimban et al., 2023). These revisions illustrate a focused strategy to balance thermal performance and energy efficiency while ensuring the feasibility of compliance for stakeholders.

This thesis has previously noted that most residential structures in Saudi Arabia are not adequately insulated, which substantially reduces energy efficiency by facilitating external heat transfer to interior spaces. The insulation materials commonly accessible and utilized in Saudi Arabia comprise Polyurethane, Perlite, Siporex, Polystyrene, Mineral wool, and Glass wool (Kumar et al., 2020). When choosing an appropriate insulation material during the design phase, several aspects must be considered, including accessibility, price, ease of installation, sound insulation properties, and fire resistance.

Various insulation materials are commonly used in retrofitting buildings in hot climates, each providing unique energy efficiency and thermal comfort benefits. Fiberglass, with a high thermal resistance (R-value of 2.2 to 4.3 per inch) and easy installation, is widely

applied in walls, attics, and floors, offering significant energy savings (Alyami et al., 2022; Lakatos, 2022). Polystyrene foam, available in expanded (EPS) and extruded (XPS) forms, has R-values of 3.6 to 5 per inch and is highly moisture-resistant, making it suitable for walls, floors, and roofs in humid climates (Alyami et al., 2022). Polyurethane spray foam, with an R-value of 6 to 7 per inch, excels in thermal resistance and air sealing, improving energy efficiency in complex building geometries and hard-to-reach areas, albeit requiring professional installation (Alyami et al., 2022).

Reflective insulation is effective in attics and roofs by reducing radiant heat transfer and enhancing thermal comfort indoors despite a lower R-value (Alyami et al., 2022). Aerogels, with extremely low thermal conductivity and high fire resistance, are used in specialized retrofitting applications like external walls and roofs, offering superior R-values and moisture resistance (Ascione, Bianco, De Masi, et al., 2019; Kumar et al., 2021; Wicklein et al., 2015). Phase Change Materials (PCMs) stabilize indoor temperatures by absorbing and releasing thermal energy during phase transitions, contributing to greater thermal mass and reduced energy use in applications like external wall cladding and ceiling insulation, though they lack a traditional R-value and are more challenging to install (Ascione, Bianco, De Masi, et al., 2019; Kumar et al., 2021). This highlights that each material presents unique benefits, with choices guided by specific climate conditions and installation requirements.

Furthermore, research by Alkenaidari & Wang (2018) revealed substantial differences in thermal insulation usage across various building types. Their study indicated that commercial and government buildings have consistently employed and improved thermal insulation techniques. In contrast, while the adoption of thermal insulation in residential

structures is growing, it remains statistically insignificant. The research findings suggest that typical homes built prior to 2002 lack sufficient thermal insulation in their doors, walls, roofs, and to a lesser extent, windows. This evidence strongly indicates that substantial improvements to the building envelope are required for residential structures to achieve high levels of energy efficiency.

2.3 The Need for Residential Buildings Retrofit in Saudi Arabia

In Saudi Arabia, a major issue arises from the fact that buildings consume 80% of the nation's electricity, with residential buildings alone account for 47.25%, and the dependence on air conditioning systems, which account for up to 70% of household energy use (Al Harbi & Csala, 2019; Alshamrani et al., 2022; Felimban et al., 2019; General Authority for statistics, 2023). The Kingdom's high temperature makes this reliance on cooling systems significantly greater given thermal comfort is essential.

Additional demands come from population growth, urbanization, and economic development, which have significant financial and environmental consequences, drive the Kingdom's energy use even more. The average annual energy use index (EUI) for conditioned housing areas in Saudi Arabia stands at 249.5 kWh/m², significantly higher than global averages. This excessive energy usage causes a significant financial burden on households, since energy costs a significant share of households' budgets (General Authority for statistics 2019b). Furthermore, this increasing energy requirement is expected to deplete all oil exports by 2035, potentially triggering an oil crisis (Alrashed & Asif, 2014a; General Authority for statistics, 2023; SEEC, 2022). This situation emphasizes the urgent necessity of energy-saving policies in every sector, especially in the building stock, which still consumes most of the electricity.

In response to this issue, Saudi Arabia has launched several initiatives aimed at decreasing energy usage and supporting the objectives of the 2030 Saudi Vision. These efforts include enhancing building regulations for new structures and implementing strategies to conserve energy as previously mentioned in chapter one. Nevertheless, achieving Saudi Arabia's 2060 Net Zero target necessitates immediate action to enhance energy efficiency in existing buildings, with a particular focus on the 5.5 million units in the residential housing sector (Kamboj et al., 2023). Therefore, improving the energy efficiency in Saudi Arabia's residential sector depends on the application of comprehensive retrofit strategies. Improvements in energy efficiency are essential for existing residential buildings, particularly focusing on walls and roofs. These structural components are responsible for most of the heat absorption, especially in regions with high levels of solar radiation.

The housing units in Saudi Arabia can be classified into three main types: villas, apartments, and traditional houses (Aldubyan et al., 2021). Saudi villa's total built area is determined by the plot of land area of the house (Alrashed & Asif, 2015b). The built-up area shall be assumed at 1.50 multiplied by the land area under the country's current regulations (Bahammam & Haidar, 2020). Subsequently, the villa's total built-up area is 675 to 937.5 square meters. The land areas in Saudi Arabia differ in size between 450 and 625 square meters (Haidar & Bahammam, 2021), which influences the built areas of the villas. The average plot size in the country stands at 625 square meters (Aldossary et al., 2015; Taleb, 2012), therefore a standard villa will cover an area of about 937.5 square meters. Villas are usually two floors with a penthouse floor (Almehrej, 2015), with a maximum height reaching up to 12 meters floor-to-roof level.

Concerns regarding larger villa sizes in Saudi Arabia branch from several factors. First, the vast size of land given to each house (Haidar & Bahammam, 2021), mostly 625 square meters (Aldossary et al., 2015; Taleb, 2012), encourages many homeowners to build more spacious homes (Aldossary et al., 2015). Villas often take a different of duplicated rooms, e.g., separate receptions for men and women, probably reflecting privacy considerations that have gone into the design of the house (Mulliner & Algrnas, 2018; Surf, 2017). Besides, occupancy affects the size of the house, with a bigger occupancy leading to the development of a bigger house (Surf, 2017). On the other hand, Alqahtany & Bin Mohanna (2019) report that the average number of a household's family members in Saudi Arabia is 6.7. All these combined make for the trend that villa sizes are larger in the country.

Apartments are described as a group of rooms that constitute a housing unit. Apartments normally consist of two or three bedrooms, bathrooms, a kitchen, a living area, and a dining area. Apartments are also known as flats at times. According to Alzamil (2014), these units are adjacent to other units that are similar and are located within a building that has multiple stories. Aldossary et al. (2014a) present a floor plan that depicts two conventional flats in Saudi Arabia (Figure 3). Every one of these flats has a space that is approximately 210 square meters in size.

An investigation conducted by Alqahtany & Bin Mohanna (2019) and Alzamil (2014), emphasized that conventional/traditional dwellings, built many years ago, are commonly found in rural regions, small municipalities, historic urban centers, and impoverished neighborhoods. According to Alrashed & Asif (2015b), this house form covers the entire land area. Commonly, these dwellings exhibit a central courtyard, encompassed by diverse rooms. Furthermore, Alzamil (2014) reported that the prevalence of this house form has

been dropping, suggesting a decreasing tendency. Consequently, these conventional dwelling units misrepresent the current housing situation in Saudi Arabia.

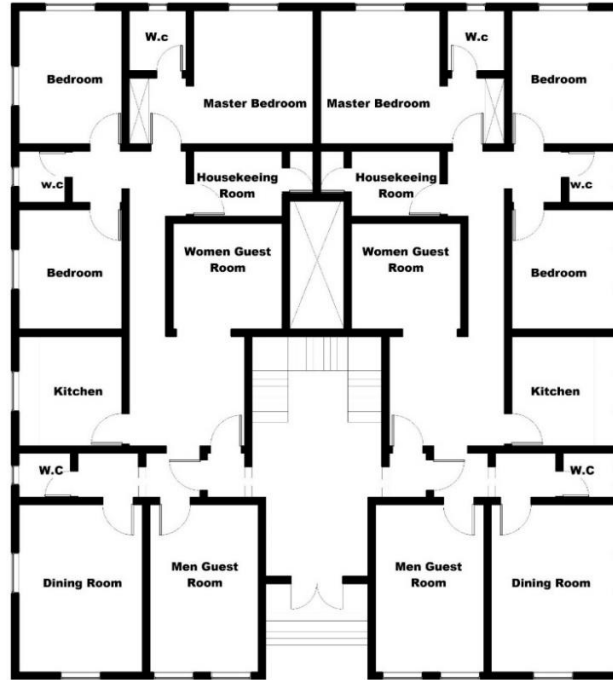


Figure 3: A typical two-apartment layout in Saudi Arabia

Source: (Aldossary et al., 2014b)

In Saudi Arabia, current renovation projects have mainly concentrated on modifying the structure or improving the visual appeal of buildings. Felimban et al. (2023) and Konstantinou (2014) highlighted four major techniques that define energy retrofit strategies: Replace, Add-In, Wrap-It, and Add-On; each presents special interventions, advantages, and challenges. The Replace approach calls for replacing façade elements, either totally or partially, with components with better energy performance including windows, walls, and insulation. Although this method usually has significant initial operations costs, it guarantees excellent thermal performance with minimum user disruption. From the inside, the Add-In technique improves building components by

adding internal or cavity insulation, thickening walls, upgrading windows, and applying sealants. This approach demands careful consideration of thermal bridging and may lower usable space even if it is appropriate for current structures and increases thermal resistance.

Despite high prices and SBC constraints sometimes limit its application, the Wrap-It technique effectively eliminates thermal bridges and increases resistance by encasing the building with external solutions such as Exterior insulation and finish system (EIFS) or second-skin façades. Finally, the Add-On approach emphasizes higher energy performance and sometimes additional inside areas by combining shade devices, balconies, or merging balconies with indoor spaces. SBC limits, however, restrict this strategy especially for low WWR applications. These techniques underline the several options depending on building requirements and regulatory systems to increase energy efficiency.

Retrofitting existing buildings for energy efficiency is crucial for reducing the environmental footprint, enhancing economic gains, and improving social welfare. However, this process encounters barriers like financial, technical, logistical, and regulatory issues (Iwuanyanwu et al., 2024; Petkov et al., 2021). Imran Khan et al. (2024) identified 46 barriers to Building Energy Efficiency (BEE) adoption in the Gulf Cooperation Council (GCC) region, categorized into institutional and governmental, financial and economic, technological and technical, awareness and capacity, cultural and social, and industry and market-related. Despite having the financial capacity for government-led energy efficiency initiatives, GCC efforts are impeded by low energy prices and the political structure of rentier states. A significant technical challenge in retrofitting is addressing structural problems (Menna et al., 2022). Many older buildings lack the structural integrity to support significant retrofits. Dauda & Ajayi (2022) argue

that overcoming these constraints requires advanced engineering and detailed design to safely integrate retrofits while maintaining structural integrity. Additionally, Umar et al. (2024) note that upgrading systems, such as installing advanced HVAC units, without disrupting daily operations, adds complexity and demands precise coordination and specialized expertise.

Prabatha et al. (2022) identify the high initial costs of retrofitting existing buildings as a major financial barrier, requiring significant investment in new technologies, labor, and materials. Funding these projects is challenging as financial institutions may be hesitant due to potential risks or uncertain returns (Imran Khan et al., 2024). Although energy-efficient retrofits offer long-term savings, the substantial initial investment and variable payback periods, influenced by energy prices, building usage, and retrofit effectiveness, create uncertainty. This can deter property owners and investors from retrofitting if they doubt recovering their investment in a reasonable timeframe (Prabatha et al., 2022). Liu et al. (2020) noted that outdated building codes and standards pose significant regulatory challenges to sustainable retrofitting, especially in the GCC, including Saudi Arabia, where older buildings often do not meet current thermal standards (Imran Khan et al., 2024). Additionally, obtaining necessary licenses and authorizations can be lengthy and complex, hindering retrofit initiatives. Updating building codes to align with modern sustainability standards is essential for streamlining retrofitting efforts (Imran Khan et al., 2024).

Bassey et al. (2024) highlight that retrofitting projects present significant logistical challenges due to disruptions they cause to building occupants. Construction activities produce noise, dust, and restricted access, impacting daily routines and business operations. In residential buildings, this disruption may necessitate temporary relocation, increasing

both project complexity and costs. Coordination among various stakeholders, each with unique priorities, is essential to keep projects on schedule and within budget, making it a demanding task.

Additionally, cultural and behavioral barriers, including attitudes, beliefs, and behaviors, hinder the adoption of energy-efficient technologies (Imran Khan et al., 2024). Upgrading structures to sustainability standards involves complex challenges in technical, economic, regulatory, and operational domains (Iwuanyanwu et al., 2024; Petkov et al., 2021). Despite these barriers, retrofitting offers significant benefits such as reduced environmental impact, energy savings, cost reductions, increased property value, and improved occupant well-being.

2.4 Previous Studies and Current Research Gap

Several past research studies have enhanced building envelopes and facade features to increase energy efficiency, lower costs, and minimize environmental effects in residential buildings. Saudi Arabia's residential sector plays a key role in the country's elevated energy consumption, which is over three times greater than the worldwide average. Addressing this concern, Ahmed & Asif (2020) examine the techno-economic possibility of upgrading existing residences in the Eastern Province of Saudi Arabia. In a complementary effort, Krarti et al. (2020) developed a Kingdom-wide residential building stock model for energy utilizing engineering bottom-up methods. This model is useful for assessing the effects of energy efficiency and demand-side management programs aimed at the residential building sector.

Addressing the substantial energy use in Saudi Arabian residential buildings, particularly with air conditioning accounting for 70% of electricity consumption, Alaboud & Gadi (2020) utilized EnergyPlus to assess the thermal efficiency of mid-rise residential buildings in Makkah. Their study compares the requirements for thermal insulation with the embodied energy of insulating materials, providing insights into energy and carbon payback. Given the arid climate of Saudi Arabia, thermal insulation emerges as a crucial component for achieving energy efficiency. Al-Tamimi (2021) found that the type and thickness of thermal insulation impact the annual energy consumption of a prototype building in three Saudi localities. The significant cooling needs highlight the need for effective insulation in this study.

In light of climate and energy goals, Cusenza et al. (2021) refurbished residential apartments to enhance vertical envelope thermal insulation. Another study analyzes the energy and environmental consequences of retrofitting and the impact of stringent thermal insulation on decisions regarding energy efficiency investments. The study utilizes a mathematical model that integrates a household focused on maximizing benefits into a building energy model to analyze Saudi Arabia's gradual investments in improving residential energy efficiency (Matar, 2021). This study highlights residential energy efficiency options for investment. Alayed et al. (2021) examine cooling needs and the building envelope in detached villas, which have high air conditioning energy demands. This study examines how cooling demand affects energy usage in detached villas.

Expanding to Mediterranean regions, Karanafti & Theodosiou (2021), examine residential building energy performance in various climates, including Saudi Arabia. The study finds that Southern European and Northern African building envelopes function better with

reduced thermal resistance, while Southern locations may benefit from higher thermal resistance. Alyami et al. (2022) investigate the building envelope's thermal characteristics to understand how location and insulation affect Saudi home energy performance. This study examines how insulating options affect energy efficiency in five Saudi Arabian climates.

The above-mentioned studies have enhanced building envelopes and façade parameters to increase energy efficiency, reduce costs, and minimize environmental impacts in residential buildings. Each study successfully reached its objectives by utilizing different design parameters and retrofit techniques. Table 1. categorizes some of the literature on residential retrofit strategies for energy efficiency, especially in Saudi Arabia's hot environment.

Table 1: Overview of previous studies on energy efficiency in residential buildings in Saudi Arabia

Ref.	Scope	Measures Variables / Strategies used	Model Classification	Tool/Software Used
(Alaidroos & Krarti, 2015)	Building envelope optimization for energy efficiency in Saudi Arabian temperature zones	Wall insulation, Roof insulation, Thermal mass, Window glazing, and shading	Typical Model	EnergyPlus software with sequential search and genetic algorithm optimization
(Krarti et al., 2017)	Energy-efficient strategies for buildings in different climates	Walls and Roofs insulation, Glazing, Equipment (Refrigerators), HVAC CoP, Shading, Photovoltaic, Lighting systems, Infiltration, and WWR	Typical Model	EnergyPlus software with sequential search and genetic algorithm optimization
(Krarti, 2020)	Evaluation of occupancy-based temperature controls	Optimal start temperature controls, flexible temperature settings, and large-scale smart thermostat adoption	Typical Model	DOE-2.2 software
(Algarni, 2019)	Reducing cooling loads in residential structures with cool roofs	Roof absorptivity and Insulation level	Typical Model	eQuest software 3.65

(Abd-ur-Rehman et al., 2018)	Feasibility of solar energy in Saudi residential buildings	Walls & Roof insulation, Glazing, Solar water heaters, and PV systems connected to the grid	Typical Model	visual software	DOE
(Aldossary et al., 2014b)	Energy consumption trends in hot and dry climate (case study in Riyadh)	Wall, window, and Roof U value, and Air tightness strategies	Typical Model	IES-VE software	
(Mahmoud et al., 2017)	Green Roofs for Hot and Humid Buildings	Roof insulation	Typical Model	DesignBuilder software	
(Ghabra et al., 2017)	Constraints and energy efficiency of tall residential building facade design.	Engineering parameters (wall and glazing) and Architectural design parameters	Hypothetical Model	TAS (Thermal Analysis Simulation) software	
(Ahmed et al., 2019)	Use of building performance simulation in Saudi Arabia's construction industry	External Color, W-W Ratio, AC CoP, Orientation, Double Glaze, Insulation, Window Shades, and LED	Typical Model	Survey, Autodesk Revit, and DesignBuilder software	
(Mejjiaoui & Alzahrani, 2020)	Decision support system for energy retrofitting in residential buildings	Insulation, Window replacement, Lighting upgrades, HVAC upgrades, and Renewable energy systems	Mathematical Model	Mixed Integer Linear Programming (MILP) Programming	
(Alardhi et al., 2022)	Impact of SBC-602 on residential energy consumption	Base case: uninsulated building, Thermal insulation meeting SEC requirements, and SBC-602 requirements	Typical Model	SketchUp and OpenStudio	
(Al-Sanea et al., 2012)	Effects of modifying thermal mass in insulated building walls	Thermal mass thickness and Insulation layer thickness	Mathematical Model	Implicit Formulation (Control Volume Finite-difference Method).	
(Al-Sanea & Zedan, 2011)	Thermal properties analysis of walls with varying thermal mass and insulation	Thicknesses of the insulation and positions.	Mathematical Model	Formulation of the problem using the control volume finite-difference method.	
(Al-Sanea et al., 2016)	Cost-effective R-values for building walls in different climates	Insulation types and Thickness of insulation	Mathematical Model	Finite-Volume Implicit Method	
(Al-Tamimi, 2021)	Impact of thermal insulation material and thickness on annual energy consumption	Insulation types and Insulation thickness	Typical Model	DesignBuilder software	
(Krarti, 2020)	A comprehensive strategy for Saudi Arabia's housing stock energy efficiency	Exterior walls and roof insulation, Glazing types, Overhang, Lighting, Air Infiltration, Cooling Set Point, Appliances, Air conditioner, and Cool roof	Typical Models	DOE-2.2 software	
(Felimban et al., 2023)	Evaluates the energy-saving potential of retrofitting	wall filling, oof insulation upgrades, air sealant,	Specific Model	DesignBuilder software	

measures for a residential building in Jeddah, KSA	window upgrades, and AC system replacements
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The above literature review provides useful energy efficiency research for Saudi Arabian residential buildings. Arranged thematically, the studies jointly enhance comprehension of effective strategies, including building design and envelope optimization, as well as the incorporation of renewable energy sources. The results emphasize the significance of strategies that take into account specific regional climate conditions and building characteristics. This detailed table provides insights into the various interventions used, such as insulation, glazing, HVAC systems, and occupancy-based temperature controls. The studies use a range of modeling approaches, from typical models to mathematical models and hypothetical simulations, highlighting the interdisciplinary aspect of the research. Software tools like eQuest, IES-VE, and DesignBuilder are crucial for the simulation and analysis processes.

However, existing studies on retrofitting residential buildings for energy efficiency reveals several gaps. Most studies focus on individual measures, like wall or roof insulation, or sometimes combined both without assessing their combined effects on energy use, carbon emissions, and cost-effectiveness. Insights from key stakeholders, such as construction professionals, are often missing, leaving implementation challenges, and material considerations unexplored. Economic and environmental evaluations, including payback periods and carbon reduction potential, are insufficiently covered. This study aims to address these gaps by evaluating practical methods for integrating insulation materials into Saudi residential buildings. Simulations on a case study will quantify energy savings, and economic and environmental assessments will identify cost-effective, low-carbon

strategies. Interviews with industry experts will provide practical insights into materials, techniques, and challenges, ensuring the development of actionable, context-specific retrofitting recommendations.

CHAPTER 3

METHODOLOGY

The study used a multifaceted approach consisting of four phases: Model development and validation; criteria development for selecting thermal insulation materials; analysis of retrofits impact on energy consumption; and analysis of the economic benefits and environmental effects (Figure 4).

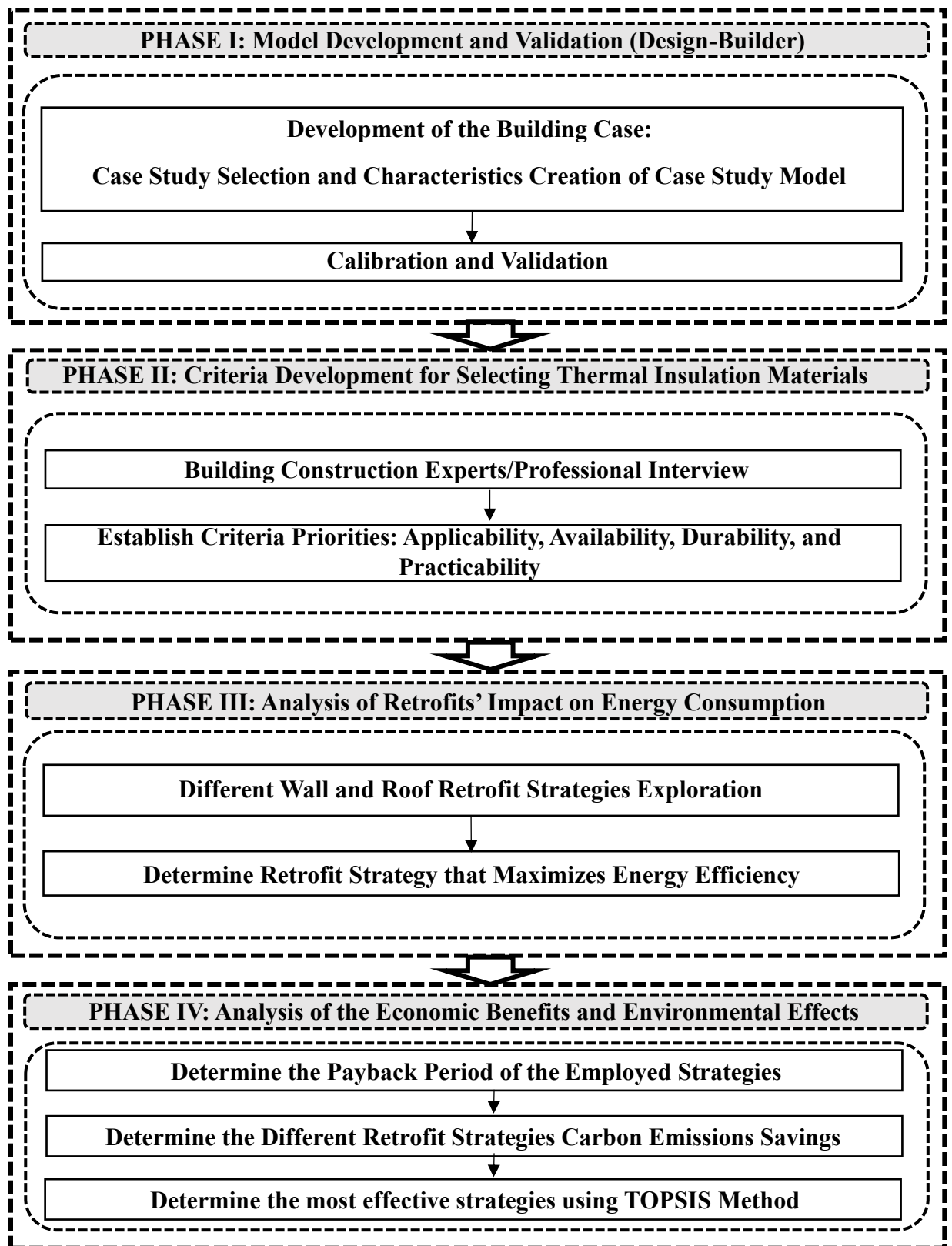


Figure 4: Flowchart of study methodology

3.1 Phase I: Model Development and Validation

3.1.1 Development of the building case

A Case study Selection

The study by Gleeson (2011) suggests that the case study approach is a common and suitable method for evaluating building retrofit initiatives. Specifically, the study focused on a retrofit project. Various energy simulation software was used in the previous literature, Crawley et al. (2008) evaluated 20 energy modeling software packages, including; Energy Plus (Delgarm et al., 2016; Schwartz et al., 2016), DOE-2 (Winkelmann et al., 1993), TRNSYS (Asadi et al., 2012; Ferrara et al., 2018), IDA Indoor Climate and Energy (IDA ICE) (Arabzadeh et al., 2019; Hirvonen et al., 2019), Building Load Analysis and System Thermodynamics (BLAST) (Kamel & Memari, 2022), EXCALIBUR (Crabb et al., 1987), and ASHRAE toolkit for building load calculations (Pedersen et al., 2003). In addition, there are simulation software mainly for daylighting including Grasshopper & Daysim (Ward & Rubinstein, 1988), and Radiance (Reinhart & Herkel, 2000).

In the context of the present study, DesignBuilder software v7.0.2.004 were used to achieve the study objectives. The reason for choosing this software is because of its intricate architectural modeling interface and plug-ins for EnergyPlus, regularly updated, and is a program that is frequently used in academic research for its precise results (Jankovic, 2019; Tian et al., 2018). The use of DesignBuilder emphasizes the necessity of selecting a tool that meets the requirements for research, enabling accurate modeling and analysis of building energy performance in retrofit initiatives.

Furthermore, A prototypical house, based on the study by (Ahmed et al., 2019; Alrashed & Asif, 2015a), was utilized. The model represents a two-story, single-family detached house, commonly referred to as a "villa," with a total area of approximately 430 square meters and a floor height of around 3.4 meters per level. As a representation of small villa design in the country, research by Haidar & Bahammam (2021) suggests reducing housing land by 50%, leading to a 50% reduction in house size. Figure 2 above in the introduction chapter depicts Saudi Arabians' villa, apartment, and traditional house housing distribution. Apartments make up about 44% of the total units. Despite this numerical frequency, several studies (Alhubashi & Roca Cladera, 2016; Alqahtany & Bin Mohanna, 2019; Alzamil, 2014) regularly list villas as Saudi Arabia's most desired housing option. Apartments are seen as temporary rentals, especially for new families, hence villas are preferred (Alzamil, 2014). Since villas are popular and important in Saudi Arabia's housing environment, this study uses them as a sample example.

B Characteristics Creation of Case Study Model

1 Climatic conditions of Dhahran

The energy potential of a region can be evaluated by examining the weather data, both historically and in the present, and in devising solutions to energy-related challenges (Bakırcı et al., 2006; Çobanyılmaz & Yüksel, 2013). In addition, the selection of the appropriate weather for a case study place provided a comprehensive framework for selecting retrofit options (Ma et al., 2012). The case study took place in Dhahran, a city that has a dry and hot climate. Dhahran has gentle, breezy, and arid winters, and the sky is usually cloudless. The summers are long, humid, and scorching. The temperature ranges

from 10°C to 43°C on average and occasionally goes under 7°C or above 46°C (Weather Spark, 2023). Table 2 and Figure 5 illustrate Dhahran's average high and low temperatures.

Table 2: Dhahran average high and low temperatures (Weather Spark, 2023)

Average	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
High (°C)	21	23	27	32	39	42	43	42	40	35	28	23
Temp. (°C)	15	17	21	26	32	35	36	36	33	29	23	17
Low (°C)	11	12	16	21	26	28	30	29	26	22	17	13

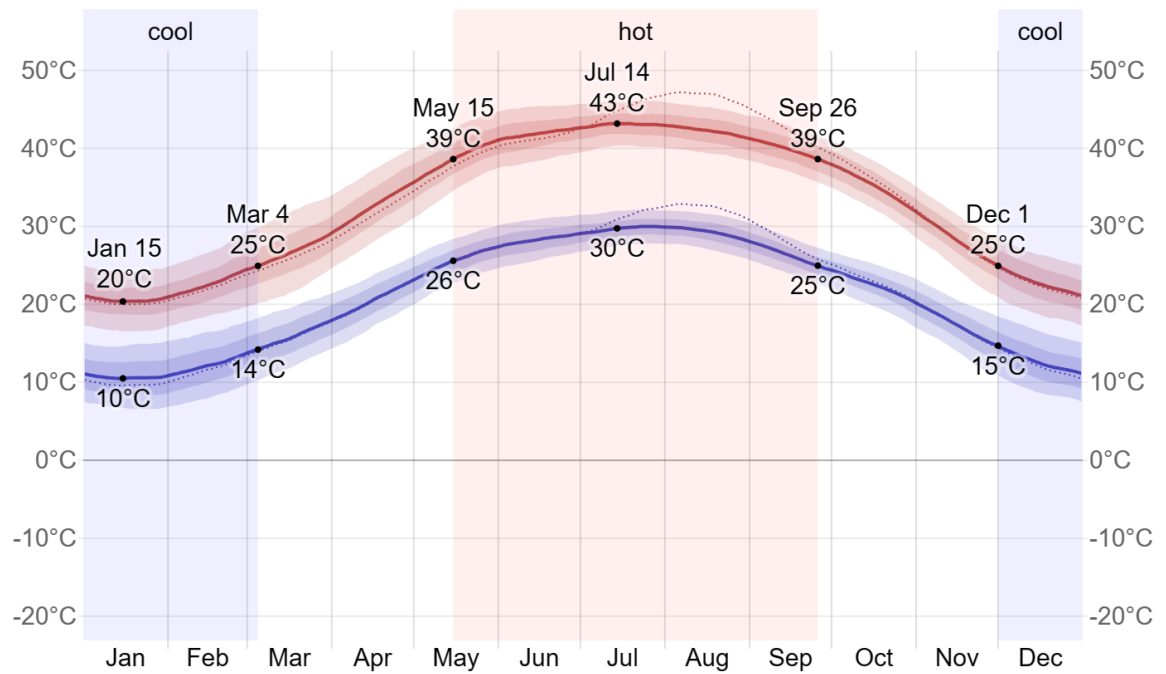


Figure 5: Dhahran's high, average and low temperatures

Source: (Weather Spark, 2023)

2 Building Characteristics

As previously mentioned, this project utilizes a prototypical villa house model based on the study by Ahmed et al. (2019) and Alrashed & Asif (2015a). The model represents a two-story, single-family detached house with a total area of approximately 430 square meters and a floor height of about 3.4 meters per story. The ground floor of the villa

comprises several essential facilities, including an entrance leading to a central hallway that interconnects various rooms. An external kitchen with an adjacent laundry room is present, as well as an internal kitchen situated in proximity to the dining area. The family hall occupies the central position of the floor plan, providing access to the women's sitting room and men's sitting room, each equipped with adjoining washrooms. A centrally located staircase leads to the first floor.

The first floor consists of multiple bedrooms, including a master bedroom with an adjoining washroom, as well as two additional bedrooms. An office space and a multipurpose room are present, all connected by a central hallway, and a potential staircase is elevated for a third floor. Figure 6 shows the layout of the villa house. Table 3 provides the detailed characteristics of the building energy models for the representative building.

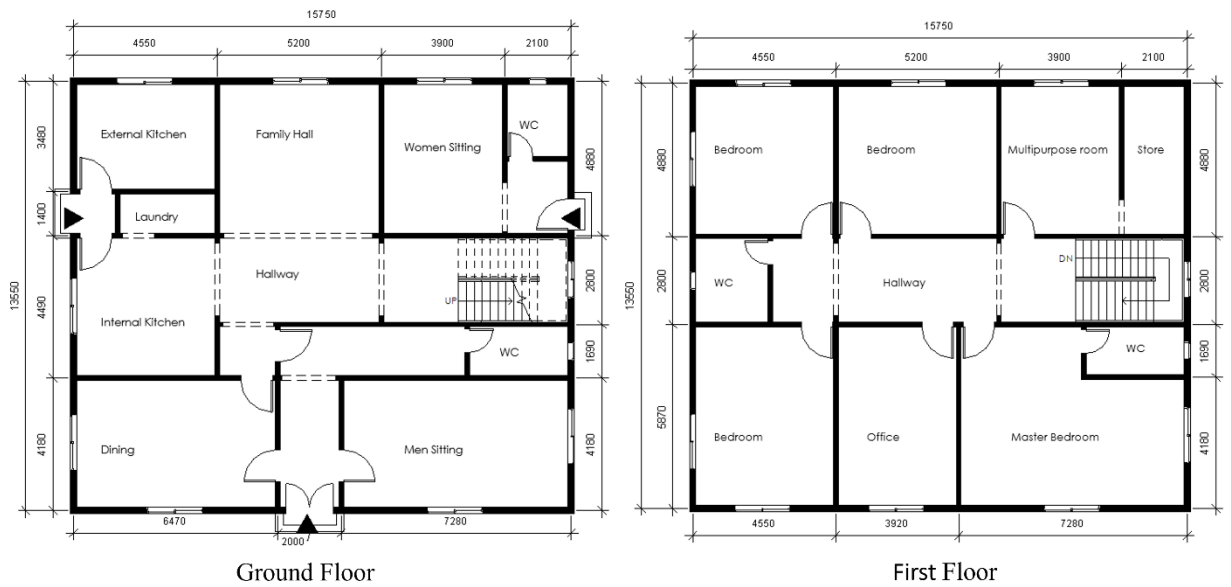


Figure 6: Floor plan of case study: ground floor (left) and first floor (right)

Table 3. Features of the simulation models for the representative villa building

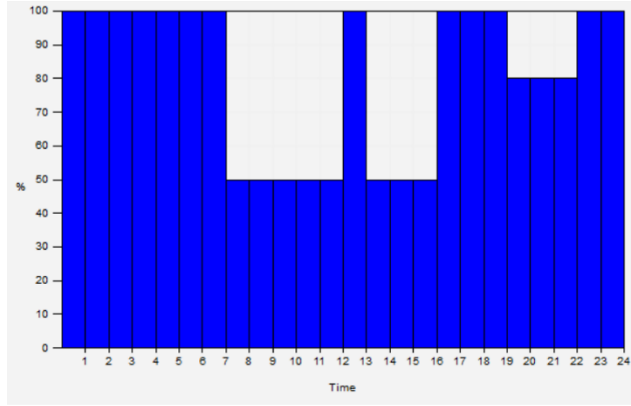
Components	Description
Floors number	Two floors
The total area of the floors	430 m ²
Number of occupants	6 people
External walls	0.025 m plaster external + 0.25 m concrete hollow block + 0.025 m plaster internal 2.230 U-value (W/m ² -K)
Roof	0.025 m built-up roofing + 0.250m concrete roofing slab + 0.040 m Vapor-permeable felt + 0.025m plaster internal 1.934 U-value (W/m ² -K)
Internal walls	0.025 m plaster external + 0.10 m concrete hollow block + 0.025 m plaster internal 1.739 U-value (W/m ² -K)
Glazing	0.06 m single glaze 5.778 U-value (W/m ² -K)
Window-to-wall ratio	11%
Cooling set point	22-Degree Celsius
HVAC system	Split no fresh air, Coefficient of Performance (CoP) = 1.5
Density of Lighting Power	5.0 W/m ² .100 lux
Infiltration of airtightness	1.2 Air Change per Hour (ACH)
Water Heater (DHW)	190 liters, with a delivery efficiency of 90%

Additional model data, including the occupancy schedule, lighting schedule, and equipment schedule, were sourced from relevant published studies on villas in Saudi Arabia (A. Ahmed, 2004; Alaidroos & Krarti, 2015), as illustrated in Figures 7, 8a, and 8b, respectively. Regarding the occupancy schedule as shown in Figure 7, for weekdays (Sunday to Thursday), the schedule indicates complete occupancy (100%) between 1:00 and 7:00, partial occupancy (50%) between 8:00 and 12:00, complete occupancy again at 13:00, and then alternating between 50% (14:00–16:00) and 100% (17:00–19:00). From 20:00 to 22:00, occupancy decreases to 80%, and it returns to complete occupancy for the remaining hours (23:00–24:00).

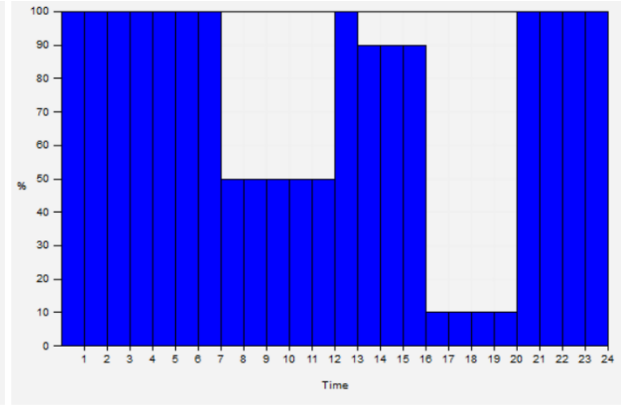
On weekends (Friday and Saturday), the schedule maintains complete occupancy (100%) between 1:00 and 7:00 and partial occupancy (50%) from 8:00 to 12:00. Complete occupancy is observed at 13:00 and from 14:00 to 16:00, occupancy is marginally higher at 90%. However, from 17:00 to 20:00, occupancy decreases to 10%, before returning to 100% for the final hours of the day (21:00–24:00). This schedule is implemented consistently throughout the year.

Figure 8a illustrates that the lighting adheres to a daily schedule throughout the year. From 01:00 to 06:00, only 5% of the lighting is utilized, increasing to 30% at 07:00. During the hours between 08:00 and 17:00, only 10% of the lighting is operational. Lighting usage reaches its peak at 90% between 18:00 and 19:00, decreases slightly to 70% from 20:00 to 22:00, and diminishes to 5% from 23:00 to 24:00.

Furthermore, the equipment schedule remains consistent for all days of the year, as depicted in Figure 8b. Between 01:00 and 06:00, 5% of equipment capacity is in operation, which increases to 50% at 07:00. From 08:00 to 17:00, 30% of equipment is functional. Equipment usage reaches its maximum at 60% between 18:00 and 20:00 before decreasing to 5% between 21:00 and 24:00.

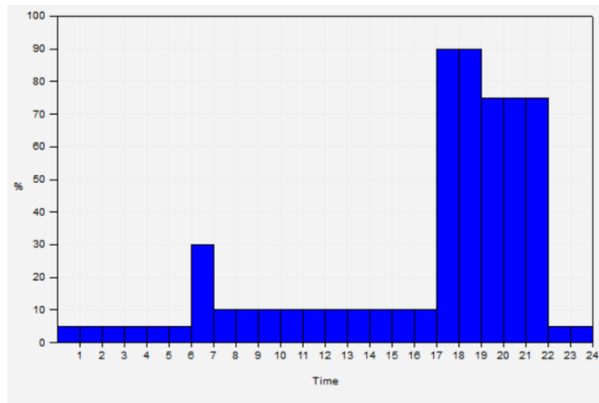


Weekday occupancy percentage schedules pattern

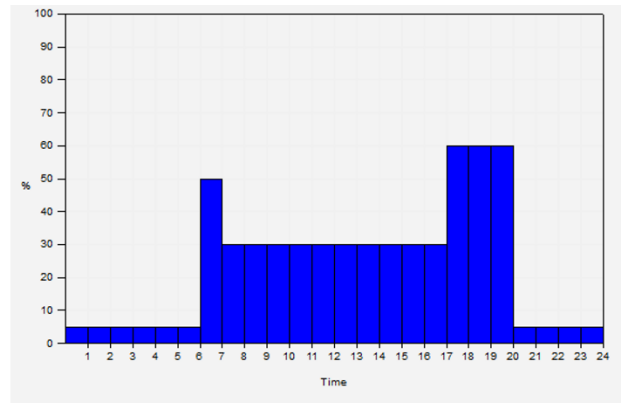


Weekend occupancy percentage schedules pattern

Figure 7: Occupancy schedule for a typical villa in Saudi Arabia (Weekdays and Weekends)



(a) Lighting occupancy percentage schedules pattern



(b) Equipment occupancy percentage schedules pattern

Figure 8: Lighting and equipment schedules for all days of the year in a typical villa in Saudi Arabia

3.1.2 Calibration and Validation

The calibration involved creating a model of the prototypical villa for energy simulation utilizing DesignBuilder software. Energy model simulations were conducted for Dhahran, Saudi Arabia, with the corresponding weather data imported into DesignBuilder. Then, the building plan was segmented into three distinct HVAC zones on the ground floor,

comprising the lounge, kitchen, and circulation areas, and into two zones on the first floor, encompassing bedrooms and circulation areas. Finally, appropriate energy consumption values for the examined prototypical residential villa, relevant input information was provided to the DesignBuilder software. This information included envelope construction materials, cooling temperature setpoint, HVAC type, occupancy, lighting, and equipment schedules, as well as additional parameters specified in section 3.1.1. above.

The energy model's validation process involved aligning the simulated energy usage with the consumption data of a villa outlined in the study by (Alrashed & Asif, 2015a) (Table 4 and Figure 9). In accordance with the ASHRAE Guideline 14 (2023), the computer model should demonstrate a Normalized Mean Bias Error (NMBE) of 5% and a Coefficient of Variation of the Root-Mean-Square Error CV(RMSE) of 15% relative to monthly calibration data. To determine these values, equations 1 and 2 were utilized for NMBE and CV(RMSE), respectively. Upon application of the formulas, the simulated model demonstrated an NMBE of 1.94% and a CV(RMSE) of 10.40% relative to monthly data of the actual villa consumption. Suggesting that the simulation closely matches the observed data on average, with minimal systematic bias.

$$NMBE = \frac{\sum_{i=1}^n (y_i - \hat{y}_i)}{(n - p) \times \bar{y}} \times 100 \quad [1]$$

$$CV(RMSE) = \frac{\sqrt{\frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{(n - p)}}}{\bar{y}} \times 100 \quad [2]$$

Where:

y_i = Reference (actual) values

$\hat{y}_i$ = Simulated (predicted) values

n = Number of months

p = Number of model parameters (typically 1)

$\bar{y}$ = Mean of the reference (actual) values

Table 4: Calibration results of the model

Months	Reference (y_i)	Simulation ($\hat{y}_i$)
Jan	2429	2504
Feb	2195	2130
Mar	2459	2119
Apr	3893	3847
May	6234	6390
Jun	7229	7751
Jul	8810	9567
Aug	9717	9925
Sep	8283	7612
Oct	5854	5994
Nov	3620	2928
Dec	3278	2096
Total	64000	62863

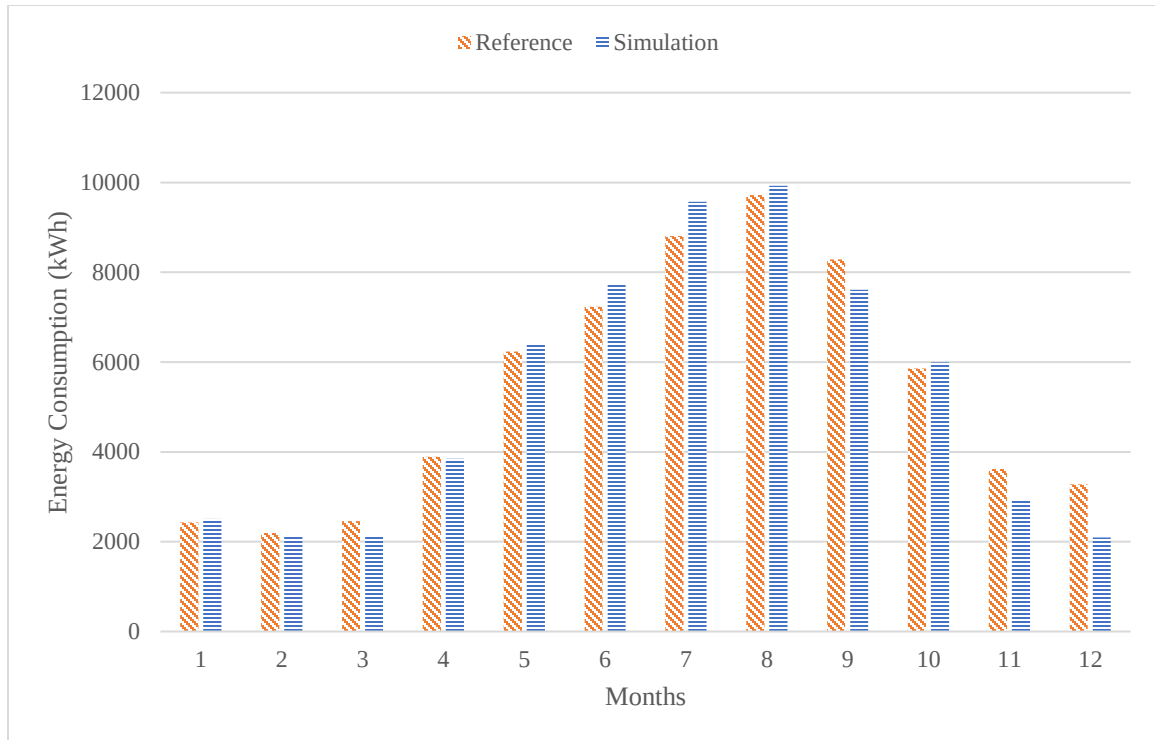


Figure 9: Calibration results of the model.

3.2 Phase II: Criteria Development for Selecting Thermal Insulation Materials

Gathering insights and opinions from experts in the field regarding the effectiveness of a service or product, whether it is already in existence or in the planning stages, constitutes a type of research (Thiel, 2014). An interview were conducted among building construction professional experts in Saudi Arabia to ascertain their perspectives. A total of thirty (30) professionals were contacted via email and phone, inviting them to participate in interviews either online or in person. The selection criteria required participants to have at least two years of experience working on retrofitting projects. Out of the 30, only eight (8) professionals responded, while some declined, citing a lack of relevant experience. Among the respondents, two (2) were interviewed in person, while six (6) participated in online interviews. All interviews were recorded with the participants' consent, and detailed notes

were taken during the discussions. The interview questions focused on the following key areas:

- Respondent Background: Current role, years of experience, type of projects, and primary regions for retrofitting.
- Techniques and Materials: Effective insulation techniques, commonly used materials, and strategies to minimize occupant disturbance.
- Cost and Availability: Impact of material costs, availability of local and sustainable options, and market trends on material selection.
- Challenges and Barriers: Key challenges, including regulatory constraints, supply chain issues, and homeowner concerns affecting retrofitting.

The interview data were transcribed and analyzed using thematic analysis, which involved identifying, examining, and reporting recurring patterns (themes) within the dataset. This approach ensured a comprehensive understanding of the depth and variety of expert perspectives.

Subsequently, Table 5 summarized the different identified energy-efficient retrofit strategies for walls and roof, which could be incorporated into the design process. These identified solutions are derived from feedback obtained through interviews with Saudi experts. To ensure comprehensive envelope design options, an optimal window glazing U-Value and the efficiency of HVAC upgrade was adopted throughout the project, based on the Updated Saudi Building Code for energy conservation. Furthermore, the different scenarios based on the identified strategies are proposed as shown in Table 6, which are modelled to achieve the study objectives.

Table 5: Identified energy-efficient retrofit strategies

Components	Strategies	
	External insulation (1)	Internal insulation (2)
Walls (W)	W1 = Base case wall + 0.0015m Adhesive Layer + 0.1m EPS + 0.002m Base coat + 0.003m Finish coat 0.346 U-value (W/m ² K)	W2 = Base case wall + 0.1m mineral wool + 0.025 m plaster internal 0.325 U-value (W/m ² K)
Roofs (R)	R1 = Base case roof + 0.1m XPS + 0.025 m built-up roofing + 0.0015m reflective paints 0.260 U-value (W/m ² K)	R2 = Base case roof + 0.1m mineral wool + 0.025 m plaster internal 0.261 U-value (W/m ² K)
Window glazing Upgrade	Double clear (filled argon) U-value of 2.51 (W/m ² K)	
HVAC Upgrade	Upgrading the split systems CoP to 4	

Table 6: Proposed retrofits scenarios

Scenarios (S)	Strategies	Description
External		
S1	W1	Applying only the external insulation walls strategy
S2	R1	Applying only the external insulation roof strategy
S3	W1 + R1	Combining the external walls and roof insulation strategies
S4	W1 + window glazing upgrade	Combining the external walls insulation strategy with a window glazing upgrade
S5	W1 + HVAC upgrade	Combining the external walls insulation strategy with a HVAC upgrade
S6	W1 + window glazing upgrade + HVAC upgrade	Combining the external walls insulation strategy with a window glazing and HVAC upgrades
S7	R1 + window glazing upgrade	Combining the external roof insulation strategy with a window glazing upgrade
S8	R1 + HVAC upgrade	Combining the external roof insulation strategy with a HVAC upgrade
S9	R1 + window glazing upgrade + HVAC upgrade	Combining the external roof insulation strategy with a window glazing and HVAC upgrades
S10	W1 + R1 + window glazing upgrade	Combining the external walls and roof insulation strategies with a window glazing upgrade
S11	W1 + R1 + HVAC upgrade	Combining the external walls and roof insulation strategies with a HVAC upgrade
S12	W1 + R1 + window glazing upgrade + HVAC upgrade	Combining the external walls and roof insulation strategies with a window glazing and HVAC upgrades

Internal		
S13	W2	Applying only the internal insulation walls strategy
S14	R2	Applying only the internal insulation roof strategy
S15	W2 + R2	Combining the internal walls and roof insulation strategies
S16	W2 + window glazing upgrade	Combining the internal walls insulation strategy with a window glazing upgrade
S17	W2 + HVAC upgrade	Combining the internal walls insulation strategy with a HVAC upgrade
S18	W2 + window glazing upgrade + HVAC upgrade	Combining the internal walls insulation strategy with a window glazing and HVAC upgrades
S19	R2 + window glazing upgrade	Combining the internal roof insulation strategy with a window glazing upgrade
S20	R2 + HVAC upgrade	Combining the internal roof insulation strategy with a HVAC upgrade
S21	R2 + window glazing upgrade + HVAC upgrade	Combining the internal roof insulation strategy with a window glazing and HVAC upgrades
S22	W2 + R2 + window glazing upgrade	Combining the internal walls and roof insulation strategies with a window glazing upgrade
S23	W2 + R2 + HVAC upgrade	Combining the internal walls and roof insulation strategies with a HVAC upgrade
S24	W2 + R2 + window glazing upgrade + HVAC upgrade	Combining the internal walls and roof insulation strategies with a window glazing and HVAC upgrades

3.3 Phase III: Analysis of Retrofits Impact on Energy Consumption

In this phase, the different retrofit strategies identified for both wall and roof were explored to identify design options that maximize energy efficiency by minimizing the total energy needs for cooling. The analyzed building's cooling energy requirements were calculated using DesignBuilder software with an EnergyPlus plug-in, which utilizes multiple program modules concurrently. This program computes the HVAC demand by balancing the heat flows. It takes into account the heat transfers inside and outside the building, the time-dependent heat diffusion, and the changes in material properties(Eskin & Türkmen, 2008).

3.4 Phase IV: Analysis of the Economic Benefits and Environmental Effects

To identify an economically efficient insulation strategy, a novel function were established based on different components. The annual cost of energy in Saudi Riyal (SAR), were determined. Appropriate pricing of materials needed for each scenario were collected from local providers and previous study (Table 7), all prices were expressed in SAR per square meter or SAR per unit for air conditioning systems, the different retrofits Scenario's payback period are calculated using Equations 3 and 4.

In addition, the different strategies employed were evaluated for CO₂ emissions reduction. The DesignBuilder program determined CO₂ emissions based on the fuel breakdown and region-specific factors outlined in the weather file. These factors represent the kilograms of CO₂ generated per kWh of fuel consumed. Finally, to determine the most effective strategies among the 24 different scenarios, we used Multi-Criteria Decision Analysis (MCDA) Using TOPSIS. The insulation materials include EPS, XPS, and mineral wool. The estimated lifespan of each insulation is outlined in Table 8. This information were used as one of the criteria in identifying the most effective retrofits strategies, because citing the payback period achieved by each strategy along without knowing the lifespan of the material used will not be fully effective, because there might be a situation that the payback period achieved may exceed the lifespan of the materials used for that strategy. More details are given in section 4.3.3

$$PP = \text{Ins.TC} / C_{ES} \quad [3]$$

$$C_{ES} = ES * C_{ETP} \quad [4]$$

Where:

PP = Payback period (years)

Ins.TC = Total cost of retrofit strategies in each Scenario (SAR)

C_{ES} = Cost of energy saved (SAR)

ES = Energy saved (the change in Annual energy usage in the baseline scenario (kWh/year) to the modeled scenario (kWh/year))

C_{ETP} = Cost of residential electricity tariff in Saudi Arabia per kWh (SAR) = 0.18 SAR/kWh of building with a monthly energy consumption of 1-6000 kWh

Table 7: Estimated costs for essential energy retrofitting materials (Felimban, 2024; Rockwool, 2024; Sadler, 2023)

Category	Unit	Cost (SAR)
Insulation		
Expanded polystyrene (EPS) (0.1 m)	m ²	56
Extruded polystyrene (XPS) (0.1 m)	m ²	70
Mineral/rock wool (0.1 m)	m ²	150
HVAC system		
Split Unit AC (4 CoP)	count	3200
Windows (Wintek company)		
Double clear (filled argon)	m ²	911
Cement mortar		
Materials and application	m ²	36
Paint		
Paint and application	m ²	15

Table 8: Insulation materials lifespan

Insulation Materials	Life span (years)	Ref.
EPS	35-50	(Felimban, 2024)
XPS	Building lifespan (50)	(Argaam, 2021; Felimban, 2024)
Mineral wool	Building lifespan (50)	(Argaam, 2021; Felimban, 2024)

CHAPTER 4

RESULTS ANALYSIS AND DISCUSSION

4.1 Expert Interview

4.1.1 Participants Characteristics

As outlined in the methodology section, a total of thirty (30) industry professionals from various disciplines were contacted for interviews. Responses were obtained from eight (8) professionals, including project managers, construction project site engineer, senior architect, senior safety engineer, facility engineers, and sustainability consultants, each with extensive years of experience ranging from 2 to 29 years, working on various retrofitting projects mostly in an urban setting. Most had been involved in large-scale projects and specialized in applying energy-efficient strategies to existing structures. A professional (E2) remarked, *“We always try to reuse existing structures, which saves at least 50% of CO₂ equivalent compared to demolishing and rebuilding.”* It is worth mentioning that some professionals declined to participate in the interview, citing a "lack of relevant experience." Table 9 summarizes the detailed characteristics of the participants.

Table 9: Characteristics of Participants

Code name	Professional role	Years of experience	Primary focus	Region of work
E1	Facility Engineer	11	Residential retrofits and offices	Urban (Aramco, Dhahran)
E2	Senior Architect	29	Residential retrofits and offices	Urban (Aramco, Dhahran)
E3	Facility Engineer/Project Manger	9	Residential retrofits and offices	Urban (KFUPM, Dhahran)
E4	Project Manger	8	Residential retrofits and offices	Urban (KFUPM, Dhahran)
E5	construction project site engineer	5	Mostly office buildings with few residentials	Urban (Aramco, Dhahran)

E6	Architect	10	Residential retrofits and offices	Urban (Aramco, Dhahran)
E7	Sustainability Consultant	2	Mostly office buildings with few residential	Urban (Riyadh)
E8	Senior Safety Engineer	7	Residential retrofits and offices	Urban (mostly Eastern Province)
Notes: The experts were coded sequentially (E1 – E8) for easy reference in the subsequent discussion				

4.1.2 Techniques and Strategies for Wall and Roof Insulation

The professionals employed diverse strategies tailored to building types and project goals. External insulation systems, such as EIFS (External Insulation Finishing Systems) as it is called an American term or an insulated render in the United Kingdom (UK), were identified by most of the experts (62.5%) as the most effective, reducing thermal bridges while maintaining aesthetic integrity. One professional (E2) explained, “*The problem with interior insulation is the creation of thermal bridges at slab junctions, which EIFS helps to minimize*”.

As shown in Figure 10, EIFS is an exterior wall cladding system that does not bear loads, comprised of several components. These include an insulation board attached to the substrate using adhesive and mechanical fasteners, a reinforced base coat, primer, and a protective finish coat with texture. The system is completed with recommended accessories such as wall panels or marble. Usually, a dark gray expanded polystyrene (EPS) board is used, because the white foam is very flammable and can create smoke and flame, which is dangerous, and using a dark gray color polystyrene foam, which can still burn, but it doesn't release any smoke or flame, so it's safer. Also, it can be of different thickness, depending on the U-value that one requires, let's say from a minimum of 50, 100, or 150 millimeters.



internal walls separating two rooms, then you should insulate it also maybe up to half a meter of that perpendicular wall, so that you limit the thermal bridge effect.” They also underlined that enhancing the efficiency of existing HVAC as another strategy used, which is an example of a minor retrofit that help reduced the building's energy usage (Felimban et al., 2023).

Furthermore, Strategies to minimize disturbance to occupants during the retrofitting projects included phased implementation, for example, normal internal activities in the house can continue while retrofitting the vertical walls and roofs, zoning by dividing the building into different loops, using high insulated doors, avoiding hard flooring by using carpets, and scheduling work during non-peak hours, as mentioned by one of the professionals (E5), *“We limit our works to after working hours and we maximize by double shifts on the weekends and holidays”*.

4.1.3 Material Availability and Cost Considerations

The availability of materials was a recurring challenge. Commonly available materials included rock wool, EPS/XPS foam, and mineral wool, with variations in quality and cost based on sourcing locations. Rock wool is usually used for internal retrofitting, especially on the walls, while EPS/XPS is used on the external walls and roofs. It is recommended to replace the polystyrene insulation board with the mineral wool rigid board, which is, of course, non-combustible. It also allows some moisture to go through it without being stopped, tackling the issues that can create mold on the walls, especially during internal insulation. It is worth mentioning that one professional (E5) said, *“Rock/Mineral wool is the most common material because it’s readily available off-the-shelf and easy to install.”*

The need for pre-planning and backup strategies is often necessitated by supply chain delays, as the required materials are not produced domestically. Professional (E1) noted that they typically plan months, given that materials ordered from abroad can take 12 to 14 weeks to be delivered. This complement the saying of E2: *“I cannot order from a foreign company directly. I need to go to a local supplier, and the local supplier will order it for me,”* this practice, while intended to support local businesses, sometimes led to delays and higher costs.

Moreover, using sustainable materials such as natural fibers or recycled alternatives was infrequent due to their high cost and limited accessibility. Because everybody wants to save money and they keep using chemical materials, then it's difficult to transition to eco-friendly materials. Nevertheless, some professionals (37.5%) also noted shifts in market trends, including the possibility of price reductions as local production expands.

4.1.4 Challenges and Additional Benefits

Key challenges included high material costs, limited skilled labor, and regulatory challenges. A lack of skilled workers was identified as the most significant challenge. Despite meticulous design and well-written specifications, the absence of skilled on-site personnel can render all design-stage efforts futile. Without the right people with the necessary expertise during implementation, even the most detailed plans and precise instructions may be ineffective. As highlighted by one Professional (E2): *“You can do the best detail at the design level, but without skilled labor, all efforts will vanish.”* Occupant behavior and aesthetic concerns also disrupted project timelines. One professional (E3) mentioned, *“Some homeowners refuse to vacate because they make some upgrade not long time ago, causing delays and logistical complications.”* Because the project is mass

housing retrofitting and it involved cutting down water and electricity, causing additional costs for providing these infrastructures to the homeowners.

A strict compliance requirement of the Saudi Building Code (SBC), which necessitates careful observation of the prescribed insulation standards and energy efficiency measures. Most (75%) of the professionals expressed that while the SBC aligns with international codes, such as the International Energy Conservation Code (IECC), its implementation in retrofitting projects can be complex. Because the implementation of building standards remains largely overlooked in new constructions, let alone in the retrofitting of existing buildings.

Two professionals (E3 and E4) explained, *“Before, insulation was not required for individual houses, which absorbed a lot of heat in summer and cold in winter. However, with recent code updates, insulation is mandatory for new buildings to receive electricity connections.”* This regulatory shift highlights the growing emphasis on energy efficiency but has created challenges in applying these standards to older buildings lacking pre-existing insulation.

In some cases, the Aramco Building Code, which is based on the SBC, imposes even stricter requirements. Design details must undergo rigorous approval processes, and any deviations will lead to project delays. One professional (E1) stated, *“Aramco inspectors ensure every detail matches the design specifications. If it doesn’t, construction is put on hold until corrections are made.”*

Additionally, retrofitting older residential buildings often conflicts with heritage preservation and aesthetic concerns, especially in urban settings. Some homeowners resist

changes, fearing that retrofitting measures like EIFS might alter the appearance of their buildings. These conflicts can result in prolonged project timelines.

The performance gap between simulated and actual outcomes further complicates regulatory adherence. One expert (E2) noted, *“Energy standards like Passive House provide a strong framework, but their strict requirements often highlight the gap between design simulations and real-world performance.”* Passive House is a voluntary standard for building energy efficiency that aims to decrease the building's carbon emissions (Zeller, 2010). Unfortunately, most of the standards are related to cooler climate regions such as the UK, but the principle is the same which can be adopted in hot climate regions such as Saudi Arabia.

Despite these challenges, retrofitting offered significant benefits, such as improved thermal comfort and reduced noise. One professional (E1) highlighted an example: *“We converted a basement into a meeting area using acoustical panels that also had thermal insulation properties. The result was a quiet, thermally comfortable space perfect for high-level meetings.”*

4.2 Analysis of Retrofits Impact on Energy Consumption

4.2.1 External Scenarios

The energy consumption data for a typical base case and 12 different retrofit scenarios (S1–S12) was analyzed to assess the effectiveness of various external energy-efficient strategies. The reference villa analyzed in this study has an annual energy consumption of 62,863 kWh. Figure 11 illustrates the impact of these solutions on energy consumption compared with a typical villa. The strategies ranged from the application of external

insulation to walls (W1) or roof (R1) to more comprehensive approaches involving addition of window glazing upgrades and HVAC system enhancements. The general pattern of the graphs remained consistent across all scenarios, showing increased consumption during summer and decreased usage in winter. Nevertheless, the total energy consumption differed for each energy-efficient strategy (Table 10).

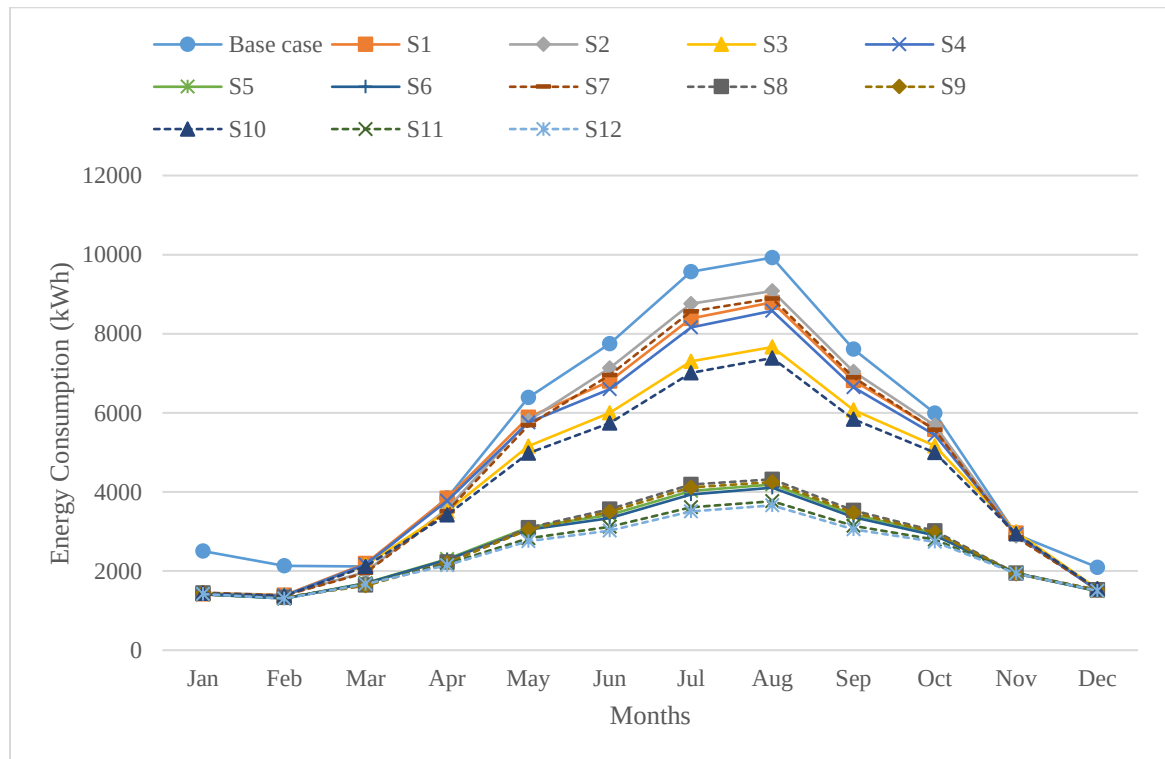


Figure 11: Energy consumption of the base case and different external retrofit scenarios

Table 10: Annual energy consumption and savings for different external retrofit scenarios

Scenarios	Annual energy consumption (kWh/year)	Saved energy (kWh/year)	Saved energy (%/year)
S1	55580	7282	12.3
S2	56339	6523	10.9
S3	50369	12494	22.1
S4	54348	8514	14.5
S5	31278	31584	67.1
S6	30820	32042	68.4
S7	55258	7604	12.9

S8	31844	31019	65.5
S9	31444	31419	66.6
S10	48784	14079	25.2
S11	29324	33539	72.8
S12	28734	34129	74.5

The results show a significant variability in energy savings, with a combination of both external walls and roof insulation integrated with window glazing and HVAC upgrades (Scenario 12 (S12)) achieving the highest total annual energy savings of 34129 kWh/year (74.5%) (Table 10). These findings are consistent with Felimban et al. (2023), who highlighted the synergetic benefits of combining multiple retrofitting interventions in hot climates. It further achieved savings of over 80% during peak summer months May to September as illustrated in Figure 12, highlighting the synergetic impact of combining all interventions. When adding only external walls and roof insulation (Scenarios 1 and 2), the total annual energy is reduced by about 7282 kWh/year (12.3%) and 6523 kWh/year (10.9%) respectively (Table 10), indicating limited effectiveness when applied as a standalone measure. In addition, with the combination of both external walls and roof insulation (Scenario 3), the annual energy consumption shows a more substantial reduction of 12494 kWh/year (22.1%) (Table 10).

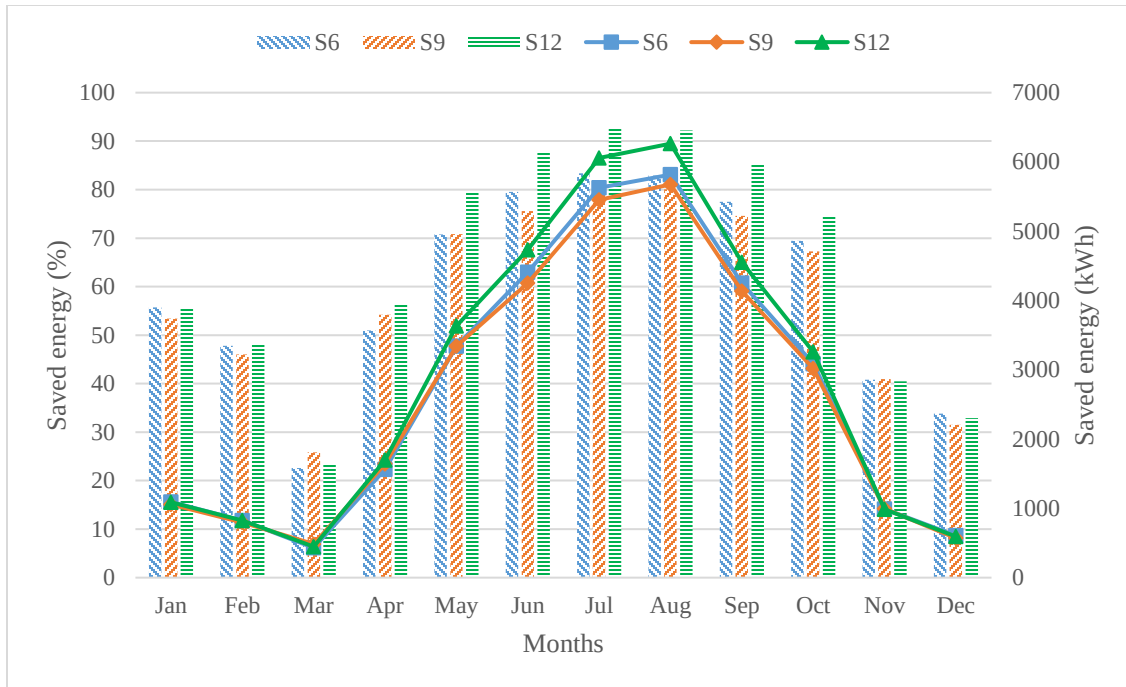


Figure 12: Energy savings from external insulation scenarios with inclusion of both window glazing and HVAC upgrades.

Monthly trends show significant energy savings during the summer months (May–September), coinciding with the peak cooling loads. Scenarios integrated with HVAC upgrades only (S5, S8, and S11) consistently achieved over 60% monthly savings in these periods (Figure 13). For instance, Scenario 5 (external wall insulation with HVAC upgrades) achieves very high energy reductions in July (5545 kWh or 81.6%) and August (5735 kWh or 81.3%), as shown in Figure 13. Scenario 11 combines both external wall and roof insulation with HVAC upgrades, resulting in even higher energy savings in July (5950 kWh or 90.3%) and August (6159 kWh or 90.0%) (Figure 13). These results indicate the significant role of HVAC optimization in hot climates and emphasizing the standalone impact of HVAC system upgrades in reducing energy consumption.

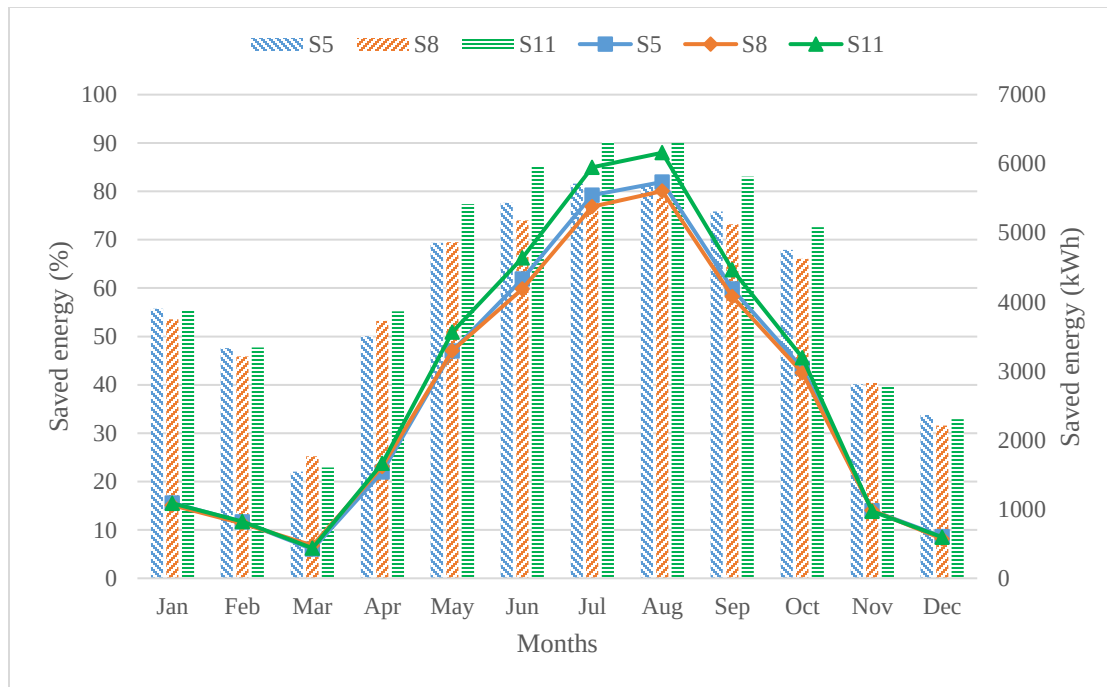


Figure 13: Energy savings from external insulation scenarios with inclusion of HVAC upgrades only

Standalone insulation strategies revealed moderate energy-saving impacts across the months. Figure 14 shows that Scenario 1 (S1: external wall insulation) achieved a significant energy savings in January (1081 kWh or 55.1%) and December (579 kWh or 32.1%), indicating that S1 was highly effective during the months with extreme heating and cooling demands. These results align with Alaboud and Gadi (2020), who emphasized that a mere 2 cm layer of polyurethane on the external walls improve the overall thermal performance of buildings. Similarly, during the summer months (May to September), energy savings ranged between 1130 kWh (12.1%) in August and 1181 kWh (13.2%) in July, demonstrating consistent performance in reducing cooling loads. However, transitional months, such as March, April, and November, often showed minimal impact or even negative energy savings, as shown in Figure 14. For instance, S1 shows an increase of energy consumption of -70 kWh (-3.2%) and -34 kWh (-1.2%) compared to the base

case in March and November respectively. These negative savings suggest that this strategy often work best when it is implemented while considering the impact on other strategies (e.g., roofs, HVAC or windows upgrades).

Scenario 2 (S2: external roof insulation), with the most significant energy savings in January (1053 kWh or 53.2%) and December (555 kWh or 30.5%) (Figure 14). This significant reduction can be attributed to the decreased reliance on cooling systems during these months. As cooling loads generally dominate energy consumption in hot climates. During the summer months (May to September), characterized by peak cooling demands, the energy savings were more modest, ranging between 620 kWh (8.3%) in June and 845 kWh (8.9%) in August, as illustrated in Figure 14. This highlights the roof insulation's ability to reduce heat gain during periods of high solar radiation. Transitional months (March, April, and November) often showed minimal impact or but do not have a negative energy savings as in the wall insulation (Figure 14). Because these negative savings in transitional months occur with wall insulation due to its tendency to trap heat and reduce ventilation, leading to overheating, unlike roof insulation, which primarily minimizes solar heat gain without hindering natural cooling (Sadevi & Agrawal, 2024).

Scenario 3 (S3) combines external walls and roof, increasing the seasonal strengths of each component. Particularly effective in summer months, with energy savings exceeding 20% in May–September, as shown in Figure 14. This finding aligns with Krarti et al. (2020), who emphasized the enhanced performance of combined insulation strategies in reducing both cooling and heating loads. Furthermore, by applying S3, the consumption increment in the transitional months reduced to -31 kWh (-1.4%) in March (Figure 14).

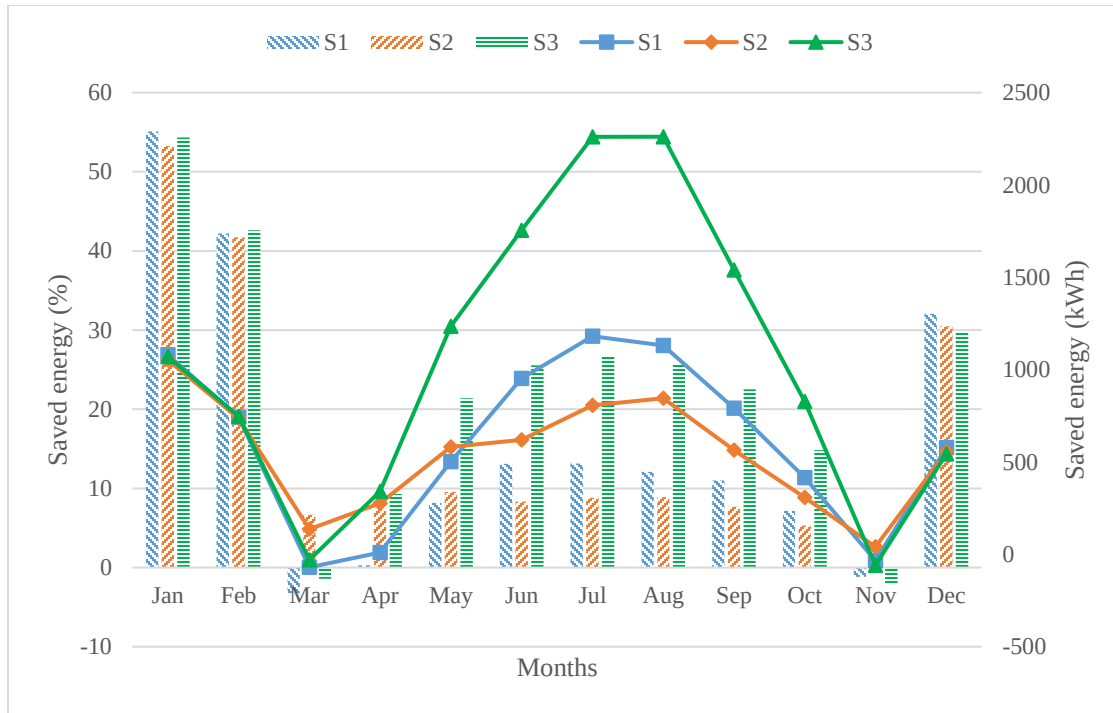


Figure 14: Energy savings from stand-alone external insulation scenarios and their combination

The performance of the combined strategies highlights their effectiveness, as demonstrated by the incremental improvements in energy savings from single measures to integrated approaches. Although Scenario 12 achieved the highest overall annual energy savings which is associated with scenarios involving HVAC upgrades, Scenarios integrated with window glazing upgrade (S4, S7, and S10) also performed exceptionally well (Table 10 and Figure 15). For instance, during May–September, Scenario 10 (S10: external walls and roof insulation with window glazing upgrades) achieved the highest energy savings with monthly reductions of 1412 kWh (24.8%), 2014 kWh (29.9%), 2553 kWh (30.8%), 2539 kWh (29.3%), and 1771 kWh (26.3%), respectively, as illustrated in Figure 15. This demonstrates the effectiveness of combining wall and roof insulation with glazing upgrades in significantly reducing the cooling demands.

Figure 15, show that Scenario 4 (S4: external wall insulation with window glazing upgrade) have moderate energy savings, with reductions of 635 kWh (10.5%) in May and 1156 kWh (16.1%) in June. However, S4 performed less compared to S10, likely due to the absence of roof insulation, which limits the overall cooling efficiency. In addition, S4 also reduced the increase in consumption of energy in the transition months (March and November) to -45 kWh (-2.1%) in March and became a positive savings of 4.615 kWh (0.16%) in November, as shown in Figure 15. Scenario 7 (S7), featuring external roof insulation with glazing upgrades, showed the lowest energy savings of 702 kWh (11.6%) in May and 716 kWh (9.9%) in September. These results highlight the limitations of roof insulation alone and the higher efficiency of a comprehensive retrofitting approach such as S10.



Figure 15: Energy savings from external insulation scenarios with inclusion of window glazing upgrades only

4.2.2 Internal Scenarios

The energy consumption data for a typical base case and 12 retrofit scenarios (S13–S24) was evaluated to determine the performance of various internal energy-saving strategies. Figure 16 shows the effects of these interventions on energy consumption compared to a typical villa. The strategies included internal insulation for walls (W2) or roofs (R2) and more integrated solutions that combined window glazing improvements and HVAC upgrades. While all scenarios showed similar trends, with higher energy consumption during summer and lower in winter, the total energy consumption varied depending on the energy-efficient approach applied (Table 11).

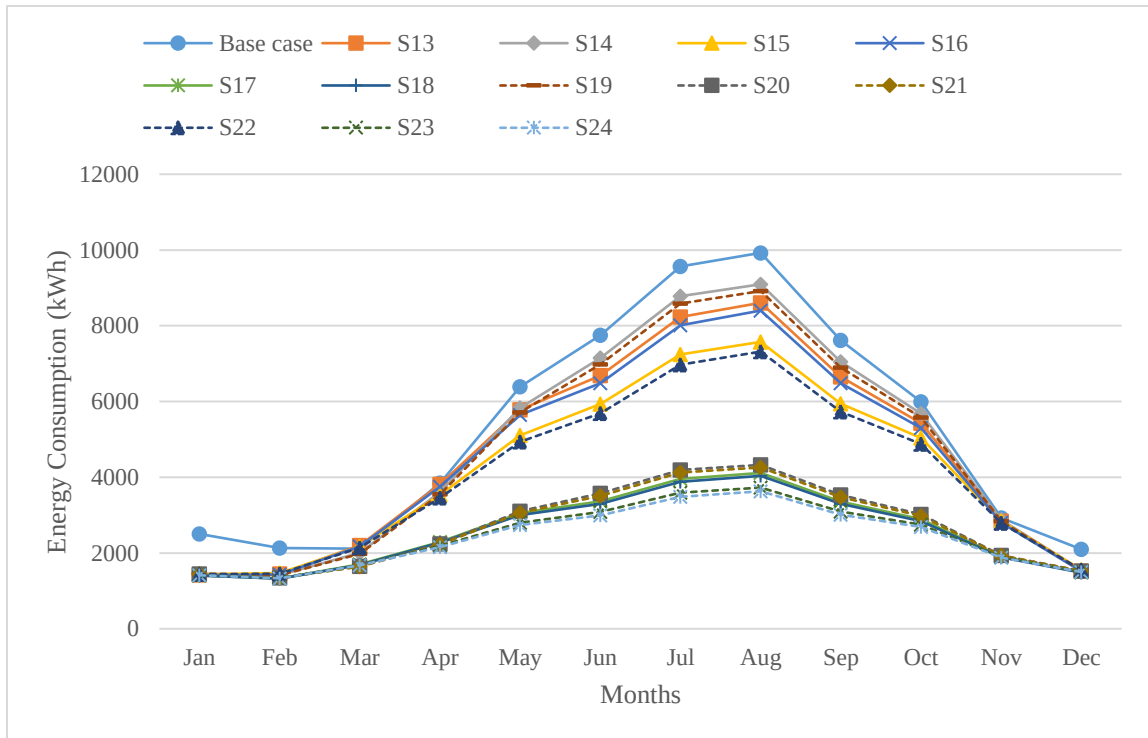


Figure 16: Energy consumption of the base case and different internal retrofit scenarios

Table 11: Annual energy consumption and savings for different internal retrofit scenarios

Scenarios	Annual energy consumption (kWh/year)	Saved energy (kWh/year)	Saved energy (%/year)
S13	54623	8240	14.0
S14	56495	6367	10.7
S15	49856	13007	23.1
S16	53416	9447	16.2
S17	30856	32006	68.3
S18	30407	32455	69.6
S19	55459	7404	12.5
S20	31902	30960	65.3
S21	31519	31344	66.4
S22	48361	14502	26.1
S23	29068	33794	73.5
S24	28512	34351	75.2

The findings indicate considerable variation in energy savings, with Scenario 24, which combines internal walls and roof insulation with window glazing and HVAC improvements, achieving the highest annual energy savings of 34,351 kWh/year (75.2%) as shown in Table 11 and with reductions over 80% during peak summer months (Figure 17). This result surpasses the savings of external scenarios and emphasizes the synergistic effect of integrating all interventions.

The application of internal insulation for the walls (Scenario 13) demonstrated a significant improvement in energy efficiency compared to a base case, achieving an overall energy savings of 8240 kWh/year (14.0%), which is higher than Scenario 1's savings. While adding internal roof insulation (Scenario 14) achieved an annual energy savings of 6367 kWh/year (10.7%) (Table 11), which is less than Scenario 2's annual savings. Furthermore, Scenario 15, which combines internal wall and roof insulation, achieves an annual energy savings of 23.1% or 13,007 kWh/year (Table 11), which is also higher than Scenario 3's

annual savings. This result achieves significant improvements over individual strategies, suggesting synergy when internal insulation is applied to both elements.

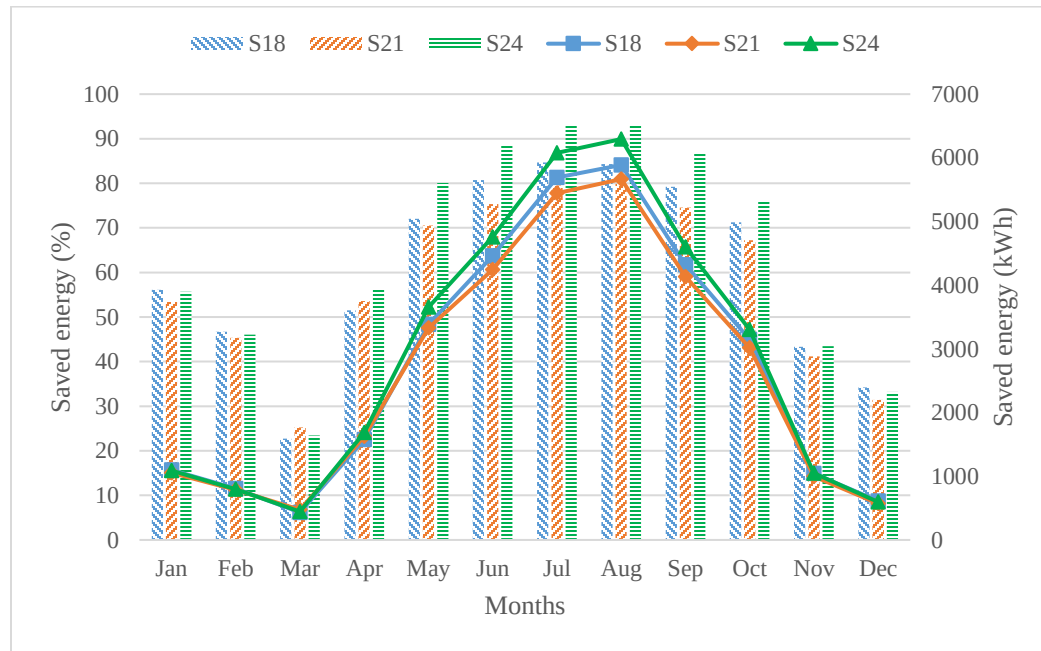


Figure 17: Energy savings from internal insulation scenarios with inclusion of both window glazing and HVAC upgrades.

Monthly analyses reveal significant energy savings during the summer months (May–September), aligning with the highest cooling demands. Scenarios involving only HVAC upgrades (S17, S20, and S23) consistently achieved monthly savings exceeding 70% during this period (Figure 18). Specifically, Scenario 17, which integrates internal wall insulation with HVAC upgrades, achieved significant energy reductions in July (5608 kWh or 82.9%) and August (5811 kWh or 82.8%) as shown in Figure 18. Scenario 23, combining internal wall and roof insulation with HVAC improvements, delivered even greater energy savings in July (5977 kWh or 90.9%) and August (6198 kWh or 90.8%) (Figure 18). These findings highlight the critical role of HVAC system optimization in hot

climates, demonstrating the substantial energy-saving potential of standalone HVAC upgrades.

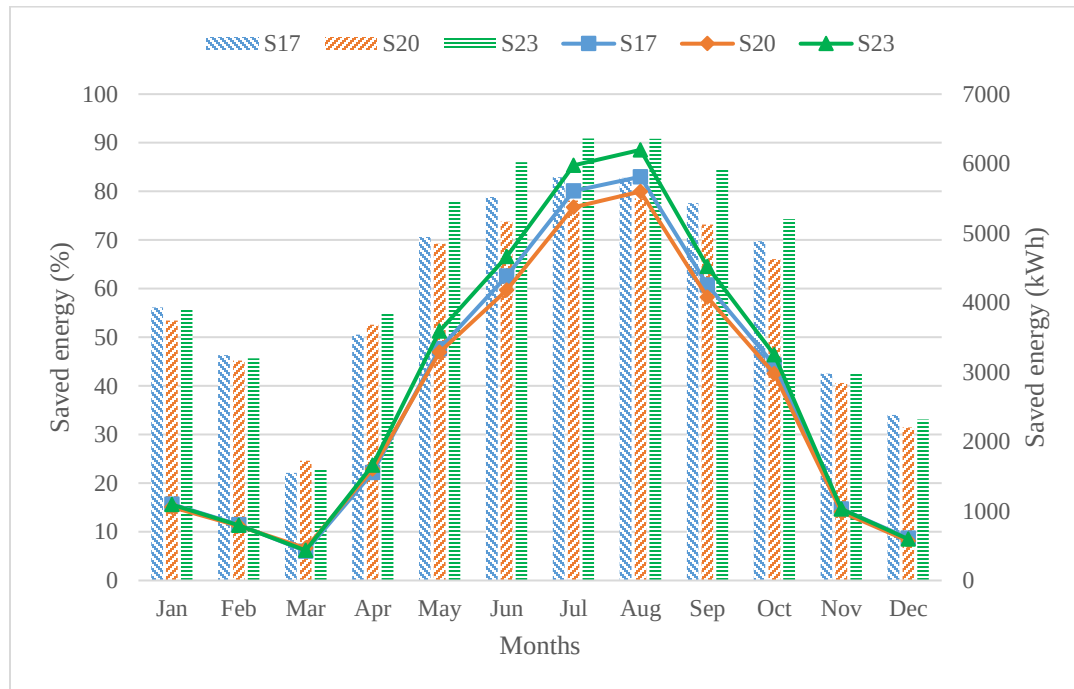


Figure 18: Energy savings from internal insulation scenarios with inclusion of HVAC upgrades only

Figure 19 shows that Scenario 13 (S13: internal wall insulation) demonstrated significant performance during winter, with the highest energy savings observed in January (55.2% or 1084 kWh). However, its performance during summer was moderate, with energy savings ranging between 13.5% (960 kWh) in September and 15.0% (1337 kWh) in July, highlighting the capacity of the insulation to minimize heat penetration through walls when external temperatures are high. It is worth noting the negative energy savings in March (-3.8%), suggesting possible unintended heat retention during transitional seasons. Although S13 shows negative savings, it outperforms S1 (external wall insulation) since its negative savings are limited to March, whereas S1 experiences them in both March and November. This improvement can be attributed to the use of mineral/rock wool for internal insulation

instead of polystyrene. As highlighted by E2, *“Mineral/rock wool permits some moisture to pass through, addressing potential mold issues on the walls while effectively reducing the amount of heat within the wall.”*

Scenario 14 (S14), focusing on roof insulation, presented a similar trend, with peak performance also in January (53.1% or 1051 kWh). During summer, however, its effectiveness was slightly lower than S13, achieving energy savings of 8.6% (788 kWh) in July and 8.7% (829 kWh) in August. Like S13, S14 underperformed in March, achieving only 5.4% (111 kWh) energy savings (Figure 19). On the other hand, Figure 19 shows that Scenario 15 (S15), which combined both insulation strategies, consistently achieved higher energy savings across all months. For instance, in June, it achieved 26.6% (1817 kWh) energy savings compared to 14.8% (1070 kWh) and 8.1% (600 kWh) for S13 and S14, respectively. Similarly, in July, also show a savings of 27.6% (2320 kWh), far exceeding S13 (15.0% or 1337 kWh) and S14 (8.6% or 788 kWh). Although March posed challenges for all strategies, S15's performance (-2.5% or -53 kWh) still represented an improvement compared to the S13. These results highlights the limitations of relying just on either internal wall or roof insulation and emphasizes the significant advantages of combining the two strategies. The combined approach (S15) uses the strengths of both S13 and S14, providing significant energy savings across all seasons while reducing the performance gaps observed in individual strategies.

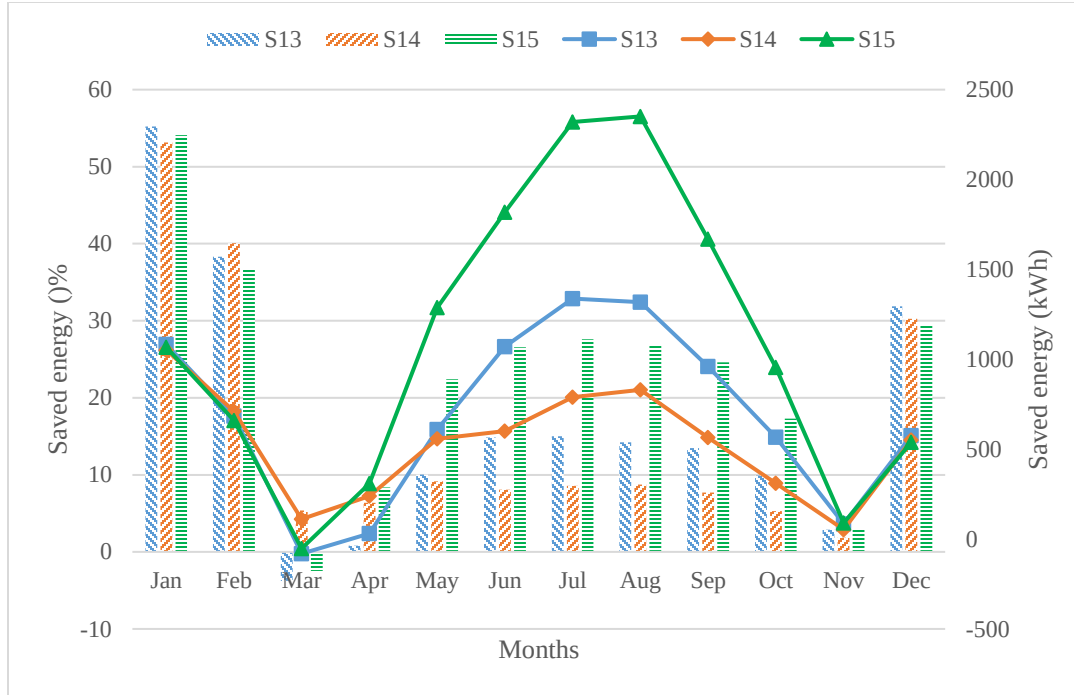


Figure 19: Energy savings from stand-alone internal insulation scenarios and their combination

The combined strategies demonstrate their efficiency through progressive improvements in energy savings when transitioning from individual measures to integrated approaches. While Scenario 24 saved the highest overall annual energy savings, primarily attributed to HVAC upgrades, scenarios incorporating window glazing enhancements (S16, S19, and S22) also achieved significant energy savings (Table 11 and Figure 20). For example, during the months of May to September, Scenario 22 (S22: internal wall and roof insulation combined with window glazing upgrades) showed the highest monthly energy savings, with reductions of 25.7% (1457 kWh), 30.7% (2063 kWh), 31.3% (2592 kWh), 30.2% (2608 kWh), and 28.2% (1879 kWh), respectively, as depicted in Figure 20. This highlights the substantial cooling demand reductions achieved by integrating wall and roof insulation with glazing enhancements.

As illustrated in Figure 20, Scenario 16 (S16: internal wall insulation combined with window glazing upgrades) achieved moderate energy savings, reducing consumption by 12.3% (740 kWh) in May and 17.8% (1268 kWh) in June, outperforming Scenario 4 (S4: external wall insulation with window glazing upgrades). However, S16 presented lower energy savings compared to Scenario 22 (S22), likely due to the exclusion of roof insulation, which constrains overall cooling efficiency. Additionally, S16 also reduced the increase in consumption of energy in the transition month (March) to -52 kWh (-2.4%), as shown in Figure 20. Scenario 19 (S19), incorporating internal roof insulation with glazing upgrades, presented the lowest energy savings, with reductions of 11.1% (675 kWh) in May and 9.8% (712 kWh) in September. These findings emphasize the limitations of roof insulation as a standalone measure and the superior performance of integrated retrofitting strategies like S22.

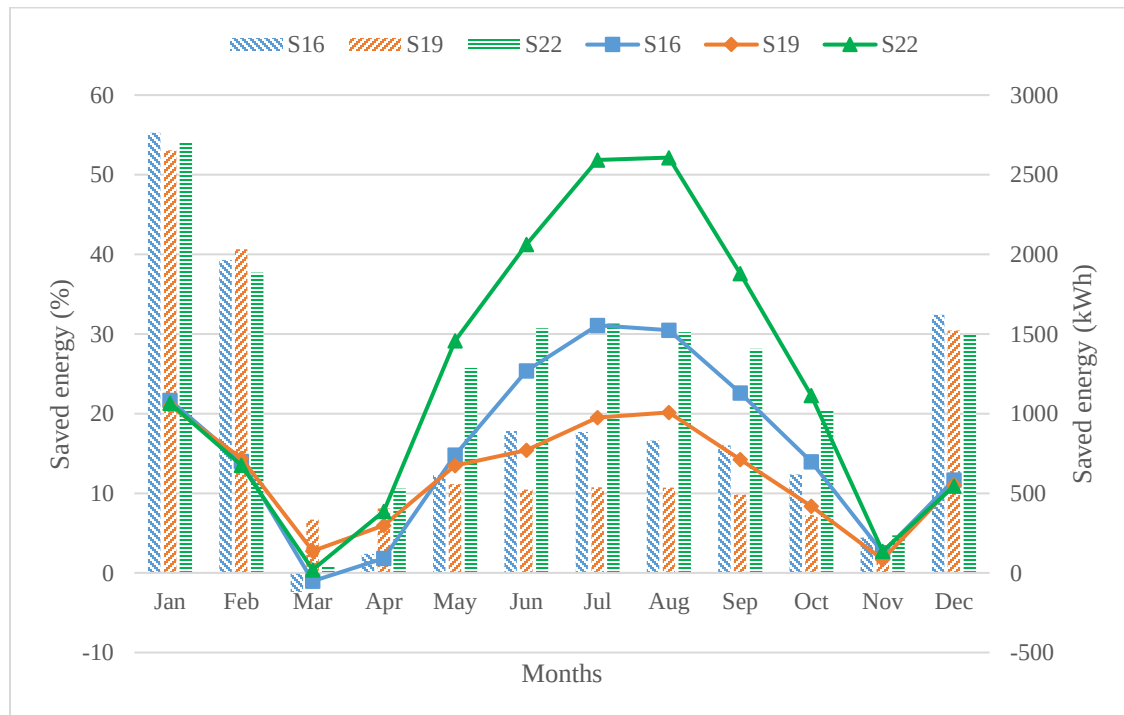


Figure 20: Energy savings from internal insulation scenarios with inclusion of window glazing upgrades only

4.3 Analysis of Economic Benefits and Environmental Effects

4.3.1 Economic Benefits

To determine the most cost-effective insulation strategy among the various scenarios (S1–24), the total cost of insulation materials in Saudi Riyals (SAR) for each of the different retrofit strategies were calculated using the corresponding materials cost defined in Table 7, as shown in Table 12. Furthermore, the annual saved energy cost in SAR was also calculated. These evaluations were carried out to compute the payback periods for the different scenarios (1–24) using Equation 3 outlined in Section 3.4 of the methodology, as shown in Table 13.

Table 13 provides a detailed evaluation of 24 retrofit scenarios (S1–S24), focusing on their economic feasibility through the cost of energy saved (C_{ES}) and the corresponding payback periods (PP). Among the external strategies, standalone measures such as S1 (external wall insulation) and S2 (external roof insulation) demonstrate moderate C_{ES} values of SAR 1,310.8 and SAR 1,174.2, respectively. However, the total retrofit cost of S1 (SAR 46420.9) leads to an extended payback period of 35.4 years, making S2 more economically attractive with a shorter payback period of 13.7 years. Combining external wall and roof insulation in S3 increases the C_{ES} to SAR 2,248.9 but results in a still lengthy payback period of 27.8 years due to the high retrofit cost (SAR 62489.3).

Strategies that incorporate window glazing upgrades with insulation, such as S4 and S7, improve C_{ES} slightly to SAR 1,532.6 and SAR 1,368.8, respectively, but S7 outperforms S4 economically with a payback period of 44 years compared to 59.1 years, which is unsustainable as it exceeds the extended SBC lifespan of 50 years to buildings in Saudi

Arabia (Argaam, 2021). External insulation combined with HVAC upgrades in S5 and S8 delivers significant C_{ES} values of SAR 5,685.2 and SAR 5,583.4, with S8 showing the most favorable payback period among all external scenarios at just 8.6 years. The most comprehensive external strategy, S12, which integrates wall and roof insulation with window glazing and HVAC upgrades, achieves the highest C_{ES} of SAR 6,143.2, but its high retrofit cost (SAR 138,609.0) results in a higher payback period of 22.6 years.

For internal strategies, standalone retrofits such as S13 (internal wall insulation) and S14 (internal roof insulation) offer low C_{ES} values of SAR 1,483.2 and SAR 1,146.1, with excessively long payback periods of 50.9 and 26.7 years, respectively, due high total cost of retrofitting and less savings of energy. Combining internal wall and roof insulation in S15 improves C_{ES} to SAR 2,341.3, but its high retrofit cost (SAR 105,985.3) leads to an unsustainable payback period of 45.3 years. Incorporating window glazing upgrades with internal insulation, as in S16 and S19, present C_{ES} values of SAR 1,700.4 and SAR 1,332.7, but their payback periods of 70.3 and 56.0 years remain lengthy.

Internal insulation combined with HVAC upgrades, such as S17 and S20, demonstrates improved economic viability, with C_{ES} exceeding SAR 5,700.00 for S17 and SAR 5,572.8 for S20. Notably, S20 achieves a payback period of only 11.2 years, making it the most cost-effective internal strategy. The most comprehensive internal strategy, S24, combines wall and roof insulation with window glazing and HVAC upgrades, achieving the highest C_{ES} among internal scenarios (SAR 6,183.1). However, its significant retrofit cost (SAR 182,105.0) results in a payback period of 29.5 years.

Overall, S8 (external roof insulation with HVAC upgrade) and S20 (internal roof insulation with HVAC upgrade) result as the most economically feasible solutions, achieving

relatively high C_{ES} values and short payback periods of 8.6 and 11.2 years, respectively. Comprehensive strategies such as S12 and S24 are suitable for projects prioritizing maximum C_{ES} but require considerable investment and longer-term planning. Standalone insulation strategies, whether external or internal, generally have limited cost-effectiveness, highlighting the necessity of integrating HVAC upgrades to optimize economic performance. This analysis highlights that retrofit strategies delivering high C_{ES} with convenient payback periods are important for achieving sustainable energy efficiency improvements.

Table 12: Different retrofit strategies cost calculations

Strategies	Area (m ²)/Quantity	Total retrofit cost (SAR)
External wall insulation (W1)	433.84 m ²	46420.88
Internal wall insulation (W2)	375.26 m ²	75427.26
External roof insulation (R1)	189.04 m ²	16068.40
Internal roof insulation (R2)	185.20 m ²	30558.00
Window glazing Upgrade	48.43 m ²	44119.73
HVAC Upgrade	10.00 units	32000.00

Table 13: Annual energy savings cost and payback period for different scenarios (S1–S24)

Scenarios	Saved energy (kWh/year)	Cost of energy saved (C_{ES}) (SAR)	Total cost of retrofit strategies in each Scenario (Ins. _{TC}) (SAR)	Payback period (PP) (years)
S1	7282	1310.8	46420.9	35.4
S2	6523	1174.2	16068.4	13.7
S3	12494	2248.9	62489.3	27.8
S4	8514	1532.6	90540.6	59.1
S5	31584	5685.2	78420.9	13.8
S6	32042	5767.6	122540.6	21.2
S7	7604	1368.8	60188.1	44.0
S8	31019	5583.4	48068.4	8.6
S9	31419	5655.4	92188.1	16.3
S10	14079	2534.2	106609.0	42.1
S11	33539	6037.0	94489.3	15.7
S12	34129	6143.2	138609.0	22.6
S13	8240	1483.2	75427.3	50.9
S14	6367	1146.1	30558.0	26.7
S15	13007	2341.3	105985.3	45.3
S16	9447	1700.4	119547.0	70.3

S17	32006	5761.2	107427.3	18.6
S18	32455	5841.9	151547.0	25.9
S19	7404	1332.7	74677.7	56.0
S20	30960	5572.8	62558.0	11.2
S21	31344	5641.9	106677.7	18.9
S22	14502	2610.3	150105.0	57.5
S23	33794	6082.9	137985.3	22.7
S24	34351	6183.1	182105.0	29.5

4.3.2 Environmental Effects

The environmental impact was assessed by quantifying carbon dioxide emissions from both existing and different external and internal retrofits Scenarios (S1-24). Using DesignBuilder software, CO₂ emissions were determined based on the fuel breakdown and region-specific factors outlined in the weather file. These factors represent the kilograms of CO₂ generated per kWh of fuel consumed. In this case, electricity was the energy source, with a defined emission factor of 0.606 kg CO₂/kWh. Table 14 provides insight into the saved CO₂ emissions and their percentage reductions of the different scenarios compared to the baseline scenario.

In external retrofit scenarios, standalone strategies like S1 (external wall insulation) and S2 (external roof insulation) showed moderate reductions in CO₂ emissions, with saved emissions of 4,413 kg/year (12.3%) and 3,953 kg/year (10.9%), respectively. However, combining external wall and roof insulation (S3) presented significantly higher savings of 7,571 kg/year (22.1%). Strategies incorporating upgrades to window glazing (S4) and HVAC systems (S5) demonstrated more substantial environmental benefits. For instance, S5 achieved a significant CO₂ reduction of 19,140 kg/year (67.1%), while S6, combining external walls with window glazing and HVAC upgrades, showed the highest efficiency with saved emissions of 19,418 kg/year (68.4%). Comprehensive strategies, such as S12,

which integrate walls and roofs with both window glazing and HVAC upgrades, provided the highest CO₂ savings among all external scenarios at 20,682 kg/year (74.5%) reduction.

Internal retrofits also presented considerable potential for CO₂ emission reductions. Individual measures, such as S13 (internal wall insulation) and S14 (internal roof insulation), achieved savings of 4,993 kg/year (14.0%) and 3,858 kg/year (10.7%), respectively. Combining internal walls and roofs (S15) improved saved emissions to 7,882 kg/year (23.1%). However, strategies incorporating window glazing (S16) and HVAC upgrades (S17) were far more impactful, with S17 achieving a significant reduction of 19,396 kg/year (68.3%). Among internal scenarios, S24, which combined walls, roofs, window glazing, and HVAC upgrades, stood out as the most effective, with saved emissions of 20,817 kg/year (75.2%).

Across both external and internal retrofit strategies, scenarios integrating HVAC upgrades consistently demonstrated the highest levels of CO₂ emission reductions. For example, S8 (external roof insulation with HVAC upgrade) and S20 (internal roof insulation with HVAC upgrade) achieved savings of 18,797 kg/year (65.5%) and 18,762 kg/year (65.3%), respectively. Comprehensive strategies like S12 and S24 offered the most substantial environmental benefits, with reductions exceeding 74%, making them the best choice for maximizing sustainability.

Table 14: Annual CO₂ emissions and savings for different retrofit scenarios (S1-24)

Scenarios	Annual CO ₂ emissions (kg/year)	Saved CO ₂ emissions (kg)	Saved CO ₂ emissions (%)
S1	33681.6459	4412.9951	12.30
S2	34141.4789	3953.1621	10.95
S3	30523.2844	7571.3566	22.07
S4	32934.8727	5159.7683	14.53
S5	18954.6121	19140.0289	67.10

S6	18677.1036	19417.5374	68.41
S7	33486.3333	4608.3077	12.88
S8	19297.2197	18797.4213	65.51
S9	19054.7948	19039.8462	66.63
S10	29562.9719	8531.6691	25.22
S11	17770.2262	20324.4148	72.76
S12	17412.6413	20681.9997	74.52
S13	33101.2518	4993.3892	14.03
S14	34236.2018	3858.4392	10.67
S15	30212.4238	7882.2172	23.08
S16	32369.8651	5724.7759	16.25
S17	18698.7467	19395.8943	68.30
S18	18426.8995	19667.7415	69.59
S19	33607.8432	4486.7978	12.52
S20	19332.7409	18761.9001	65.34
S21	19100.3595	18994.2815	66.42
S22	29306.4848	8788.1562	26.08
S23	17615.4371	20479.2039	73.52
S24	17278.1324	20816.5086	75.19

4.3.3 Multi-Criteria Decision Analysis (MCDA) Using TOPSIS

To identify the most optimal retrofit strategy among the 24 scenarios evaluated in this study, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) was applied. This method integrates multiple criteria into a single framework, allowing for the comparison of alternatives based on their overall performance (Madanchian and Taherdoost, 2023; Reddy *et al.*, 2019). Three key criteria were considered: energy savings, payback period, and the lifespan of materials. The carbon emission reduction was disregarded as it's associated with the amount of energy saved as kg/kWh (as mentioned in section 4.3.2).

The first criterion, Energy Savings (%), was maximized to reflect the efficiency of each retrofit in reducing energy consumption. The second criterion, Payback Period (years), was minimized to ensure the economic feasibility of each strategy. Lastly, the Lifespan of

Materials (years) was maximized to prioritize the durability and sustainability of the chosen materials. To maintain an unbiased evaluation, each criterion was normalized and assigned an equal weight of 0.33 for three criteria.

The analysis began with the construction of a decision matrix, in which the performance of the 24 scenarios across the three criteria was compiled. To ensure comparability, normalization of the criteria was applied using vector normalization. Equation 5 shows the formula for normalization as:

$$R_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^n X_{ij}^2}} \quad 5$$

Where:

R_{ij} represents the normalized value for scenario i under criterion j ,

X_{ij} is the original value for scenario i under criterion j ,

n is the total number of scenarios (24 in this case).

After normalization, equal weights of 0.33 were applied to each criterion to ensure that all aspects were treated equally in the evaluation.

The next step was the identification of the Ideal and Nadir Solutions. The Ideal Solution (denoted as A^+) represents the maximum value for the benefit criteria (Energy Savings and Lifespan) and the minimum value for the cost criterion (Payback Period). Conversely, the Nadir Solution (denoted as A^-) corresponds to the minimum values for the benefit criteria and the maximum value for the cost criterion.

Following this, the distance of each scenario from the Ideal and Nadir Solutions was calculated using the formulas in equations 6 and 7, respectively.

$$S_i^+ = \sqrt{\left(\sum_{j=1}^m W_j (R_{ij} - A_j^+)^2 \right)} \quad 6$$

$$S_i^- = \sqrt{\left(\sum_{j=1}^m W_j (R_{ij} - A_j^-)^2 \right)} \quad 7$$

Where:

S_i^+ and S_i^- represent the distances from the Ideal and Nadir Solutions, respectively,

W_j is the weight assigned to each criterion,

m is the total number of criteria being considered in the analysis (3 in this case)

Finally, the Relative Closeness to the Ideal Solution for each scenario was calculated using equation 8.

$$C_i = \frac{S_i^-}{S_i^+ + S_i^-} \quad 8$$

The relative closeness C_i indicates how close each scenario is to the Ideal Solution. Scenarios with higher C_i values are closer to the Ideal Solution and are considered more optimal. Based on the calculated C_i values, the scenarios were ranked accordingly.

Table 15 illustrates the evaluation of 24 retrofit scenarios, encompassing a combination of external and internal insulation strategies, based on their annual energy savings, payback periods, lifespan, and overall closeness to the ideal solution (C_i). Among the external

scenarios, S8, combining roof insulation with an HVAC upgrade, emerged as the most effective strategy with a C_i of 0.92. This combination achieved a remarkable energy savings rate of 65.5% while maintaining a relatively low payback period of 8.6 years, demonstrating its potential for addressing both energy and economic efficiency in retrofitting. The synergy between roof insulation and HVAC system upgrades effectively reduces heat transfer while improving indoor cooling performance.

The second-best scenario, S20, involved internal roof insulation paired with an HVAC upgrade, achieving a similar energy savings rate of 65.3% but with a slightly higher payback period of 11.2 years. The high performance of both S8 and S20 highlights the critical role of roof insulation in hot climates where heat gains through the roof significantly impact cooling loads. Meanwhile, S5, which integrates external wall insulation with an HVAC upgrade, ranked third with a C_i of 0.64, delivering energy savings of 67.1% at a moderate payback period of 13.8 years. This highlights the effectiveness of external wall insulation in reducing heat transfer through building envelopes while complementing HVAC performance.

Scenarios combining multiple interventions generally exhibited strong energy-saving potential but faced challenges in economic feasibility due to higher initial costs. For instance, S12, which combines external wall and roof insulation with window glazing and HVAC upgrades, ranked eighth with C_i of 0.49 and achieved substantial energy savings but was constrained by an extended payback period of over 21 years. Similarly, mid-performing scenarios like S11 and S9, incorporating various combinations of wall, roof, and glazing upgrades with HVAC systems, demonstrated significant energy savings above 65%, yet their payback periods ranged from 15.7 to 18.6 years.

In contrast, standalone scenarios, such as S1 and S2 (external wall and roof insulation) and S13 and S14 (internal wall and roof insulation), present lower energy savings (around 10%–15%) and correspondingly longer payback periods, ranking them among the least favorable options. The lowest-ranked scenarios, including S4, S16, and S19, were characterized by high material costs and minimal energy savings, leading to unsustainable long payback periods of over 50 years, exceeding the lifespan of the building. These findings emphasize that retrofit strategies with minimal or single interventions lack the effectiveness needed to justify their costs, particularly in contexts prioritizing rapid cost recovery.

Table 15: Multi-criteria evaluation of all the retrofit scenarios: energy savings, payback periods, lifespan, and performance rankings.

Scenarios	Annual Energy Savings (%)	Payback Period (years)	Lifespan (years)	Closeness to Ideal (C_i)	Rank
S8	65.5	8.6	50	0.92	1
S20	65.3	11.2	50	0.76	2
S5	67.1	13.8	50	0.64	3
S11	72.8	15.7	50	0.60	4
S9	66.6	16.3	50	0.57	5
S17	68.3	18.6	50	0.53	6
S21	66.4	18.9	50	0.51	7
S12	74.5	22.6	50	0.49	8
S23	73.5	22.7	50	0.49	9
S6	68.4	21.2	50	0.49	10
S18	69.6	25.9	50	0.45	11
S24	75.2	29.5	50	0.45	12
S2	10.9	13.7	50	0.43	13
S3	22.1	27.8	50	0.20	14
S14	10.7	26.7	50	0.19	15
S10	25.2	42.1	50	0.14	16
S22	26.1	57.5	50	0.12	17
S15	23.1	45.3	50	0.12	18
S1	12.3	35.4	50	0.12	19
S7	12.9	44.0	50	0.07	20
S13	14.0	50.9	50	0.05	21
S16	16.2	70.3	50	0.04	22
S4	14.5	59.1	50	0.04	23
S19	12.5	56.0	50	0.03	24

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study provides a comprehensive analysis of retrofit strategies aimed at integrating thermal insulation to enhance energy efficiency in residential buildings within Saudi Arabia's hot climate. Each study objective was addressed comprehensively through the structured methodology. The first objective, identifying practical thermal insulation integration strategies, was achieved through comprehensive literature reviews and expert interviews and synthesizing their insights with simulation data to propose practical retrofit solutions of 24 different scenarios involving internal and external insulation, window glazing upgrades, and HVAC improvements. The second objective and some parts of the third objective, evaluating energy impacts and CO₂ analysis, was fulfilled through rigorous DesignBuilder simulations, which quantified the energy and CO₂ savings of various scenarios. Comparing payback periods, was addressed by detailed economic analysis. Finally, identifying the most effective strategies were achieved through multi-criteria method using TOPSIS.

The study identified effective measures such as external and internal wall and roof insulation using materials like expanded polystyrene (EPS), extruded polystyrene (XPS), and mineral wool. These strategies were tailored to the hot climatic conditions of Saudi Arabia and considered practical implementation challenges such as cost, material availability, and installation techniques.

External retrofit strategies demonstrated significant potential for improving thermal performance and reducing cooling energy demand. Among these strategies, external wall insulation combined with HVAC upgrades (S5) achieved substantial energy and CO₂ savings of 67.1%, with a payback period of 13.8 years. External roof insulation paired with HVAC upgrades (S8) emerged as the most cost-efficient solution, with a payback period of just 8.6 years. Comprehensive external strategies, such as combining external wall and roof insulation with window glazing and HVAC upgrades (S12), presented the highest energy savings, reducing energy demand by over 70% and CO₂ emissions by 74.5%. Despite the high initial costs, these strategies offer substantial environmental benefits with a payback period of 22.6 years, making them suitable for long-term sustainability goals.

Internal retrofit strategies provided valuable alternatives for enhancing energy efficiency, particularly in cases where external retrofitting are not feasible. Internal wall insulation combined with HVAC upgrades (S17) achieved significant energy and CO₂ savings of 68.3%, respectively, with a payback period of 18.6 years. Comprehensive internal strategies, such as S24, which integrated wall and roof insulation with glazing and HVAC upgrades, achieved the highest savings among internal retrofits, with a 75.2% reduction in energy and CO₂ emissions. However, these strategies required higher upfront investments, with payback periods exceeding 20 years, emphasizing the need for economic considerations in their adoption.

The results further indicate that standalone insulation strategies, whether internal or external, offered moderate energy and CO₂ savings with limited economic feasibility due to long payback periods. For instance, S1 and S2 (standalone external wall and roof insulation) achieved moderate energy and CO₂ savings of 12.3% and 10.9%, respectively,

but required over 13 years for cost recovery. Similarly, internal standalone strategies such as S13 and S14 (internal wall and roof insulation) showed long payback periods exceeding 25 years.

The findings from the most effective strategies demonstrate that retrofit strategies combining roof insulation with HVAC upgrades, particularly scenarios S8 and S20, offer the most effective solutions in hot climates by achieving significant energy savings (over 65%) and maintaining relatively short payback periods. While more extensive interventions involving multiple upgrades, such as S12 and S11, deliver substantial energy performance improvements, their longer payback periods challenge their economic viability. Conversely, scenarios with minimal interventions provide limited energy savings, rendering them less favorable for achieving sustainable and cost-effective retrofitting. The findings highlight the importance of integrating synergistic measures, such as insulation and HVAC upgrades, to maximize energy efficiency while ensuring economic practicality.

Despite its contributions, this study has some limitations. First, the analysis is limited to a single climatic zone, potentially restricting the generalizability of the findings to other regions with different climates. Second, while the cost and payback periods are considered, the broader socio-economic factors, such as homeowner willingness, were not explored. Lastly, while DesignBuilder excels in architectural modeling and energy simulations, it has limitations in accurately addressing complex thermal bridging phenomena which may have effects on the energy performance. Future research should address these limitations by expanding the scope of the analysis to include diverse climatic regions. Moreover, integrating socio-economic factors and renewable energy systems into retrofit strategies can further enhance their feasibility and alignment with sustainable development goals.

5.2 Recommendations

Building on the findings of this research, several recommendations are proposed to enhance the adoption and effectiveness of thermal insulation retrofitting in Saudi Arabia:

- **Design for Integrated Retrofitting:** Comprehensive retrofitting strategies, such as S12 and S24, should be prioritized for achieving maximum energy savings and environmental benefits. These strategies demonstrate the importance of integrating insulation, advanced glazing, and HVAC upgrades.
- **Economic Feasibility and Policy Incentives:** Policies should incentivize retrofits with favorable cost-to-benefit ratios, such as S8 and S20, which combine insulation and HVAC upgrades with short payback periods. Financial subsidies and tax incentives can further enhance the feasibility of these solutions.
- **Emphasis on External Insulation:** External insulation strategies, particularly those involving roof insulation combined with HVAC upgrades, should be prioritized due to their cost efficiency and shorter payback periods. These strategies also minimize disruptions to building occupants.
- **Post-Retrofit Monitoring and Feedback:** To validate and optimize retrofit strategies, post-retrofit performance monitoring should be implemented. This will help refine models, improve decision-making, and ensure alignment with projected energy and environmental outcomes.

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APPENDICES

Appendix A. Interview Questions and Letter Format

Interview Questions:

Introduction Section: Respondent Characteristics

What is your current job title/role?

How many years of experience do you have in building construction or retrofitting?

Have you been directly involved in any residential retrofitting projects involving thermal insulation? (If yes, I will ask the number of projects)

What type of buildings do you primarily work on for retrofitting projects?

In which region do you primarily carry out your retrofitting projects? (Urban areas, Rural areas, Both urban and rural, others)

Which insulation materials have you worked with in your retrofitting projects?

Techniques and Strategies for Retrofitting:

What insulation techniques do you find most effective for retrofitting residential buildings in this region?

Can you share specific strategies that you use to minimize disturbance to occupants during retrofitting projects?

Are there any insulation methods or materials that you consider particularly suited to local building conditions?

Price of Materials:

How do the costs of different insulation materials (e.g., fiberglass, polystyrene, polyurethane foam) compare in the context of local retrofitting projects?

How does the price of materials impact your choice of insulation for retrofit projects?

Have you noticed any recent changes in the market prices of insulation materials, and how do they affect the feasibility of retrofitting?

Availability and Sustainability of Materials:

Which insulation materials are readily available locally for retrofitting purposes?

Are there any sustainable insulation materials (e.g., recycled materials, natural fibers) that you have used or considered using in retrofits? If so, what has been your experience?

How do supply chain constraints (e.g., availability of specific insulation materials) influence the selection of insulation materials for retrofitting?

Commonly Used Insulation Materials:

In your experience, which insulation materials are most commonly used in local retrofits, and why?

What factors (e.g., climate, building type, cost) influence the choice of insulation material in the retrofitting projects you've worked on?

Barriers to Retrofitting:

What are the key challenges you encounter when implementing thermal insulation in residential retrofit projects?

How do building regulations and codes impact the implementation of insulation retrofitting strategies?

Are there any specific homeowner concerns (e.g., cost, disturbance, aesthetic changes) that often act as barriers to retrofitting?

Complementing Simulation Data:

From your experience, how do the actual performance outcomes of retrofitted insulation compare to the expected results from energy simulations?

Could you provide examples of how occupant behavior or building use patterns have affected the effectiveness of retrofit strategies in practice?

What additional benefits (e.g., improved thermal comfort, noise reduction) have you observed that are not typically captured in energy reduction simulations?

Follow-up and Discussion Points:

Discussion with the interviewees how practical constraints (e.g., budget, homeowner preferences) align or conflict with the simulation results.

Exploration of the trade-offs between the choice of insulation materials and the practical outcomes (e.g., performance, sustainability) versus what is suggested by the simulation data.

Letter Format:**Subject: Request for an Interview**

Dear Professional name,

I hope you are doing well. I am Hassan Hassan Umar, a Master's student from the Architecture and City Design Department at the King Fahd University of Petroleum and Minerals (KFUPM). I am currently working on my thesis titled Retrofit Strategies to Integrate Thermal Insulation for Energy Efficiency in the Residential Buildings of Saudi Arabia. kindly gave me your contact or referred me to you.

I would like to conduct an interview with you, as I am seeking expert opinions for my research. The interview will focus on thermal insulation techniques used in residential retrofits, the cost and availability of materials, sustainable practices, and the challenges in retrofitting.

If possible, could you kindly suggest a convenient time for us to schedule either an in-person or online interview via Zoom, Microsoft Teams, or Google Meet?

Thank you very much for your time and consideration. I look forward to your response.

Best regards,

Hassan H. Umar

Master of Science in Architecture

King Fahd University of Petroleum and Minerals (KFUPM)

0592655456

archhumar@gmail.com

Appendix B. Selected Transcripts from Interview Recordings

Expert 1:

Okay, thank you. So, I'll just start with some introduction, so like, what's your current job now? Okay, so I work as a facility engineer in Saudi Aramco. I've worked with them for 11 years now.

I worked as a... When you're a facility engineer in Aramco, you wear several hats. You're the interior designer, you're the space coordinator, you're everything at once. So, have you been directly involved in residential retrofitting projects? Yes, I have just completed an interior design project for a boutique hotel in Aramco, two years ago.

That was one of the major projects they had. And we are currently working on other projects. Okay, so like, you mentioned that most of the building is primarily residential? I did work for the first eight years in office interiors, and then the past four years was in residential.

Okay, so these projects are mainly in the rural or in the cities, over? In here, yes. So, like, coming to the insulation material, so which type of material do you usually use? As an interior designer, for offices, if I can go, for offices, if we have such a space, or a commercial space, we usually go with sealing materials that are insulated. This is a very important aspect to us.

We avoid hard floor flooring, we always go with carpet. Even walls, we do use wallpapers to, the interior walls, like the gypsum walls, they have insulations within them, just to ensure that waste doesn't go over. But these are standardized within the office.

For residential, you need to understand that we always are working with already built buildings. They're old buildings that need to be renovated. So not much can be done with the structure itself for insulation, so we have to play with the materials we're using inside.

Whether it's furniture, whether it's finishes, ceiling, floorings. What we struggle with the most, I believe, is that, because this is fairly new, and when I say fairly new, it's, I would say, it hasn't been even 10 years since people realized that, oh, we need to look into this. So it's been less than 10 years, so the materials are not very widely available here in Saudi.

So the struggle is always that we need to plan ahead, so each project needs to be considered, like we need to have a three to six month plan for it. Considering that we need to order materials from outside, because we require specific specifications. The ones within Saudi, or at least the companies that we've worked with, or that we've went to and asked and seen their products, what they have readily available is always from China.

I'm not saying China is bad, but sometimes the quality isn't as good as the ones we get from other countries. So this is where we struggle the most. I do know of a company that capitalized on the installation of sound absorbance and the cooling and heating, so they started creating the wall panels that have fabric, they're covered with fabric to insulate.

And they just started three years ago, I think, by now, it's been three years ago. So it's fairly recent. And the quality we've seen with them so far is as good as the quality we're receiving from outside.

But within Saudi, it's a struggle, it's not easy. Even the floorings, if we have certain specifications, if we want to go with wooden floorings that have insulation, that are padded, these need to be ordered in advance. It all takes 12, 14 weeks to arrive.

And then you have the customs that will take two, three more weeks, and so on. So it's not an easy job. So there is so much challenges.

Yes, yes. We'll come to that. So the scale of your company is large, medium? Large.

But the type of companies you work in, is it international or local? With furniture and materials? Yeah. We work with both, but I think four or five years ago, they started to go with trying to localize the orders. So if I'm from Saudi Aramco, I cannot order from a foreign company.

I need to go to a local. I can't go to an international directly. I go to the local, and the local will order it for me.

So this is the process at my company, at least. I know other companies, no, they go ahead and... Okay. So coming to the techniques and the strategies you use, which type of techniques or strategies do you use to integrate? Because you know that these buildings are already existing.

So how do you integrate the thermal insulation, for instance, into the walls and the roofs? We always try to use the windows. If they're small, we try to go for bigger for warmth, for sunlight, for direct sunlight. This is very important to us.

Wallpapers. Now wallpapers, they come in different forms. You have fabric, you have a lot of textures. They exempt some warmth. Furniture is very important to us also. It's the lighting as well, as an interior designer.

Doing the exterior, there's not much we can do. We can only play with what's inside. If it's a structure, it's very hard. Because we're talking about buildings that were built in the 50s, 40s. So they have their historical aspect to them. But if... Yeah, go ahead.

Okay. Okay, so... So you've mentioned, like, for instance, residential buildings. So when you are doing retrofits, there is so much of disturbance.

So how do you minimize this? For residential? Yes. We work on the insulation between the walls, whether it's ceilings and floorings. Whether it's walls or ceilings.

The insulation is very important. The ducts sometimes come in as very noisy. So these need to be fitted in a way that... When we don't hear the vibration of the AC. The doors. Doors are very important to us. To ensure that they are very well structured in a way that they absorb the sound.

I'm going to go back to my example. The last project we completed. We had to ensure that when we're walking, that the people inside the rooms wouldn't hear us walking in the corridors. Okay. So I think we tried two or three doors to ensure that when we're walking we cannot hear anyone. So it's the thickness of the door.

What the door is made of was very important to us. Okay. Furniture plays a huge role. Floorings. We go for either wooden floors that are padded. It's not real wood. It's a laminate. It has insulation. Yes. Specifics has that. We go with carpet floorings to ensure that... This is not for residential. Yeah. But we go for carpet floorings also. Furniture. We try to avoid hard surfaces for furniture. We go with soft. Because the soft always absorbs the sound. And it's warmer. Even for heat. So we always go for fabric. We go for padded furniture. That's the best choice. Okay. Thank you.

So, for instance, which type of material do you think is locally available now? Locally? I do know that we have a few shops. The wooden floors are good so far. They're realizing that. So, so far, that is... There are the floors. As I mentioned, there's this company. Al Mudairi Company. They're the ones who do the panels. They're actually metal panels. Where they just click them on the... And they create... I wish I have photos. I don't. It's where they create... Like walls. And we create fabric walls. So they do that for us. They retrofit it for us. The sizes that we want.

Whether we want it as a ceiling. Whether we want it as a wall. So there's this company right now. They're doing this. What else? There are a few companies that actually provide the... Acoustical panels. They come in different shapes and different... It's not the usual triangular one.

They give us texture. If we want a wall, if we want a drop ceiling. So they give us some shape and they give us some texture. Again, most of these materials are ordered from outside. But they are available locally if we wanted them. They can do that for us. They can bring them for us. So, yeah, companies... It's just recent. Within the five past years, that's when that started booming. Before that, that wasn't readily available for us. So, all right. Coming to the... Now we are in the age of sustainability.

So have you tried any sustainable material? Maybe like natural fibres? Very difficult. It's very difficult. Very difficult. With... At least, we are always rushed to do projects. So we cannot think sustainable and design at the same time. So we always sacrifice the sustainability.

But when we think, we don't think... It's not pure sustainability, but we do consider that... We want these things to last us at least ten years to go. I did attend a conference, I think Index, last... The year before, two years ago. And they told me, they mentioned, maybe that would be... That would help you. They were talking about how they used the seed of the dates. Have you heard of that? Yeah, they said they used it into creating some furniture. That was interesting to me. That was the first time I heard of it. I'm like, wow. I didn't know people were that enthusiastic about it.

But unfortunately, no. Okay. That's very hard. We're trying, though. This initiative is, again, new to us. So we're trying to incorporate as much as possible. Okay. It's very difficult. Okay.

So, for instance, coming to the availability of the material. For instance, the supply chains. Yes. Constraints, maybe. Sometimes if you are looking for another material and you do not get it. So does it influence the selection of your material? Maybe you change to another one that is readily available? Yes. Always. That's the point of being a good designer. Is that if you cannot have what you want, you have to figure out an alternative to make it work. Okay. So, like, how does the price of the material, like... affects the choice of the installation? It depends. It depends on what the client wants. It depends on what the result you want is. There are clients who specifically say, we only want Italian. As an interior designer, I'm talking. That would be way expensive. That's too much. What we are trying to do right now is implement a mix and match methodology. Where we're like, okay, we cannot go for a high budget. Okay. But going for a low budget is not acceptable either.

So we go somewhere in between. So we'll try to get something from there. And we'll try to get something that's acceptable from the low budget. And we mix and match and see if it works. Okay. For the most part, it does work. Nobody would know. Okay. So, like you mentioned, this is new. Yes. So a lot of people have not experienced. So have you noticed any recent stints in the market price? Like for the insulation, that will affect maybe the feasibility of people going back to retrofitting? Everything insulated is quite expensive.

If you're looking for insulated, it's not cheap. It's not cheap. And I think that's why a lot of people opt to do things on their own. Rather than going through an expert. Okay. Yeah. Yeah. Now that I'm considering the insulation, I can give you examples. There are two companies that we've worked with.

There is Gallery Design, who gives us an insulated. Whether they're suspended ceiling extensions or whether they're wall-implemented, wall-planted. They come from a European country. So they're quite expensive. But there is another company. Again, this is offices, so it's a bit old. Eideck. They're both local, these companies. Eideck gets me different shapes, different colors, anything I want. They were designed to the way I wanted. But it's China. Okay. There is a difference in price. Okay. But it depends on the quality you're looking for. Okay. The quality is different. You can notice the difference between Eideck and Gallery Design. Okay. So it depends on what the designer or the architect is willing to sacrifice for the end result. Okay. So it's all a personal preference. Do you want a certain look? Do you want a certain finish? Okay. But it's available. And there is a price range. So it depends on the person who's selecting. Okay.

Okay, so coming to the challenges and the barriers. For instance, what are the key challenges you encounter? Like when implementing thermal insulation, such as high material cost, lack of skill level, and availability of material, all this. Okay. We've talked about

availability. It's all pre-ordered. Nothing is readily available. You all have to pre-order it. I have nothing in the market that I can say, I want it next week and they'll give it to me. It's available, unfortunately. And there is a plan with, at least my company, with these companies through B2B. You're familiar with B2B? It's buyer to buyer. Okay. It's a system, it's a portal. Okay. Where we told them you need to have at least this quantity readily available for any surprise projects that we might have, any rush project that we might have. We need you to have this quantity available for this year. Okay. So this is something that we created to prevent this challenge.

But if I'm going to talk as a separate entity, like on my own, if I'm doing this as my own business, it's going to be a struggle to find it available. Because I'm one, it's a company who's willing to pay this amount of money to ensure that the material is available. That was one.

What are the other aspects? The costs, the labor scale? Labor. We struggle with skills here. Unfortunately, the labor that come to work, this is not their, how do I say it, this is not their place of expertise. He might know nothing about, so he learns it as he goes. Okay. So every project, at least that we do, we have to ensure that we are with them the whole time. And if we notice that if there is any problems, rectify this, this is not right. So this causes sometimes delay on projects. Sure. A lot of frustration. Extra money because they need to do the job once or twice. And sometimes we try to negotiate that they didn't do it right the first time, so you didn't charge me for the labor.

So we get into a lot of problems with the vendors in this regard. Just because the labor they're bringing in, they're learning the job as they go. It's not something that they are an expert as in they brought them and they're like, you know how to create an insulated wall, come do it for me. No. He doesn't know what, he just knows that this is the process. But what goes into it? I don't know. This is something we struggled with. Okay. But what's the third aspect that you found? The costs. Costs, okay. As a company, if, again because I've worked in the company for 11 years, we're always charged double or triple. Okay. The regular price. So if I'm going to them as an individual, for example, let's say they're going to charge me 1,000 for five square meters. Yes.

But if I'm from the company, they charge me extra. Because there are challenges within the supply chain, getting their money and so what, so they ensure that for the delay and everything. They get a profit out of it. Yes, a percentage out of it, yes. Okay. So like, how do they, like building courts, like for instance regulation or like, so the building courts like, in fact the implementation of the retrofits or insulation side of this? Not a lot go by it, to be honest. If I'm going to go, for example, my parents' house, they didn't ask a designer to do it for them. They did it as they, a lot, 70% of the houses are done, were done based on the owner's. Preference.

Yeah, so they had no awareness of the building court, they don't even know what a building court is. I agree. But nowadays I do see that people are more aware of it. My husband who is not an engineer, he's an IT, he's aware of the building court. He's commenting, he's like, see the streets, I don't know, do you see the signages in the streets? Yes. The names of the streets? Yes. This is new. This is, it's not by the building courts, but this is by the Saudi courts, so people are more aware that all these changes are because of something that's called courts. They're asking, what are the courts? Okay.

In Aramco, if that would help you, we have a department specifically created for the courts. So when we create designs and materials that are specified, we put it in a portal for them to have a look at. And if it's an execution, they go and visit the site. Okay. And they have their own codes and they have their own regulations. Aramco has its own codes. That are even more, the Saudi building codes are more forgiving. Aramco's codes are a bit more strict. So they go and they check.

So we have people who are checking after our work, ensuring that we are doing things correct. And if we're not, construction is put on hold until we rectify, and then we go ahead. So, at least the engineers here are very well aware of the codes. Okay, so like, for instance, are there any homeowners concerns? Like, you know, sometimes when you are in the project, maybe the issue of costs or disturbance or maybe aesthetic changes that usually affects us or suffers a barrier to... Yes. In our projects, we always have management. Yes. They are eventually the client. They are the client. They are our clients when we do the project.

So he's like the owner. So when we're doing a project, he has an electrical background or a mechanical background. And he would come in here and be like, I don't like this. Do something else for me. Or, no, they do impose their opinions. So without any rational judgment, they will just... Because he thinks it's aesthetically more pleasing to him. Yeah. It is subjective. It is.

And that's why I'm studying my master's in a different, because I hated my life the past 11 years because a lot of people had to intervene with my projects. And it just, it's frustrating. A lot of people have a lot of opinions. And they think they're more... We cannot argue with the clients. Sometimes we have to see if the client is always right. If they don't listen to the rationality we are explaining, we have to do what they want at the end of the day.

Okay. Okay, so is there any additional benefits that you observed when using thermal insulation in traffic projects, like maybe thermal comfort, noise reduction, and also that are not usually mentioned? We had a project. I can give you from my experience. We had a project once. It was in a basement of a building. And you know that basements are very loud. There's a very loud echo sometimes. It's not the best way to conduct any meeting. And they wanted to convert that basement into a meeting area. And they wanted it at a high level. So it was very difficult turning a very disturbing basement, where there's a lot of traffic, people coming in and out, because it's a basement. Yes, and also on the top of it, people are also... Yes.

So a lot of... it wasn't thermal insulations, but it was the acoustical panels that we used, which they have thermal insulations in them, within them, but we used them everywhere. Okay. The result was beautiful. The ceiling was all covered with acoustical insulated... suspended acoustical panels. The walls were covered with the panels of acoustical... it was beautiful. Okay. And they called it the cave. That was the name they gave it. They called it the cave. It's soundly insulated now. It was... it wasn't cold. It was... the temperature was very good.

Again, I'm not very much into thermal, but we have experts who are familiar with that, who ensured that... It's thermally comfortable. It was very comfortable. The only issue they had was they kept... they said... The noise that was coming from the AC. Okay. And they fixed that. They did some insulations on the ducts. I don't remember what it was exactly, but if you want, I could get back to you with

that, what the process they did for the ceiling, for the AC. And it worked perfectly. Top management have their meetings there now. That's nice. Okay. Okay.

I think we've come to the end, but maybe I don't know if you have any... Like, you know, sometimes people, like, make simulation, like, for instance, before going into the main projects. Yes. Like, you simulate and you see, like, you already, like, you know that this project is going to. So is there any, for instance, like, how practical constraint between the simulated project and the actual, like, for instance, maybe, you know, sometimes people like use simulation to calculate the budget and, like, look at the homeowner's preference. Unfortunately, that is not being done. Okay. The only simulation we do is the 3D Max. This is where we can show you what the end result is going to look like. But nothing of, no simulations of thermal, no simulations of even that. And this is a problem. They're trying, I do know now that they're trying to integrate BIM into all the work that we're doing.

Okay. So, but still no projects have been created using BIM, at least implemented. They're giving them the fake projects they can make believe, just to see if it's working, if it's feasible. But nothing has been implemented using BIM in Saudi Arabia, from our projects. Nothing. Okay. Thank you so much. I think that's all. If you have any comments.

I hope I helped you. Yeah, sure. I will try to see if I have, again, I think they're not professors, but I can see, I'll see if I can connect you with someone. If you need further. Yes, I need to because I. If someone from academia, I can. But yeah, I'll try. I'll try my best. I'll get back to you sometime next week. All right. Okay.

Expert 2:

As you said, it is very important to retrofit a building rather than demolishing it and rebuilding it. If you carry a life cycle assessment, there are many studies and many examples done worldwide by reusing an existing building, by reusing its structure mostly, so they steal and reinforce concrete of a building instead of demolishing and rebuilding it. In one, you save at least 50% of the CO2 equivalent. Yeah, sure. So that's very important, your strategy, and it's the less damaging to our planet and the more sustainable way of doing things is to try to improve what we already have instead of building a new one. Yeah, sure.

Okay, so we'll start with some introduction, like what's your current job now, how many years of experience do you have? Sure, sure. Just to give you a quick summary, I'm currently working for Stadio Aranco, within their community services, and my role is as an architect, as a consultant, helping with existing buildings, with projects to remodel, repurpose, sometimes adding to existing buildings, and rarely building new ones, designing new buildings, but that is quite rare. My professional experience has been spanning over 29 years.

Ah, that's good. I started in Italy, yeah. Wow. I work in Italy, I work in New York for 5 years, in the Netherlands, and then UK another 10 years, and I've been in Aranco for more than 10 years now. That's good. And recently, especially during the lockdown, when I had more time for myself, because of my personal passion, I decided I wanted to know more about what you actually are studying, to know more about how to reduce energy consumption in buildings, so I took an online class to become a certified Passivhaus designer.

Passivhaus standard is maybe the most stringent standard worldwide in terms of energy saving in buildings, and can be applied both to new projects and to retrofits. That's good. Currently, I think I checked the database on the Passivhaus Institute, which is based in Germany, but it's used worldwide. In Saudi Arabia, there are only two certified Passivehaus designers. One is me, and the other one I think is a Saudi architect. Okay. Unfortunately, I didn't have any chance to apply Passivhaus principle in full here during my work, but I try to apply at least some strategies whenever it's possible. Okay, that's nice. Yeah.

In a nutshell, my background. Okay, that's very nice. You mentioned you have been working maybe in some of retrofits. So, is it mostly in the residential buildings, or which type of building do you usually work on? Within Aranco, we deal with many types of buildings, from office buildings, warehouses, residential buildings, of course, and some community buildings. Okay. So, all types of buildings, more or less. Because Aranco is a town, it's quite large. Yeah, sure. It's almost a self-sustained community. I mean, there is everything. Yeah. We deal with everything. Yeah, it's the Zaharan. All of Zaharan now is Aranco. Yes, that's true.

Okay. So, have you, I don't know, been directly involved, maybe using thermal insulation integration in the residential building? Yes, yes. Now, usually, once the strategy that has been applied by Aranco since the past, I don't know, before I joined, so I'm talking about more than 10 years, maybe 15 years. Okay. It's what I find is maybe the most efficient way of building here, which is the external insulation applied to existing envelope, building envelope. Okay. So, we're talking about what in the United States is called EIFS. Yeah, external insulation is this thing. Yes, I forgot the F. EIFS. It has different names. In the UK, it's called FETIX, external, again. Okay, yeah. I forgot, but you can search. Yeah, it's called external insulation finish system. Finish system, yeah, EIFS, so that's the American term. But it's known as, or insulated render also is known in the UK. Okay. So, it's basically the same thing.

And what is that? It's basically polystyrene or like an insulation board, which in my personal experience is mostly chemical-derived, so it's the same kind of board that you see when you open a new television box to protect it from, again, from getting broken. So, it's that rigid foam. Okay. Now, what we are using now, because the white foam is very flammable and can create smoke and flame, which is dangerous, because we are using a dark gray color polystyrene foam, which can still burn, but it doesn't release any smoke or flame, so it's safer. Okay. And then that can be a different thickness, depends on the U-value that you require, because let's say from a minimum of 50 millimeters to 100, 150, if you go to passive out standard, it can even reach 200 or 300 millimeters, but that's more extreme for mostly cold weather. So, it depends on your calculation about the local, what is the U-value you want to achieve. Okay. And then on top of that board, you've got different layers of cementitious layer, like, I don't know how to call it.

It's like a stack, but it's made of a cementitious material, and then you've got one or two fiberglass mesh, and then you've got the final coat, which is very rigid, very quite robust finish coat, also that is a cementitious. Okay. So, outside they look quite, I mean, I like the

aesthetics, you can have, it looks like a stucco, what we call in Italy stucco. Yes, okay. And then you can have different texture, and of course a thousand different colors, whatever you like. Okay.

Now, the good things of this compared to interior insulation is that if you design it properly, it will limit the amount of thermal bridges. Okay. The problem with interior insulation is

quite straightforward, but when you put interior insulation, maybe because the building is a building where you don't want to change the external aesthetics. Yes. Especially in Europe, there are many old buildings, you don't want to cover them with EIFS, you want to leave the external aesthetics, like bricks, marble, stones. Yes.

And then you have to go inside, you've got internal insulation. The problem with interior insulation is that whenever you hit a perpendicular wall to the external wall, or the slab itself, there you have thermal bridges. Yes. You have to tell various details to try to avoid that, but it's more complicated. So, it's more complicated, I think less efficient as well. Okay.

So, that's what, sorry, this is one part of the building envelope, is the vertical wall. Okay. So we say EIFS, then of course the windows. Now I notice, unfortunately, in Saudi Arabia the quality of windows is still not up to my expectation. Sometimes they still use aluminum windows without thermal breaks. Yes. So, the thermal break is what you put, if you have a metal frame, it's what you put between the internal and external layer of metal in the window, so that the heat will not pass through the metal directly from outside to inside. So, it's basically a rigid plastic that separates the two layers of aluminum. And I notice in some occurrences you have a window exposed to the sun, you touch the frame and you can cook an egg there, it's so hot that it's really a waste of energy.

And the frame is more, I mean, the glass quality is fine most of the time here. You've got very big companies that produce glass at the international standards and they have a very good U-value and the G-value. Yeah. So, the weak part is the frame, so we have to be very careful how to specify the frame and of course where to locate the frame. Okay. In an existing building, so what you do, you replace maybe the window which are poor quality, low U-value, and you place new ones.

But then when you, later when you add the EIFS, you have to be sure that this EIFS somehow overlaps the edges of the frame. Yes. To limit the thermal breach as much as possible. Yeah, sure. And of course the roof, that's maybe the most important one because it's horizontal, it's perpendicular to the sun rays most of the time, especially during midday. So that also needs a lot of insulation and it's recommended to be even higher U-value than the walls.

Now for roof. Yes, okay. Okay, what I've been experiencing here within Aramco is when we deal with maybe retrofitting a warehouse and make it an office building, what we do is we take out all the external envelope and we leave just the structural steel. And then we recover the whole thing. So it's quite drastic. Yeah, sure. But in a residential, then yeah, it's all about details. So either you put a rigid board underneath, I don't know, if the roof is a tiled roof, you need to take out all the tiles and add rigid insulation boards on top of it and then put the tiles back. Okay, now here the weak point again is the connection between the sloping roof and the external walls. So you have to be sure that it's detailed properly so that there are no thermal bridges. Sorry, can you give me just a second? Sorry, hold on a second. Okay.

I need to respond to a message. All right, no problem. One second. No problem. Okay, Hassan, sorry. Okay, no problem.

It's okay. So where were we? Yeah, yeah, thermal bridges between roof and external wall is quite important. I mean, there are hundreds of different situations, so I cannot make a generic statement. But yes, in short, I would say these are the three most important items. So windows, vertical walls. Yes. To be, let's say, upgraded. Okay. Now in this climate, slop is not that problematic as in colder climates.

Yeah, sure. To pass a standard, maybe in Germany or UK or North America, they all have a quite high U-value for the slop. So even the ground floor slop needs to be insulated so that no cold goes through the soil into the apartment. Okay. But here it's less problematic. Okay. In that respect. Okay. Right.

So, you know, residential buildings, usually sometimes if you are having a retrofit, there is so much disturbance. So how do you minimize such disturbance to the occupant? Maybe that, you know, especially that you are working in Aramco, I know there is so much residential buildings. So maybe sometimes if you are going to retrofit some areas, so you will be disturbing some areas. So how do you minimize such? Yes. Now here I have to give you two answers. In Aramco it's quite lucky because there is, I mean, the resident will be relocated to another building. Okay. So that's easy answer. But in a normal situation where you cannot relocate the dwellers or the people who lives in the building, then you have to do things in, I recommend to do things in phases to minimize the disruption. Okay. Now, the site will be, as I mentioned before, it's mostly outside. So you can still have internal activities, normal internal activities in the house while they retrofit, for example, the vertical walls.

Okay. Now maybe there is windows, those needs to be scheduled properly. So the rooms where the windows are replaced cannot be used by the people who lives in the house. So that requires some project management, some scheduling. So you have to non-occupy or to leave those rooms unoccupied when you replace the windows because that will be, of course, not ideal to have a big hole in your wall in summer. Okay.

So you have to do things in phases. Roof also can be accessed from, it depends on the situation, but most of the times it can be accessed from outside. So again, the disruption can be minimal. So it's case by case and it's mostly about good phasing and good project management. Okay. All right. So, all right. So which insulation material is locally available for retrofit strategies here? Yes, insulation material, it's quite a good offer, I noticed. We got, of course, all kind of EPS, they use mostly, as I said, it's a polystyrene, which is the... EPS? So, yeah, for the EPS, yes, it's available here.

Now, if you want to be, even add more safety, you can replace the polystyrene with rigid mineral wool. Okay. Now, this, I know it's possible, but I haven't had the direct experience in Saudi, but I know it's something possible. In that way, if the building requires some fire strategy because, I don't know, it's adjacent to an existing building and you don't want the risk of a fire affecting a neighboring

building, then I recommend replacing the polystyrene insulation board with the mineral wool rigid board, which are, of course, non-combustible. Okay. So, it's a bit for the peace of mind, even when it's not needed by God.

And, of course, mineral wool is a little bit more breathable, so it allows some moisture to go through it without being stopped. Okay. Or creating some, I don't know, issues that can create molds. Now, if you put external insulation, usually I never had the problem with molds or trapping humid air in the wall. Okay. That, instead, can be a problem when you do internal insulation. If you don't do proper detailing, proper calculation, you may risk to create an interstitial, I don't remember the term. It's basically the water drops are stopped inside the wall. Okay. That basically stop the humidity coming in, but at the same time allows the wall to breathe. This should be on the hot side. So, in this case, in this country, on the external side.

Okay. In the case of the EFS, this vapor barrier, it's basically defined the system itself act as a whole vapor barrier. It's actually, it doesn't, it's quite sealed in terms of air leakage. It doesn't allow air to come in. The only weak area are the edges between the windows and the edge of the EFS. You have to be careful with the entire detail and install properly so there are no cracks between the two. Okay. When you have cracks, then you have the risk of hot and humid air coming into them. That's an issue. It's quite delicate. Okay. Now, there are software in the market.

I haven't used it, but I know the system that can calculate what is the dew point in a wall. So, it can calculate where, based on your architectural detail of the wall or of the roof, it tells you if it's a good design or if it's risky because it can create this interstitial problem of humidity and stop being trapped between the layers of wall or roof. Okay. But that goes into a bit in physics. So, it's a specialization I haven't seen in this country. There are very good people in physics and a webmaster in that respect. There are a few in the UK and, as far as I know, in North America. Yeah, sure. But it's still an area which is not a project.

You have to know a bit in physics in order to, how do you say, not create new problems, especially with regards to moisture or to the vapor movement from one side to the other. Because sometimes you have an existing house, it's full of holes, cracks, and the windows are not good. It's highly inefficient, but there is so much movement of air inside that it's very rarely possible to have a problem. But when you start to insulate it and seal the whole heating, then you're sure it's not creating an extra problem that was not there before. Okay. I mean, all of this topic is a topic for a whole master. And I'm not an expert, but it's a big one. Consider whenever you do. Yeah, sure. These are very important.

Okay. Are there any sustainable insulation materials that maybe you have used or considered using in retrofits? For instance, maybe recycled material or natural fibers? Sure. Okay. Yeah. Okay. Okay. Okay. Okay. Okay. Okay. All right. So... Okay. Okay.

So, how do you like, for instance, supply chains, maybe the availability of the material influence the selection of material that you are going to use in retrofitting projects? Okay. So, that's a big, big issue. And the only way to solve this issue is quantity. So, the more project we start to demand natural material, more likely there will be lower cost of producing here and more available. But if there is no demand, because everybody wants to save money and they keep using chemical, then it's difficult to transition to... Okay. So, it's again, it's about supply and demand.

Okay. Okay. So, what about the costs? Yeah. I think the cost is for EIFS. They come from a small sphere of chemical material that is produced, I think, in Belgium by, I think, EASF company. And then here is expanded.

So, they got a facility in Saudi Arabia where this little sphere goes into some process and they become, they expand, they tie together and they create the rigid board. Okay. So, in that case, it's something that is, let's say, half made in Saudi. Of course, costs will drop. But if you have to import wood fiber insulation, I don't know, from Scandinavian country, that's a big cost. I don't know the numbers, but still the natural material is not, I mean, from my experience, I don't know, countrywide, but are not readily available in Saudi yet.

Okay. All right. Okay. So, have you noticed any recent changes, maybe, in the markets, price, maybe, and how it's going to affect, maybe, the retrofitting for these materials? Yeah, I noticed they are, I spoke with a vendor recently of an insulation company. I think it was Kingspan, I think. Yeah, they are basically building factories here. Okay. Before, they were importing from Madagascar region. Now, because of the increased demand of a new building in the kingdom, mostly, I think, large projects that are going on in Riyadh or elsewhere.

They start to, a big manufacturer, start to look at Saudi Arabia, more interest and more potential for selling points. So, they are starting to build their own factories in the kingdom. I think that will, again, reduce the cost of the material and increase the availability. Okay. Now, if that can move towards more natural material, I would be happier, but I don't know yet. Okay. We'll see.

All right. So, going back to the, maybe, challenges. So, what are the challenges you found, maybe, during your project that's, maybe, trying to implement the insulation into the residential project? Maybe, such as, high material cost, lack of skill level. The second one, I think, is for me the most challenging. Not to skimp labor. You can do the best detail at the design level, you can write the best specification, but then, if on site you don't have the right people with knowledge, all your efforts at the design stage will vanish. So it's very important to have a trace for key elements in the building. You need to have skilled labor, and that's, I think, missing here. So that's, for me, challenge number one.

Cost, it's second, again. I think the main thing is to convince the client, the proponent, as we call it in Aranco, that you may pay a little more, but you are making the building more efficient energy-wise. That's something that we as architects should push for it. And of course, as I say, once this becomes a standard approach, it can be done kingdom-wide, then prices start to fall. So, for example, I remember there was an example of a typical passive house design compared to a traditional high-quality design, and I remember at that time it was an average of maybe 8% more expensive to have a passive house. But, of course, the more they are doing, this difference becomes less and less.

So the goal is to build an excellent building or to retrofit a building at a high standard, and that would be the same price as using non-energy-efficient details. So I think that's the goal. You have a high-quality design and the same cost as a not-so-high-quality design, just

by adopting the right strategy. So it's about material, but also it's about knowing what you are doing and having a design rather than another design. I suggest you, if you allow me, to read more about... There are a couple of things that you may be interested in in your retrofitting study. One is to search more about the retrofitting of buildings according to passive house standards, which is called Enerfit.

So it's basically a certification they give you if your existing building is retrofitted to this standard and achieves specific values in terms of energy consumption. The other one I'm also a member of is a good association in the UK called AECB, which is an association for energy-conscious buildings. They also offer a standard, or they manage a standard, which is the AECB. And specifically for retrofit, they have a lot of information on their website. Unfortunately, most of these are related to cooler climates, but the principle is the same. And the most important thing, which I noticed, is this standard, the passive house on Enerfit, compared to more common energy standards like LEED in the United States or BREEAM in the UK, is that the passive house actually works on numbers.

So it's very scientific. It's not about checking boxes on a list, saying, oh, I'm doing this, I'm doing this, I'm doing this. And then in reality, the building is doing something completely different. So it's not just wishing well. It's actually, after the building is used, it should match what you calculated at the design stage. So there is a specific amount of energy limit that the building can use for cooling or heating it. That should be matched after the building is completed. So what you design, what you calculate, it's also what is the real performance of the building. And it's certified by third parties. So it's not you that you certify. It's third parties that assess this number and say, OK, what you achieve is meeting the goal, and we can give you certification. So it's not something you can twist.

There is some kind of police looking over you and saying, oh, you're doing the right things, and we give you certification. So you cannot fake it. So it's very, very accurate and very scientific as an approach. All right. So how do the regulations and court, maybe, for instance, the Saudi building court, in fact, the implementation of retrofit? Yeah, what we are using is, of course, the Saudi building court now, as you know. Actually, we say Saudi Aramco building court, but that is based on Saudi Arabia building court.

Also, Saudi Arabia building court is 99.9% based on the international building court, which is part of the international court standard in the U.S. And that is referred to the International Energy Conservation Code, IECC, which changes every three years. And that gives you the limits, limiting your value about different parts of the building and consumption limit and so on. It's quite good. It's good. It's not, of course, it's not as stringent as the passing laws, but at least if everybody is following that, that would be a big step forward. Now, we are using Aramco still the 2015 International Energy Conservation Code, but I noticed from the latest edition, I think now it is 2024, IECC, and it's improving.

Every three years, it's more and more stringent, like everywhere else in the world, these codes, because they need to help meeting the country, reaching whatever goal they are trying to reach, like, I don't know. So, what's my name? Well, this is... So, this is... So, it's disrupted. Where is it? Recording in progress. Sorry, sorry. Okay. That's okay, I don't know what happened, but yeah. Yeah, it just got disrupted, sorry. That's okay. Now, I forgot where we were. Yeah, we are talking about the courts and Saudi court and Aramco.

Oh, yeah, the court, yes, yes, yes. Yeah, so, yeah, as you know, it's important when we're referring to the code to use the latest one, especially when you talk about energy efficiency, because the codes are updated every new version is more stringent with regards to energy saving requirements. So, the International Energy Conservation Code, I think you should look at the 2024 one. Okay, all right, all right. So, is there any maybe homeowner concerns, maybe aesthetic changes that open maybe as barriers to retrofitting when you are doing retrofits? Yeah, that's a good question. If you use the external EIFS, of course, it changes. Yes. Okay. Sorry. All right. Can you still hear me? Yes, I can hear you. Okay, okay, good, good.

So, yeah, aesthetics are, I mean, you can have a very good aesthetic with EIFS, but, of course, you change the pre-existing building. Okay. Another way is to, you have what is called the rain screen system, which is an insulation board. Yes. That can be, again, can be a mineral wall or a rigid wall, and then a metal frame connected to the existing wall. It goes through this insulation and holds maybe a metal cladding of some sort.

Yes. This is more for industrial, commercial building. It's not really for residential. Okay. Or if the residential building has some feature that you don't want to hide with the new external insulation, then, of course, you have to go towards internal insulation, internal wall insulation. And as I said, that is more challenging. Okay. As a rule of thumb, for example, when you put insulation on the internal side of your wall, of your external wall, Yes. and when you hit a perpendicular wall, which is maybe internal walls separating two rooms, Yes.

then you, as a rule of thumb, you should insulate also maybe up to half a meter of that perpendicular wall, Okay. floor to floor, so that you limit the thermal bridge effect. And then when the vertical wall touches the roof, then it's better. Okay. If there is a... Okay, let me rephrase it. Okay.

Another example I came across here in Aranco, in residential buildings, where you have a pitch roof with a loft, what is called a loft space or... Yes, okay. an inhabited space between... Between the ceiling and the actual roofing. Yes. Yes. In that case, what we do here, sometimes we put insulation horizontally on top of the ceiling. Okay. Okay. Okay, in America they call it attic space. Attic, yes. Yes. Now, in that case, insulation becomes, needs to be increased a lot. I think now it's R-58 for the American imperial standards.

Okay. R-58 is quite thick. It can go easily 200 millimeter thick or more, or 250, I think, 250 millimeter thick mineral wool insulation blanket laid on top of the ceiling. But then the attic should be ventilated above the insulation because the attic can become like a furnace, can become much hotter than the external temperature. Yes. External ambient temperature. So if outside is 40, the attic can go up to 60 easily because you trap the hot air inside and there is no circulation. Yeah. So you have to have... This is all in the code, it tells you the size of the air inlet and outlet, so to allow air movement above the ceiling for the attic insulation. So that's another way. Okay. You can insulate your house without changing the roof appearance or without re-roofing it.

Okay. You can work on the attic level. Okay. All right. Maybe, is there any occupant behavior or building use patterns like, you know, maybe usually that affects your projects when you are doing retrofitting? Sorry, I didn't catch the first part of the question. Is there any...

Maybe the occupant behavior or the building use patterns, maybe how they... Oh, the occupant behavior. Yeah, occupant, yeah. Yes, yes. Yes, of course, that's always the case.

Yeah, it's... Because I come across one of... There is this project that they are doing now inside here in KPVM, in Farukots. So there are a series of residential buildings there. So all the occupants vacate their buildings, but one of the homeowners says he is not going to vacate his building because he recently made some upgrades in his building. So they have been now dragging. After now, they will not be able to start the project because of him. So I don't know.

Because of the... People will not leave... No, sorry. What's the problem? They are not leaving? They cannot leave the building? Yes, he said he cannot leave his building, so... Right, right, yeah, I understand that. In that case, yeah, you have to... If it's possible to put insulation on the outside, on the outside... Okay. So that people can still have their own activities inside of the building. Okay. But then again, when it comes to windows, maybe the day they replace the window, maybe just one day is needed. You have to vacate the room or the apartment or the accommodation, whatever you call it, so that they can replace the window properly. Okay. All right, so... That can be one way.

But, yeah, in that case, forget about interior insulation. That is too disruptive and nobody can stay inside. Only do interior insulation. Yeah, sure. Okay, so maybe... Did you observe any additional benefits of thermal insulation retrofit project, maybe apart from just the thermal part, maybe improve thermal comfort, noise reduction and so on? Oh, yes, yes, yes. Noise reduction is the first. Thermal comfort is also good. Again, if you do like windows, like if you have a good window and you are next to it, if the window is good, you don't feel any discomfort. Okay. Or little discomfort. But I notice here in Morocco, maybe they installed not the window that we specified or lower quality. Okay.

And you start to see people putting all kind of shading devices on the glass because they are too hot or the glare is too much, so it's a lot of discomfort. Okay. So... And also I'm quite against the much use of glass in this climate. We should reduce the amount of glass as much as possible. So I'm totally against all full glazed painting. It's a waste of energy, discomfort from the sun glare.

So I think we should go back more to traditional construction and limit the amount of glazed surface. Yeah, because I don't know why this is hot climate and they are insisting on using too much glazing. I don't know. Yeah, I think it's a lot of pressure to match what is going on in the other part of the world where the climate is different. They want to mimic maybe what's in, I don't know, New York rather than London. But it doesn't make any sense.

When you design, it should be related to... Your own climate, yes. Absolutely. Okay. All right. Thank you. And I don't know, since you said you have experience and you even took a course that has to do with energy, did you maybe... How... There are any practical constraints maybe that are complex between the simulated result and maybe when you come to the actual work and find there is maybe some differences or something like maybe the performance or the sustainability suggested by this simulation and it's not practical. That's a very good question. Now, that's the term that comes to my mind. In my theoretical experience, by studying, by doing this, I was learning and also learning by myself. I do a lot of... I'm studying a lot by myself, not related to work, but because I like the subject. What you describe is called the performance gap. Yes. So you design something, but the outcome is not what you design. Yes. And that all the time, it's happening all the time.

And that's when I mention LEEDs and Brium, it's kind of standard, there are a lot of performance gap, my experience is telling me. You got... In Aramco, you got the Almedra Tower building, which is a LEED Platinum, but I noticed there were a lot of energy problems. Yes. I tried to fix it. Sure. So, you said in the past, because of the process, you start with modeling the PHPP, which is the Personal Planning Package, which is an Excel spreadsheet, a very sophisticated Excel spreadsheet where you input all your design information.

Okay. And the outcome tells you how much energy the building you design will use. And if the construction on site is done properly, then the performance gap is almost zero.

So, the actual performance are 95% the same as what you design, so it's very, very accurate. Okay. But that requires a good design, good workmanship, and good supervision on site, so that what you design is, and the material you specify and the way they are assembled are exactly as you envision, as you design. Okay. So, it's all about a good systemic approach. Everybody should be on the same page.

Okay. You cannot specify triple glazed window with high performance and then on site somebody arrives with double glazed and bad performance, so the whole thing falls apart. So, you need all the people from the designer to that user be on the same page. Okay. That is the only way to achieve high results. All right. Yes. All right. I think we concluded.

Thank you so much. Thank you. It was nice to interview you because I have learned a lot. Okay. I don't know if you can share with me some maybe technical details of how you have this type of retrofitting, maybe both the external and the internal for the wall and the roof, maybe, and the glazing. I don't know if you have such materials. Yeah. I will share with you by mail some of the guides maybe I find more useful. Okay. And, yeah, just give me some time because I have to search for this information and then I will also give some website links that can be helpful for your research. Okay. All right.

Thank you so much, Architech. Okay. No way. Thank you, Hassan. All right. Best of luck with your thesis. All right. Thank you so much. Okay. Thank you. You're welcome. All right. Bye. Bye. Bye.

VITAE

Name	:Hassan Hassan Umar
Nationality	:Nigerian
Date of Birth	:1993
Email	: archhumar@gmail.com
Address	:No. 3, Adjacent Malam Kuri District Head Residence, Pantami Street, Gombe, Gombe State
Academic Background	:Master of Science (MS) in Architecture, king Fahd University of Petroleum and Minerals (KFUPM), Dhahran, Saudi Arabia, 2022-2024 :Bachelor of Technology (B.Tech.) (Hons) in Architecture, Modibbo Adama University of Technology (MAUTECH), Yola, Nigeria, 2014-2020
Research Paper	: Umar, H.H. , Mohammed, M.A. and Kanu, R. (2024), "A post-occupancy performance evaluation study on user satisfaction with university student housing facilities", Facilities, Vol. ahead-of-print No. ahead-of-print. https://doi.org/10.1108/F-04-2024-0064