Holistic Energy-Efficient Retrofit Strategies in Support of Saudi Building Code: A Path Towards Sustainable Residential Building

A Thesis submitted in fulfillment of
the conditions for the award of the degree of Doctor of Philosophy

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Abstract

The Kingdom of Saudi Arabia has experienced significant changes over the past few decades, leading to a notable increase in energy demand, especially in the residential sector. This presents an opportunity to explore innovative and sustainable solutions, such as energy-efficient technologies, to meet the country's growing energy needs. Saudi Arabia's rapid population growth, urbanization, and industrialization have made it a major energy consumer in the Middle East, with air conditioning loads accounting for approximately 50-60% of residential electricity consumption. With electricity demand rising by about 5–8% annually, oil production and consumption are expected to increase by 2035.

In response, the Kingdom has established the Saudi Energy Conservation Code (SBC-602) to promote energy-efficient practices and enhance construction sustainability. This study evaluates the impact of various energy-efficient measures on a typical residential building in Saudi Arabia, aligning with global sustainable development goals and Saudi vision 2030. Using the Integrated Environmental Solutions Virtual Environment (IES-VE) simulation tool, the thermal performance of building envelope elements at three locations in Saudi Arabia was assessed. The methodology involved creating a detailed model of a typical residential building and simulating its energy performance under different retrofit scenarios. Additionally, a cost-benefit analysis was conducted to evaluate the financial feasibility of the proposed solutions. The findings indicate that the optimal retrofit strategy can decrease peak electricity demand by nearly 60%. Specifically, retrofitting measures reduced energy consumption in Riyadh by 54%, leading to annual savings of $4,942.41. In Jeddah, energy consumption decreased by 57.6%, resulting in annual savings of $6,713.88, while in Dhahran, a 55.4% energy reduction led to savings of $5747.8 Integration of rooftop solar panels can further increase overall energy savings to 70% in each city, underscoring the additional benefits of renewable energy technologies.

Moreover, the study found that carbon emissions (CO_2) could be reduced by 77%, 74%, and 74.6% in Riyadh, Jeddah, and Dhahran, respectively, compared to base case buildings. These results highlight the importance of identifying optimal solutions to minimize energy consumption in building envelopes, promoting sustainable development, and reducing the environmental impact of residential buildings in Saudi Arabia.

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Abbreviation

AC: Air Conditioning

ASHRAE: The American Society of Heating, Refrigerating and Air-Conditioning Engineers

BC: Base Case

BPS: Building Performance Simulation

BREEAM: Building Research Establishment Environmental Assessment Method

CDD: Cooling Degree Days

CFL: Compact Fluorescent Lamps

CO_2: Carbon Emissions

COP: Coefficient of Performance

DBT: Dry Bulb Temperature

ECRA: Electricity and Cogeneration Regulatory Authority

EEMs: Energy Efficiency Measures

EER: Energy Efficiency Ratio

EIA: Energy Information Administration

EUI: Energy Use Intensity

FEMP: Federal Energy Management Program

FIT: Feed-In Tariff

GAStat: General Authority for Statistics

GAS: General Authority for Statistics

GCC: Gulf Cooperation Council countries

GCC: Gulf Cooperative Council

GDP: Gross Domestic Product

HDD: Heating Degree Days

HVAC: Heating, Ventilation, and Air Conditioning

IEA: International Energy Agency

IES-VE: Integrated Environmental Solutions-Virtual Environment

IPMVP: International Performance Measurement and Verification Protocol

KACARE: King Abdullah Centre for Atomic and Renewable Energy

KSA: Kingdom of Saudi Arabia

LCC: Lifecycle cost

MENA: Middle East and North Africa

MEPS: Minimum Energy Performance Standard

MoH: Ministry of Housing

MoMRAH: The Ministry of Municipal and Rural Affairs and Housing

NCSBC: National Committee of the Saudi Building Code

OFAT: One Factor at a Time

PV: Photovoltaics

PUR: Polyurethane

RE: Renewable energy

SAMA: Saudi Arabian Monetary Authority

SAR: Saudi Arabian Riyal

SASO: Saudi Arabian Standards Organization

SBC: Saudi Building Code

SEC: Saudi Electricity Company

SEEC: Saudi Energy Efficiency Centre

SEEP: Saudi Energy Efficiency Program

SEER: Seasonal Energy Efficiency Ratio

SGBC: Saudi Green Building Council

SHGC: Solar Heat Gain Coefficient

SPT: Setpoint Temperature

TWh: Terawatt-Hours

UIH: Urban Heat Islands

Chapter 1

Introduction and Contextual Framework

1.1. Introduction

This study explores the holistic retrofit strategies for building envelopes, focusing on enhancing energy efficiency in residential buildings in Saudi Arabia. The investigation aligns with the country's sustainability goals, addressing the unique challenges of local climate and existing construction practices. Energy efficiency within Saudi Arabia's residential sector is essential; given the region's high energy consumption rates within the rapidly expanding population of Saudi Arabia, there is an urgent need to improve energy efficiency in the residential sector. This chapter sets the foundation for the study by expressing the research problem and its significance. It outlines the research objectives, and the comprehensive methodological approach used to achieve them. Furthermore, the chapter provides a detailed roadmap of the thesis, outlining the structure of the subsequent chapters.

1.2. General Background

Globally, the construction sector is a substantial consumer of energy and natural resources. The building sector alone is responsible for nearly half of global energy consumption and a considerable proportion of greenhouse gas emissions (GHG). This issue is particularly noticeable in some developing areas, especially in the Gulf region, where economies depend largely on the extraction of fossil fuels. As awareness of global warming and its effects grows, environmental concerns in these areas become more obvious.

In this context, Saudi Arabia, with its extreme desert climate, experiences high temperatures reaching 51.1°C, as reported by Piccolo (2010). Saudi Arabia ranks as one of the 20 most environmentally impacted nations worldwide because of its high ecological footprint, which is about double the global average. Its high energy consumption is largely attributable to its oil-dependent economy (Samargandi, 2021). Therefore, the building sector is highlighted by the high per capita electricity usage and carbon dioxide emissions

CO_2, emphasizing the environmental effects of the nation's energy-heavy infrastructure and urban growth (Al-Tamimi, 2017).

In Saudi Arabia, enhancing energy efficiency in residential buildings is a complex challenge with several key aspects. The most significant is the high energy demand, mainly for air conditioning, due to the country's hot climate (Kanani et al., 2017; Al-Tamimi, 2017). The country's energy sector is rapidly growing, with residential buildings accounting for almost 50% of the total national energy consumption (Al-Homoud and Krarti, 2021). Energy policy has traditionally focused on fossil fuel resources, resulting in subsidized energy prices and a lack of emphasis on energy conservation in residential construction. Additionally, there is a lack of awareness regarding energy-efficient practices among homeowners and residents (Krarti and Aldubyan, 2021). Another study conducted by (Susilawati and Al Surf, 2011) emphasizes the need for increased public awareness, emphasizing the importance of public awareness and understanding of sustainable housing concepts in Saudi Arabia.

Moreover, financial challenges arise in implementing energy-efficient retrofitting solutions in existing residential buildings, primarily due to the high initial costs involved (Kanani et al., 2017). Despite the significant upfront costs, the long-term benefits of energy efficiency, such as reduced energy bills and lower environmental footprints, offer substantial potential. However, overcoming these financial barriers requires strategic planning, potentially including government incentives and public-private partnerships to

Additionally, all these upgrades must also align with local building codes and regulations, which may have specific requirements for energy efficiency. Compliance with these standards is essential for legal and safety reasons, as well as for qualifying for any available incentives or certifications. In 2018, Saudi Arabia implemented new construction codes (SBC, 2018). Despite this, by January 2019, it was observed that about one-third of the newly constructed residential buildings were still adhering to the older building code regulations, specifically those outlined in the Saudi Code 2007 (Felimban et al., 2019). Furthermore, data from the Saudi Energy Efficiency Centre (SEEC) indicates that over 70% of the current residential buildings in the country do not have thermal insulation. This situation leads to significant demand for electricity, especially considering the roughly 5.5 million existing residential structures (SEEC, 2017). This high electricity demand is largely driven by the need for air conditioning to cool these buildings (Felimban et al., 2019). To efficiently implement energy efficiency measures in Saudi Arabian structures, a complete strategy that takes into account financial, regulatory, and behavioural concerns is required (Felimban et al., 2023b).

Several studies highlight Saudi Arabia's high energy demand for residential structures, with air conditioning systems alone accounting for 60-70% of electrical consumption due to the country's hot and humid environment (AlGhamdi, 2020; Alaidroos and Krarti, 2015b; Al-Sanea et al., 2012; Krarti et al., 2017). To address the increasing energy demand, the Kingdom of Saudi Arabia (KSA) is planning to invest more in renewable energy and expand its energy resources (Krarti and Aldubyan, 2021). The country is setting plans to incorporate renewable energy into its energy portfolio, aiming to decrease its dependence on oil and gas. To reduce its dependence on oil and gas, the country is planning to incorporate renewable energy into its energy case (Zell et al., 2015). This target is a part of Saudi Arabia's broader strategy, reflecting a major transformation in its approach to energy production and consumption. This initiative not only aligns Saudi Arabia with global sustainability trends but also represents a proactive step in reducing its carbon footprint and enhancing energy efficiency for future generations.

Increasing the energy efficiency of existing buildings is one of the most effective strategies for energy retrofitting. The retrofitting process, characterized by its complexity and need for detailed planning, involves the implementation of energy conservation measures that significantly increase building performance and sustainability (Felimban et al., 2020). Many factors contribute to building energy efficiency, including the use of advanced insulation materials, the installation of high-performance glazing, and the upgrade of HVAC systems. These retrofitting interventions offer an effective way to reduce overall energy consumption in the Saudi built environment, which faces unique climatic challenges. The adoption of such measures not only contributes to achieving the country’s sustainability objectives but also demonstrates a commitment to forward-thinking energy management practices.

The residential building sector in Saudi Arabia, is facing a significant challenge due to its high energy consumption, largely driven by existing construction methods and the region's hot climate. This issue is crucial for Saudi Arabia's environmental development goals, particularly in line with Saudi Vision 2030. Residential building practices are experiencing a major shift, especially following the amendments to the Saudi Building

Code in 2017, which was originally introduced in 2007. Previous construction methods and outdated regulations have limited the potential for achieving optimal energy efficiency in many residential buildings. While the Saudi Building Code (SBC) provides a framework for construction standards, its enforcement, particularly in retrofitting for energy efficiency varies across regions. Additionally, the current regulatory framework lacks financial support for retrofit projects, making the initial investment costs a significant barrier for many homeowners

There is a pressing need to examine existing regulations and policies related to building retrofitting in Saudi Arabia and their alignment with energy efficiency goals. While previous studies have addressed general energy efficiency in Saudi Arabia, they have not specifically focused on retrofitting measures that align with the updated Saudi Building Code (SBC) requirements for residential buildings. This study addresses this significant research gap by evaluating retrofitting measures that comply with the updated SBC, integrating both passive and active strategies.

This research takes a holistic approach to retrofitting by incorporating passive measures, such as building envelope improvements, and active measures, including the integration of renewable energy technologies like photovoltaic systems. It not only aligns with the updated SBC but also explores the combined impact of these measures on energy efficiency, which has not been comprehensively investigated in prior studies.

Additionally, this study makes a unique contribution to the economic analysis and environmental benefits of such retrofitting strategies in the region. By providing a comprehensive cost-benefit analysis, it advances the current understanding of the financial viability of implementing retrofitting measures. Although initial costs can be significant, the study demonstrates the long-term financial benefits associated with energy-efficient retrofitting, including lower energy bills and reduced environmental impacts. This approach fills existing gaps by proposing practical guidelines for stakeholders on sustainable retrofitting practices, offering new insights into how such strategies can be economically attractive for homeowners and investors in Saudi Arabia.

Retrofitting residential buildings in Saudi Arabia holds significant potential for improving energy efficiency, reducing CO_2 emissions, and advancing national sustainability goals, such as those outlined in Saudi Vision 2030. Despite this potential, challenges remain, including the absence of a comprehensive regulatory framework specifically addressing retrofitting, limited integration of renewable energy technologies, and insufficient financial incentives for homeowners. This study addresses these challenges by evaluating both the technical and regulatory aspects of retrofitting while ensuring alignment with the SBC.

By identifying these challenges and proposing practical solutions, this research offers clear guidelines and recommendations for locally adaptable retrofitting practices. Focusing on energy-efficient strategies tailored to local regulations and climatic conditions, the study establishes new benchmarks in the field and contributes significantly to the global discussion on sustainable construction practices in hot climates. The findings provide valuable insights for stakeholders, including policymakers, architects, and investors, encouraging them to make informed decisions that promote sustainable building practices. Overall, this study advances knowledge on how retrofitting strategies can be optimized both technically and economically, offering adaptable solutions that further global sustainability efforts.

1.3. Motivation of the Study

Over the past ten years, there have been reports of a significant annual growth rate in electricity consumption, reaching 8%, and an increase in the number of consumers by 5% (Arabnews, 2014) Projections indicate that by 2040, electricity consumption in KSA could soar from 277 TWh/year to an estimated high of as much as 850 TWh/year (Asif, 2016b). As demand continues to rise rapidly, it will be necessary to implement effective strategies for reducing energy consumption. In Saudi Arabia, there's a growing need to reduce energy use in buildings due to the hot climate and high electricity demands, especially for air conditioning to keep indoor spaces cool in the summer. The high energy consumption of residential buildings in Saudi Arabia is primarily due to inefficient thermal performance of the building envelope. Consequently, most residents consume excessive amounts of energy, leading to substantial utility bills. This issue is particularly critical as households represent the largest segment of energy users in the country According to the Saudi Energy Efficiency Centre (SEEC), residential energy consumption accounts for a significant portion of the national energy use, highlighting the need for improved energy efficiency measures in the housing sector (SEEC, 2018). Making them more energy-efficient is important not just for saving energy, but also for supporting Saudi Arabia's Vision 2030 goals for a sustainable future. This presents a significant challenge, involving economic, social, and technological aspects, particularly in Saudi Arabia. Saudi Vision 2030 is an ambitious strategic effort aimed at reducing the country's reliance on oil, expanding the economy, and enhancing the public sector, with a strong emphasis on environmental sustainability and resource efficiency.

The increasing importance of energy efficiency in residential buildings, especially following the mandate of the Saudi Building Code (SBC) in 2017, emphasizes the need for comprehensive research in this area. Active measures, such as photovoltaic panels and efficient HVAC systems, use technology to actively manage and reduce energy consumption. In contrast, passive measures, including enhanced insulation and energy-efficient windows, focus on leveraging design and materials to naturally minimize energy demand. This study is driven by the necessity to evaluate the combined impacts of both active and passive measures on energy savings, cost-effectiveness, and payback periods.

Furthermore, this research seeks to serve Saudi society by identifying the causes of excessive energy consumption in residences and proposing practical, cost-effective solutions. It also aims to explore how innovative solutions, aligned with the SBC, can significantly advance national goals related to energy efficiency and sustainable development. The specific aims and objectives of this study are detailed in the subsequent sections.

1.4. Aim and Objectives

The primary aim of this research is to develop and propose holistic retrofit strategies that significantly enhance the energy efficiency of residential buildings in Saudi Arabia. This includes optimizing energy performance, minimizing CO_2 emissions, and evaluating the economic viability of these strategies through cost-benefit analyses. The research aligns with Saudi Arabia's Vision 2030 goals and focuses on a comprehensive framework for assessing the effectiveness of various retrofit strategies while ensuring compliance with the updated Saudi Building Code (SBC).

Research Objectives:

1. To evaluate current energy efficiency levels in residential buildings.
- Review the performance of existing residential buildings in Saudi Arabia, focusing on energy inefficiencies.
  - Identify inefficiencies in building fabric that contribute to excessive energy consumption.

2. To assess the impact of building fabric on energy consumption.
- Investigate how different elements of building fabric, such as insulation and windows, affect energy efficiency.
- Use simulation tools to model thermal performance and identify key areas for improvement.

3. Verify and Validate the Model
- Ensure the accuracy of the energy models, such as energy bills, to assess model accuracy and evaluate performance.
- Use simulation models to implement the developed retrofit strategies.

4. To analyse retrofit strategies.
- Examine a range of retrofitting methods (e.g., insulation upgrades, window replacements) to determine their effectiveness in improving energy efficiency.
- Identify key challenges in implementing retrofitting measures, including technical complexities, regulatory compliance with the Saudi Building Code To explore the integration of renewable energy sources.

5. To explore the integration of renewable energy, with a focus on solar panels.
- Investigate the feasibility of integrating renewable energy sources, particularly solar panels, as part of retrofit strategies.
- Justify the focus on solar panels based on their local applicability and compatibility with Saudi Arabia’s climate.

6. Assess the effectiveness of developed retrofit strategies.
- Implement the developed retrofit strategies on simulated models to assess their impact on energy efficiency.
- Evaluate how the proposed retrofit strategies align with the SBC’s energy efficiency requirements.

7. To measure energy savings and assess long-term impacts.

- Implement the developed retrofit strategies: apply the proposed retrofitting measures to simulated models to evaluate their effectiveness in enhancing energy efficiency in residential buildings.
- Quantify energy savings: measure both immediate and long-term energy savings resulting from the retrofitting interventions. this includes analyzing reductions in energy consumption over time, assessing how these savings contribute to overall cost efficiency, and evaluating the sustainability of energy performance improvements.

8. Conduct a cost-benefit analysis of retrofit interventions.

- Analyse the financial feasibility of each retrofit strategy, focusing on return on investment and payback periods.
- Include labor and material costs, along with any available financial incentives.

9. To quantity the reduction in CO_2 emissions resulting from retrofitting measures.

- Quantify the environmental benefits of the proposed retrofit strategies by evaluating the reduction in CO_2 emissions over time.

10. To provide guidelines for stakeholders on sustainable retrofitting practices.

- Develop clear guidelines for stakeholders on implementing sustainable retrofitting measures that are economically viable and aligned with the SBC.

By achieving these objectives, the study aims to provide recommendations to improve the energy efficiency of residential buildings in Saudi Arabia, thereby contributing to the country's sustainable development goals and effective implementation of Saudi Arabia's Construction Code.

1.5. Research Questions

This study explores retrofitting strategies aimed at significantly reducing energy consumption while emphasizing the identification of long-term, sustainable solutions. This leads to several key research questions:

1. How does the existing residential building fabric in Saudi Arabia relate to current energy consumption?

This question addresses the essential elements of building and construction that contribute to excessive energy usage.

2. Which retrofitting strategies can improve residential buildings' energy efficiency in Saudi Arabia the most effectively?

   This includes investigating various retrofit alternatives and their potential influence on energy conservation.
3. How do the proposed retrofitting strategies for residential buildings support the Saudi Building Code (SBC)?

   This question investigates the viability of retrofitting solutions with current regulations and
4. What is the environmental impact of retrofitting on reducing CO_2 emissions in the residential sector of KSA?

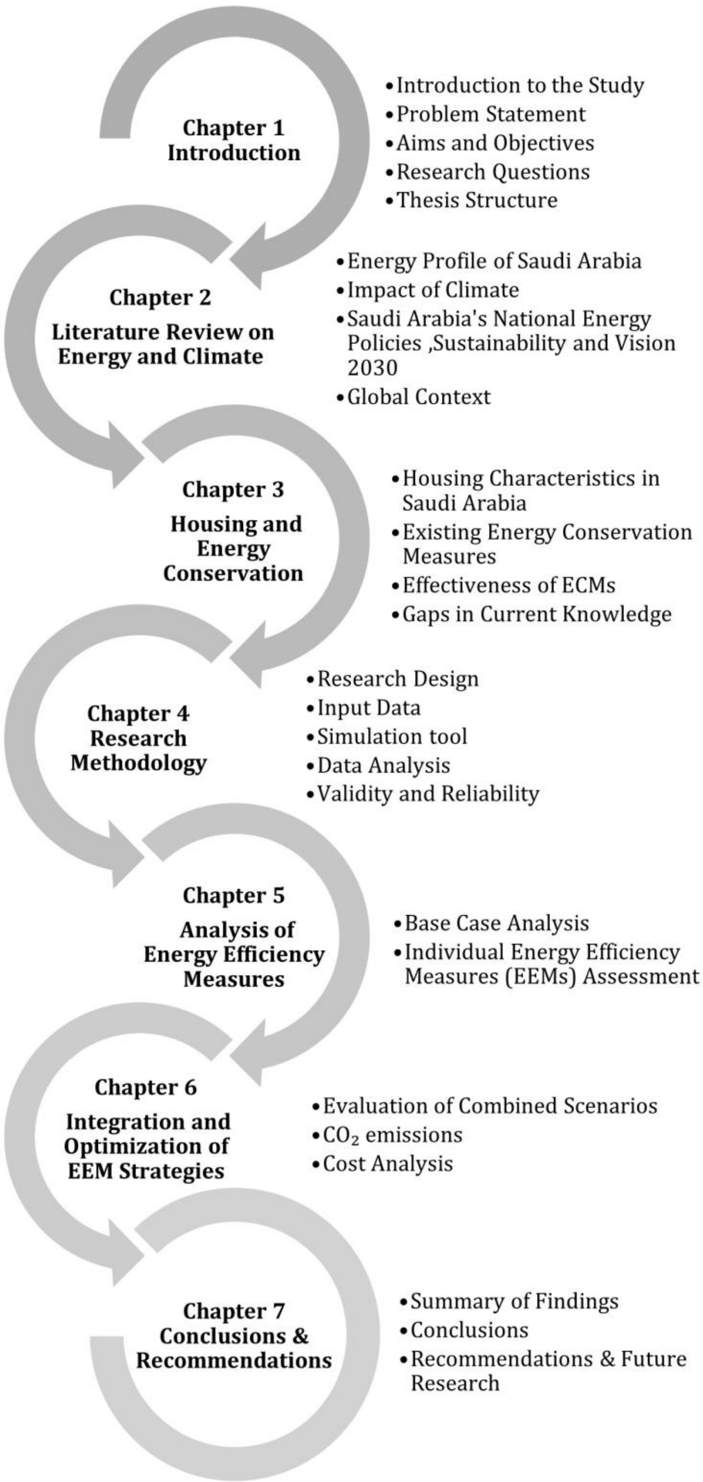
   This seeks to quantify the potential environmental benefits, in terms of CO_2 emission reduction, resulting from energy-efficient retrofitting.
5. What are the economic benefits of applying energy-efficient retrofitting measures?

   This includes a cost-benefit analysis to determine the financial viability of retrofitting activities.
6. What are the challenges to adopting energy-efficient retrofit solutions in Saudi Arabia's residential buildings?
7. What are the long-term impacts of the adoption of retrofitting strategies on the residential energy landscape in KSA?

   This question considers the long-term effects of retrofitting on energy consumption patterns and sustainability.

1.6. Thesis Structure

Figure 1 .1 Thesis Structure flow chart.



Chapter 1 This chapter lays the groundwork for the research by introducing the topic of energy efficiency in residential buildings in Saudi Arabia. It outlines the problem statement, clarifying the need for improved energy efficiency measures in the Kingdom's residential sector. The aims, objectives, and guiding research questions of the study are presented, providing a clear roadmap for the investigation. This chapter also defines the scope of the research and briefly introduces the structure of the subsequent chapters, laying down the foundation for the entire thesis.

Chapter 2: Literature Review; Saudi Arabia's Energy Profile and Climatic Challenge

In this chapter, a comprehensive review of Saudi Arabia's current energy profile is provided, highlighting the country's reliance on energy resources and the impact of its climatic conditions on energy consumption. It delves into the broader implications of energy usage in the face of Saudi Arabia's Vision 2030 and sustainability goals. Additionally, this chapter positions Saudi Arabia's energy challenges in a global context, examining how similar challenges are addressed internationally.

Chapter 3: Literature Review; Housing Characteristics and Energy Conservation Measures in Saudi Arabia

This chapter offers an in-depth review of the typical housing characteristics in Saudi Arabia and how they influence energy consumption. It evaluates existing energy conservation measures (ECMs) implemented in Saudi residential buildings, analyzing their effectiveness and limitations. This review sets the stage for the research to contribute new insights into energy conservation in Saudi housing.

Chapter 4: Research Methodology

This chapter describes the methodology employed in the research, including the study design, data collection methods, and analysis techniques. It explains the rationale behind the chosen methodology and how it aligns with the research objectives. The chapter also discusses the measures taken to ensure the validity and reliability of the research findings, detailing the rigorous approach adopted for data collection and analysis.

Chapter 5: Analysis of Base Case and Individual Energy Efficiency Measures

Focusing on observed findings, this chapter analyses the base case scenario of current energy performance in typical Saudi residential buildings. It assesses the impact of various individual energy efficiency measures, comparing their effectiveness. The chapter provides a detailed analysis of how each measure contributes to energy savings, forming the basis for developing more comprehensive energy efficiency strategies.

Chapter 6: Integration and Optimization of EEM Strategies (Improved Model), Evaluation of Combined Scenarios

This chapter focuses on integrating and optimizing various energy efficiency measures (EEMs) to form an improved model for residential energy efficiency. This chapter discusses the methodology for integrating these strategies, and their optimization for the Saudi context and evaluates the effectiveness of combined retrofit strategies. It provides a holistic view of how combined EEMs can significantly enhance energy efficiency in residential buildings.

Chapter 7: Conclusions & Recommendations

This chapter draws conclusions that directly respond to the research objectives and questions. It reflects on the implications of these findings for energy efficiency in Saudi Arabia and offers practical, actionable recommendations for policymakers, stakeholders, and future research. The chapter also outlines potential areas for further research, suggesting continued exploration in the field of energy efficiency in residential buildings.

The following chapter reviews building energy conservation strategies. It will examine building energy-saving methods. Identifying and assessing ways to conserve energy can help create more sustainable and environmentally friendly construction practices. This chapter demonstrates conservation can be implemented in buildings to reduce construction energy use.

Chapter 3

Literature Review: Housing Characteristics and Energy Conservation Measures in Saudi Arabia

3.1. Introduction

The first part of this section provides an overview of the current housing stock and its distribution across Saudi Arabia. This section aims to provide a thorough overview of the current types of residential buildings, their architectural designs, and construction practices employed within the kingdom. Additionally, it explores regional variations in housing characteristics that may arise due to differences in climatic conditions and cultural influences across different areas of Saudi Arabia. This section of the literature review provides context for the discussion on energy conservation measures and building envelope parameters.

The second part of the literature review presents a comprehensive review of numerous studies that have explored the benefits of applying energy-saving measures to Saudi residential structures. Focusing on building envelope factors, it provides practical strategies for optimizing energy usage in residential and other types of buildings. It reviews studies conducted within Saudi Arabia to discover the current state of literature in this domain and to align the discussion with the considerations and objectives of this study. This part of the review seeks to build a solid foundation for understanding how the optimization of building envelope parameters can significantly enhance energy efficiency and reduce energy consumption in residential buildings.

3.2. Population Distribution Across the 13 Provinces of Saudi Arabia

The Kingdom of Saudi Arabia, the largest nation in the Arabian Peninsula, divides into 13 regions, each with varying levels of population and public utility infrastructure development. In each administrative region, there is a city representing the region's headquarters. More than the other regions, the population is high in Al-Riyadh, Makkah Al-Mokarramah, and the Eastern Region, due to urbanization (GAStat, 2018b).

It is worth mentioning that the population in the three main regions accounts for around 65% of the total population (Abdul Salam et al., 2014). Al Riyadh is the top region in Saudi Arabia among 13 regions as shown in Figure 3.1. It is dominated by young middle-class Saudi Arabians who are first-time homebuyers, as 45% of the country´s population is below 20 years old. The city of Riyadh has the highest population of over 4 million. The most recent published population survey in KSA showed that the population has risen to 34.2 million (GAStat, 2019c) Based on the statistics provided by Macrotrends (2022), there has been a substantial increase in the population of Saudi Arabia throughout the period from 1985 to 2023, with data rising from 12.89 million to 36.95 million as seen in Figure 3. 2. Between 2019 and 2023, the population of Saudi Arabia increased from 35.8 to 36.9 million, with an annual growth rate of 1.4%. The forty-year period highlights Saudi Arabia's transition from rapid population growth to a more moderate rate, reflecting the country's changing demographic dynamics.

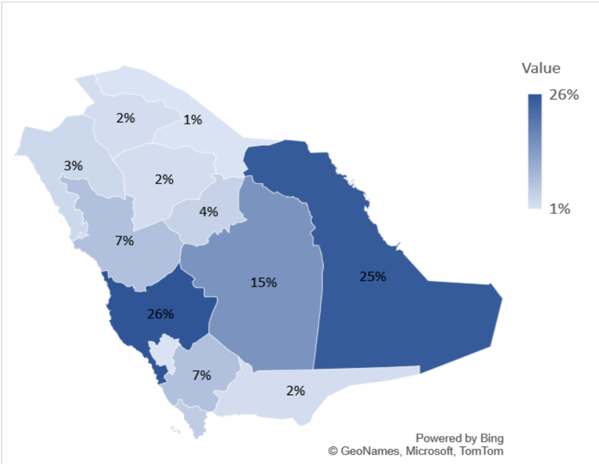


Figure 3. 1 Percentage of Population in the Administrative Regions in KSA created by the author.

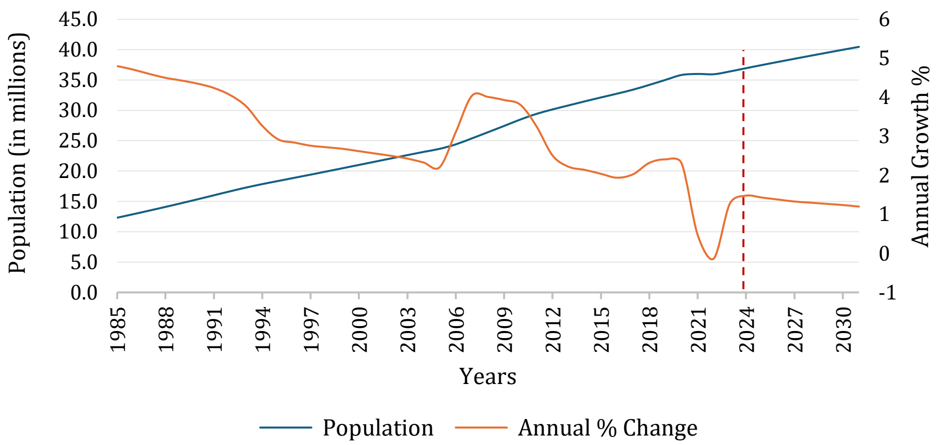


Figure 3. 2 Saudi Arabia's population and annual growth from 1985 to 2030. Sources: (Macrotrends, 2022)

Over the past few decades, the Kingdom of Saudi Arabia has experienced remarkable population growth, becoming one of the most populated countries in the Middle East. This growth is attributed to the country's economic development, which has attracted many emigrants seeking employment opportunities in various sectors. Rapid urbanization has accompanied this demographic expansion, with a substantial portion of the population dwelling in urban areas, significantly influencing housing demand, infrastructure development, and energy consumption patterns across the nation. Furthermore, the country's population distribution is uneven, with a higher concentration in certain provinces like Riyadh, Makkah, and the Eastern Province. This difference implies regional divergences in energy demands and urban development.

Rapid urban growth has led to infrastructure, housing, and transportation challenges, prompting the Saudi government to invest significantly in urban planning and development initiatives. The residential sector is one of the fastest-growing energy consumers in the United Kingdom, with the highest electricity demand. Residential housing and the high demand for residential energy use are the most pressing needs of the rapidly rising population. This demographic increase, particularly in the context of residential buildings, necessitates enhanced strategies to manage escalating energy demands, optimize housing development, and mitigate environmental impacts. It additionally highlights the necessity to embrace energy-efficient methodologies while adhering to the Saudi Vision 2030, which conceptualizes a pathway toward sustainable national development.

3.3. Housing description in KSA

Saudi Arabia's housing infrastructure has changed over the past few decades due to increased urbanization, economic progress, and population expansion. This change represents a variation from traditional practices and reflects the country's changing economic environment. While the country was once known for its classic mud-brick buildings, it now features a variety of modern homes for its large and varied population. The government has substantially invested in the housing sector to address the increasing demand. Large-scale housing projects have been initiated in various regions, providing homes that blend contemporary design with elements of traditional Saudi architecture.

Contemporary Saudi Arabian designs often incorporate elements of traditional Saudi architecture. Moreover, due to rising income levels and evolving lifestyle preferences, there has been a noticeable shift towards apartment complexes and villas in urban areas. Nevertheless, rural and individual houses with open courtyards continue to be preferred. The variety of dwellings in Saudi Arabia is considerable, with multiple sizes and configurations. The King Abdul Aziz Centre for Science and Technology funded a 2019 study that found the average area of a Saudi villa to be 592.3 m^2. Additionally, the study estimated the average size of a Saudi household to be 5.86 persons (GASTAT, 2019).

Based on these numbers, the researchers estimated that the area of a typical Saudi two-story villa would be 256 m^2 per floor. Based on the survey data conducted in 2019, the Saudi housing unit has on average, 6 and 4 rooms for a villa and an apartment, respectively. Most of the housing units are relatively old, more than ten years of age, and have no thermal insulation. They may benefit from renovation, including effective energy efficiency measures. The most common air-conditioning systems are of the direct expansion type, mainly window and split air-conditioners Saudi homes typically have at least three bedrooms, with over 70% of them. Data from 2018 reveals that newer homes aged five years or less make up just 8.31% of total housing, while homes aged between 10 and 20 years represent the most significant portion at 31.09%. Concrete is the dominant building material, accounting for nearly 90% of structures. Traditional houses might use block, clay or stone. Ceramic is the preferred flooring choice in 64% of homes.

According to the household energy survey, a substantial number of Saudi homes lack thermal insulation (GAStat, 2018b). Over 50% of homes are without this insulation, as highlighted in a study by Al-Homoud and Krarti (2021). Following a review of the housing stock, villas appeared to be a popular housing choice among Saudi families, so an archetypical model was selected to comply with Saudi building regulations.

3.4. Saudi Arabian Housing: An Overview of Residential Building Types

The construction industry in the Kingdom of Saudi Arabia is the largest and most rapidly growing among the Gulf Cooperation Council (GCC) countries (Alshamrani and Mujeebu, 2016). The GCC countries are experiencing a remarkable increase in constructions, which raises concerns about the growing use of energy. It is estimated that there will be 2.32 million new dwellings by 2020 to fulfil the demand of the expanding population (Alshamrani and Mujeebu, 2016). The General Authority for Statistics (GAS) in Saudi Arabia conducts periodic surveys and releases official statistics related to various sectors, including housing.

The specific types of housing units reported by GAS represent Saudi Arabia's housing distribution.

1. Villas: These are detached residential structures, often spacious and designed for a single family.

2. Apartments: residential units in multi-story buildings. These can range from small units to large units.

3. Traditional Houses (older structures).

According to the General Authority for Statistics' housing data, Saudi Arabia's housing trends from 2010 to 2018 reveal significant growth in apartments and villas, with apartment shares increasing from 34.30% to 43.79% and villas from 25.50% to 29.42%. In contrast, there was a decline in other dwelling types, including traditional houses. The choice of housing varies by region, with a preference for apartments in urban areas and villas or traditional houses in other regions, indicating varied cultural and economic preferences.

Based on the recently reported housing survey results, Saudi households' total number of housing units reached 3,681,927 in 2019 (GAStat, 2019b). The number of individuals occupying such housing units is estimated to be 21,592,448, resulting in an average size of 5.86 people in the Saudi household. Three characteristics are considered to represent the KSA residential building stock. First, as discussed in previous studies, three main housing units are available in KSA: villas, apartment units, and traditional houses (Alhubashi and Roca Cladera, 2016; Al-Homoud and Krarti, 2021). Over three years, from 2017 to 2019, several regions in Saudi Arabia viewed considerable increases in housing units. Makkah Al-Mokarramah, Al-Riyadh, and the Eastern Region showed significant growth, likely influenced by urbanization, economic development, and population dynamics, as illustrated in Figure 3.3.

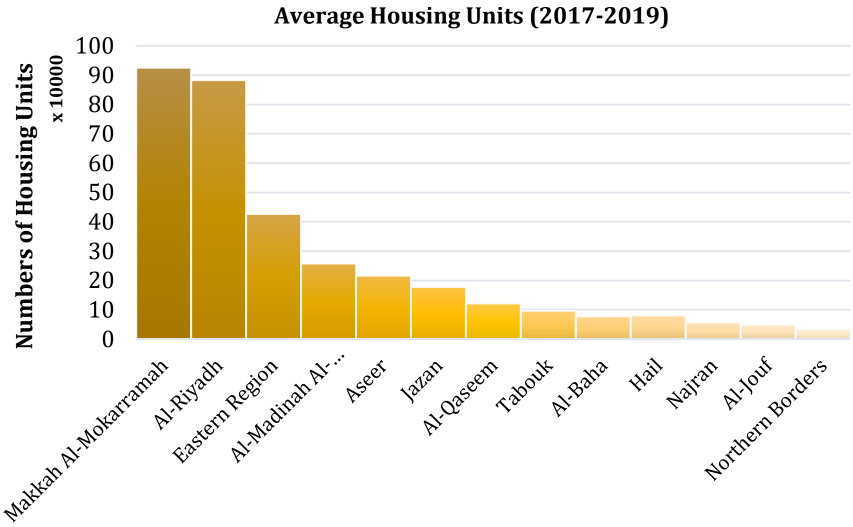


Figure 3. 3 The average housing distribution in 13 regions from 2017-2019, data source: KAPSARC data portal.

Housing units' distribution by type across regions:

As seen in Figure 3.4, over the three years from 2017 to 2019, the housing landscape in Saudi Arabia showcased notable patterns in the preference for housing types across various administrative regions. This trend is influenced by a variety of factors, including population growth, economic opportunities, and lifestyle changes.

Between 2017 and 2019, Makkah Al-Mokarramah had a notable increase of around 2.19%. Meanwhile, although Al-Riyadh exhibits a slight decrease of about 1.16%, it still maintains a considerable portion of its housing units as apartments. The dominance of apartments in Makkah Al-Mokarramah suggests a lifestyle potentially driven by population density and urbanization. Conversely, Al-Riyadh experienced a slight decrease in the percentage of apartments, which could reflect different housing preferences. Factors such as infrastructure development and investment patterns may contribute to this trend. This includes addressing housing affordability, infrastructure development, and sustainable urbanization to ensure the long-term viability of urban areas across the Kingdom.

In conclusion, based on data obtained from the GAS Housing Survey 2019 Al-Riyadh, the capital city, displayed a greater tendency towards villas, making up about 45.71% of the housing units. Apartments, on the other hand, made up the highest percentage of dwellings occupied by Saudi households in the Makkah Region. See Appendix A: Table A. 2 Housing Units by Type.

Low-income buyers favour tiny homes or apartments in cities like Riyadh, Jeddah, and Dhahran. According to Opoku and Abdul-Muhmin (2010), financial concerns, house aesthetics, and street location are the main variables influencing their decisions. Alhubashi and Roca Cladera (2016) observed that big cities like Riyadh have a noticeable preference for independent housing, like villas, revealing of the cultural focus on family lifestyles. Rapid urbanization in major cities such as Riyadh, Jeddah, and Dammam has become more challenging in meeting the housing needs of their expanding populations. These cities have experienced significant shifts in housing preferences, with an increasing emphasis on more sustainable housing options. This trend highlights the pressing requirement to integrate Saudi Arabia's unique cultural and climatic features into the design of urban dwellings (Surf et al., 2012).

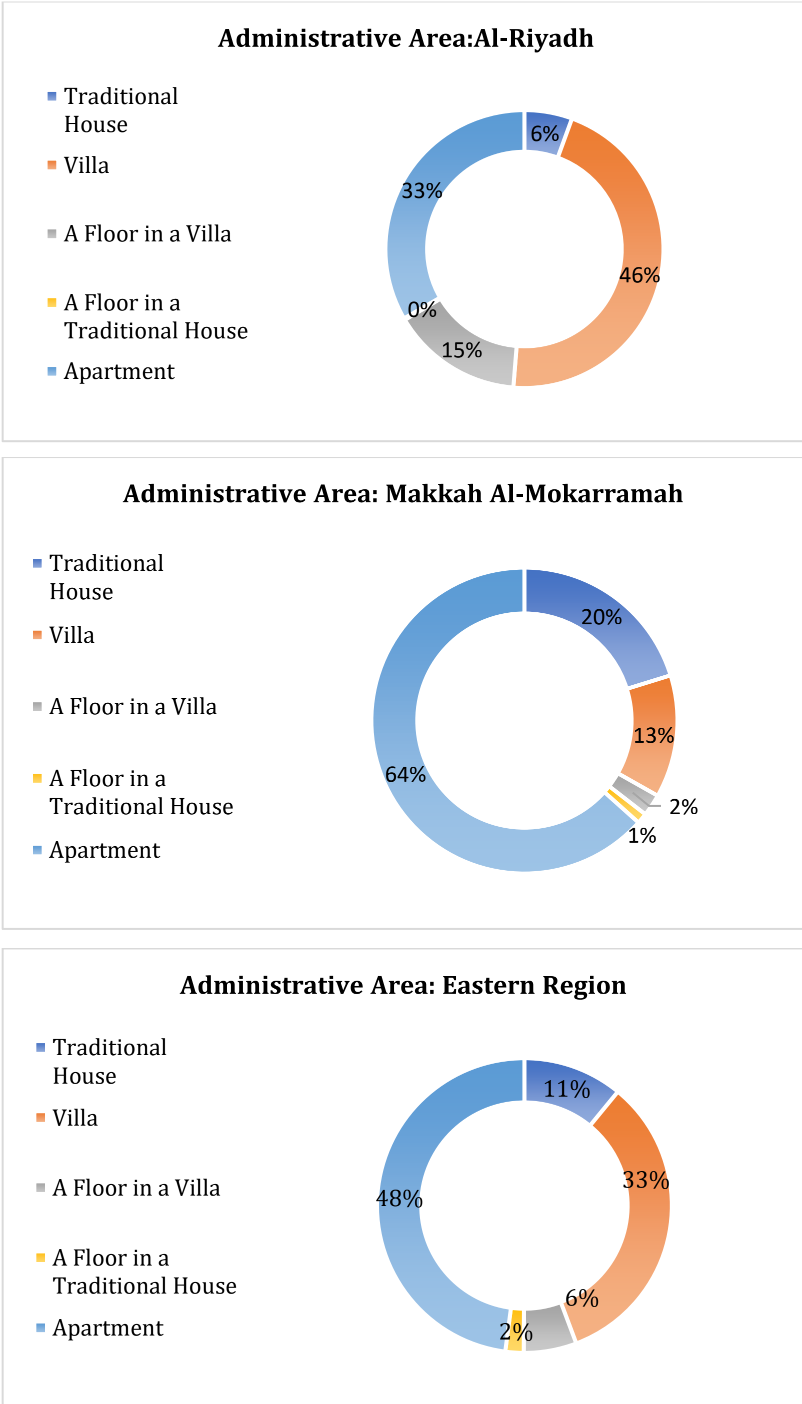


Figure 3. 4 Distribution of Housing Unit Types in Al-Riyadh Region, Eastern Region, and Makkah Region, Saudi Arabia: Highlighting the Three Major Housing Unit Categories; Housing Survey 2019. Source (GAStat, 2019b)

According to the above analysis findings, the percentage increase in villas compared to other housing unit types is 6%. In comparison, the percentage increase in apartments and traditional houses is 5, 21% and 3%, respectively.

11. Makkah Al-Mokarramah: The "Villa" units experienced an increase of approximately 4.45%, suggesting a growing preference or availability for villa-type housing in this region over the observed period.
12. Al-Riyadh: The growth was even more pronounced, with "Villa" units witnessing a rise of about 5.51%, indicating a significant upward trend for villas in the capital city over the years.
13. Eastern Region: Villas dominated the growth rate in this region with a remarkable 7.75% increase.

3.5. Housing construction and materials

Various factors, including the local climate, cultural traditions, and the need for sustainable and energy-efficient designs, influence housing construction and materials in Saudi Arabia. Housing construction in Saudi Arabia has experienced notable transformation throughout its history, shifting from traditional mud-brick buildings to modern architectural designs that utilize innovative construction materials. Historically, the desert climate influenced building material selection, with mud-brick leading to its excellent insulation properties. The mud-brick dwellings, characterized by their large walls and limited fenestration, protected occupants from intense solar radiation and preserved heat during colder evenings.

Traditional houses in Saudi Arabia have unique characteristics that reflect the country's geography and climate. Traditional Najd region building envelopes, including cities like Riyadh, are constructed using thermal mass systems and dense materials for roofing, floors, and walls (Aldersoni et al., 2022). Traditional houses often feature walls that can reach a thickness of 450 mm. These walls are constructed using clay blocks and a combination of clay and gypsum-based render. This construction method is intended to provide thermal mass to the house while effectively reducing heat gain. Additionally, traditional houses in the Najd region often incorporate courtyards, which are an essential element of traditional architecture in Saudi Arabia. These courtyards serve as a response to human needs, culture, and the environment, and they also provide a cooling effect in the hot desert climate of Saudi Arabia (Alnaim, 2023). The courtyard is a central open space that is surrounded by the house's rooms and is used for various purposes, such as socializing, relaxation, and ventilation (Al-Hussayen, 1995). One of the most significant advantages of a long-narrow courtyard house is access to natural light (Abdelsalam, 2015). In summary, a courtyard in a traditional house in Saudi Arabia has several benefits, including a cooling effect, natural light, privacy and security, a gathering place, and accessibility. As shown in Figure 3. 5.

Figure 3. 5 Traditional house structure. Source: (Aldersoni et al., 2022).

With rapid urbanization and economic development in recent decades, there has been a significant shift in contemporary times. Modern housing construction in urban centres like Riyadh, Jeddah, and the Eastern Province now mirrors transnational standards with a mix of contemporary designs. High-rise apartments and villas have become widespread. Contemporary residential structures exhibit more oversized windows and open spaces than traditional dwellings.

In KSA, residents construct their homes using a diverse range of materials, including concrete, clay, block brick, stone, and more. As per a 2019 GASTAT study, the predominant construction material is concrete, making up 89.54% of homes. Following this, bricks, or blocks, account for 10.44%. Concrete blocks, called Concrete Masonry Units (CMUs), are widespread in Saudi Arabia. These blocks are available in two main varieties: solid and hollow. These blocks typically measure 20cm in width and have a 60 x 20 cm surface. While cement plaster is a standard external finish, other options include stone and marble facades. Table 3.1 details the thermal characteristics of walls commonly used in Saudi residences, including their U-value and thermal resistance. Studies suggest that the external structure of a typical Saudi home includes layers of plaster on both the outside and inside, with a hollow block in between. One common wall structure, called Wall I, features a hollow bricklayer and plaster on its exterior and interior. Thermal insulation can enhance thermal efficiency and reduce the need for cooling in walls.

Table 3. 1 Thermal characteristics of walls used mostly in Saudi Arabian residential buildings (Ahmad, 2002).

Wall Type	**Thickness of wall components (m)**	**Thermal conductivity W/mK**	**Wall conductance ($W/m^2.K$)**	**Wall Resistance ($m^2.K/w$)**
Wall I				
External Plaster	0.2	1.2	2.25	0.44
Hollow block	0.2	0.9		
Internal Plaster	0.03	1.2		
Wall II				
External Plaster	0.02	1.2	2.98	0.336
Concrete	0.2	1.75		
Internal Plaster	0.03	1.2		
Wall III				
Stone	0.2	1.7	2.28	0.438
Concrete	0.07	1.75		
Hollow block	0.2	0.9		
Plaster	0.03	1.2		
Wall IV				
Stone	0.2	1.7	1.62	0.617
Concrete	0.2	1.75		
Air gap	0.05	0.28		
Bricks	0.1	0.9		
Plaster	0.03	1.2		

The GASTAT survey in 2019 also noted ceramics as the primary flooring material, used in 64% of all homes. This is followed by plain tiles, which account for 26%, cement tiles at 6%, and parquet flooring at 1%. Several research studies have explored energy models specific to standalone houses in Saudi Arabia. These investigations have assessed the energy implications of different building materials and suggested ways to increase energy efficiency, including strategies for wall and roof insulation, glazing techniques, and the incorporation of thermal mass (Krarti et al., 2017; Alaidroos and Krarti, 2015b). The King Abdullah Petroleum Studies and Research Centre (KAPSARC) presents various wall and roof construction materials, as shown in Figure 3.6. These include Hollow concrete block configurations with insulation levels ranging up to 200mm.

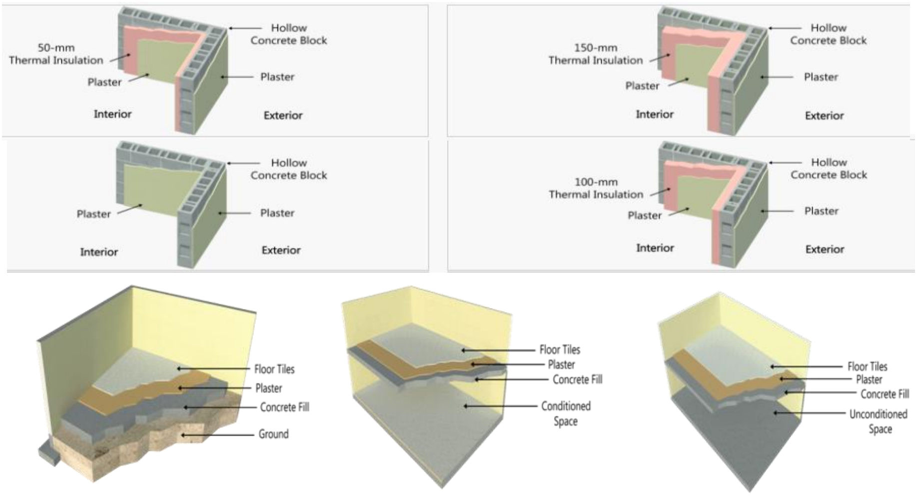
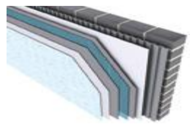


Figure 3.6 Wall and roof construction materials of the villa. Source :(KAPSARC, 2021a).

According to SEEC (2021), 70% of residential structures in Saudi Arabia do not have thermal insulation. This insulation can be positioned either inside or outside a wall. Table 3.2 represents wall construction methods with thermal insulation. Within the framework of Saudi Vision 2030, the objective is to enhance the energy efficiency of building performance, thereby reducing energy demand. This goal is supported by the Saudi Building Code (SBC) and the mandate requiring thermal insulation in all new constructions, reflecting a strong commitment to sustainable practices (Alyami, 2023). However, implementing the SBC across the construction sector has not been widely adopted (Aldossary et al., 2014a). This situation shows the complexity of aligning construction practices with the sustainability goals outlined in Saudi Vision 2030, emphasizing the need for more effective strategies.

Table 3. 2 wall construction methods in Saudi Arabia (SEC,2019).

Wall Types and Description	
Single Wall: This system, also known as the single wall system, is constructed from insulated cement blocks. The insulation used typically includes materials like extruded polystyrene and polystyrene. The common sizes for these blocks are (20x20x40 cm) and (25x20x40 cm).	
Composite Wall: This represents the traditional wall system. In the composite wall approach, two walls are built parallel to each other, with thermal insulation placed in the space between them.	
External Wall ins: This insulation approach involves placing the insulating material on the building's exterior walls. Subsequent external finishes, such as glass or stone, are then applied over the insulation.	

In summary, typical housing units are either villas or apartments. These units are built with reinforced concrete and ceramic floor materials. Traditional houses are made of brick, clay, stone, a cladding layer, and reinforced concrete, regardless of the number of floors. Overall, the choice of building materials in Saudi Arabia is evolving towards more sustainable and energy-efficient options, which align with the sustainability objectives outlined in Vision 2030. These options focus on utilizing local materials and reducing the environmental impact of construction.(Surf et al., 2014; Alhammadi, 2022).

3.6. Impact of Building Envelope on the Energy Demand

This section provides a comprehensive assessment of prior research conducted on building energy. Reviewing previous studies on building energy performance is crucial for understanding the current state of research in this field. Additionally, this review provides a foundation for building upon existing knowledge and developing new strategies to improve building energy efficiency.

The building envelope serves as a physical barrier between the interior of a building and the external environment, significantly affecting energy consumption within residential structures (Lim et al., 2019). Each building's walls, roofs, windows, and entrances contribute significantly to the structure's overall thermal performance and determine the heating and cooling energy requirements (Aldawoud, 2017; Mujahid, 2021).

In warmer climates, heat transfer through a building's structure significantly contributes to its total thermal load, influenced by the ratio of glass to wall and the air leakage rate. Minimizing this heat transfer is essential for reducing electricity consumption and decreasing energy bills, as it directly affects the demand for air conditioning in buildings. The building envelope is the critical barrier between the interior and exterior environments, influencing energy efficiency and thermal comfort (Mathur and Damle, 2021).

By incorporating energy-efficient building envelope technologies, architects can promote energy sustainability in their designs (Akinola et al., 2018). Sustainable building envelope design involves considering various factors, including compatibility with the surrounding environment and using passive and active technologies to provide a comfortable indoor environment (Kumar and Raheja, 2016). Strategies for improving the building envelope in Saudi Arabia include retrofitting existing buildings with thermal insulation, using shading devices to reduce solar heat gain, incorporating PV systems on roofs, and optimizing the building envelope design to minimize energy consumption and thermal discomfort. Passive design features, such as thermal mass, can also be used to improve energy efficiency by absorbing and storing heat energy during periods of high solar insolation and releasing it when the surrounding air begins to cool, thus reducing the heating and cooling demand of the building itself. Furthermore, utilising high-performance glazing systems with favourable U-values and Solar Heat Gain Coefficients (SHGC) in windows and doors minimises unwanted heat gain and loss, fostering energy conservation.

The choice of materials and technologies used in the building envelope also plays a vital role. The selection of appropriate materials and technologies can contribute to energy efficiency and sustainability goals (Singhaputtangkul and Low, 2015). For instance, the U-value influences the thermal performance of the building envelope and aids in estimating the effective thermo-physical material for the envelope (Iranfar and Al-Din, 2020). Building-integrated photovoltaics (BIPV) is another technology that can be integrated into the building envelope to enhance energy efficiency (Farghaly and Hassan, 2019). The environmental impact of the building envelope is another critical consideration. Life-cycle assessment studies have shown that the environmental impact of the building envelope is significant, with usage, production, transportation, disposal, and construction stages all contributing to its overall impact (Yang et al., 2020). Therefore, sustainable building envelope design should minimise the environmental impact throughout its life cycle. Compatibility with sustainability goals is also a key factor in building envelope design. Consider energy efficiency, environmental impact, and compatibility with sustainability requirements to achieve sustainable and buildable building envelope designs (Singhaputtangkul and Low, 2015).

Accordingly, the building envelope is crucial in facilitating efficient energy conservation. The transmission of thermal energy via a building envelope accounts for a substantial proportion, typically ranging from approximately 40% to 45% of the overall thermal loads the structure encounters. Applying efficient strategies could reduce heat transfer via the building envelope, leading to a reduction in electricity usage and substantial financial savings on utility expenses. Several studies have investigated optimizing and evaluating building envelope components to determine their contribution to energy consumption.

In 2022, over 100 countries lacked compulsory energy standards for buildings, resulting in more than 2.4 billion square meters of construction not adhering to energy performance standards; to align with the Net Zero Emissions by 2050 goal, all nations must introduce zero-carbon-ready energy codes for all buildings by 2030 and upgrade 20% of existing structures to meet these standards (IEA, 2022b). These investigations underline the necessity of integrating energy-efficient designs and materials in the building envelope to minimize energy consumption, promote sustainability, and substantially reduce energy demand for heating and cooling in residential buildings.

In conclusion, the building envelope is a critical component of building sustainability. Its design and construction have a significant impact on energy performance, economic feasibility, and indoor comfort. By adopting energy-efficient technologies and considering various factors in the design process, architects can promote energy sustainability and create sustainable and buildable building envelopes.

3.6.1. Thermal mass

Thermal mass refers to the capability of a material to store and release heat. In summer, all exposed walls and floors begin to absorb heat from the outer surface, storing this heat until the environment cools down to begin releasing it. This mechanism aids in maintaining internal temperatures and preventing overheating during summer days.

Conversely, in winter, the thermal mass can store heat from the sun during the day and release it at night when temperatures drop.

Numerous studies have highlighted the impact of thermal mass on energy consumption, demonstrating that it can reduce cooling needs and air temperature elevation by slowing down heat transfer through the building envelope and absorbing heat generated inside (St Clair, 2009). According to a study by Al-Sanea et al. (2012), increased thermal mass in building walls leads to decreased energy consumption, emphasizing the direct correlation between thermal mass and energy efficiency. In hot climates, the impact of thermal mass on building energy consumption has also been studied. Thermal mass helps to absorb and store heat during the day and release it at night, reducing the need for mechanical cooling.

Furthermore, the examination of the heat storage capacity of building envelope components highlights that optimizing thermal mass minimizes heat gains associated with direct solar radiation and high outdoor temperatures, thereby reducing the dependency on mechanical air conditioning.

3.6.2. External Wall Efficiency

Thermal performance and energy efficiency have a significant impact on the external walls of buildings. The thermal insulation of external walls is one method to reduce the consumption of thermal energy in a building (Dylewski, 2019). The heat transfer loss in building envelopes, particularly in the walls, accounts for a significant portion of the total heat transfer loss in a building (Meng et al., 2015). Therefore, improving the thermal performance of the building's external envelopes, especially the walls, is crucial for creating a comfortable indoor environment, improving indoor comfort, and decreasing building energy consumption (Meng et al., 2015)

The location of the thermal insulation layer in the wall also affects the dynamic thermal response rate, especially under intermittent air-conditioning operation (Zhang et al., 2017a). The types and thickness of insulation used in the external wall structure also impact the dynamic thermal characteristics, indoor thermal comfort, and building energy savings (Yuan, 2018). Thermal insulation is a key component in retrofitting buildings in hot climates, such as Saudi Arabia and the Middle East. It aims to reduce heat transfer, significantly lowering energy consumption by maintaining cooler interior environments without excessive air conditioning. Both experimental and computational research has shown that insulating both roofs and walls can significantly cut down on heat transmission and energy use.

Proper insulation in building envelopes can significantly reduce cooling demand and improve energy efficiency. In the study by Almushaikah and Almasri (2020b), applying energy efficiency measures (EEMs) specifically to the walls of residential buildings could significantly reduce energy consumption. In Riyadh, the implementation of EEMs on walls led to a 27% reduction in energy usage, while in Qassim, a slightly higher impact was observed with a 29% reduction. Using low-conductivity insulation materials is essential to minimize heat transfer and reduce the cooling load in hot climates (Rehman, 2017). The study demonstrates the effectiveness of different solar insulating materials for energy savings in hot climates like the UAE. Specifically, retrofitting standard building materials such as solid concrete with polyisocyanurate (PIR) and reflective coatings, or replacing them with energy-efficient dry insulation material walls like the exterior insulation finishing system (EIFS), resulted in energy savings ranging from 7.6% to 25.3%.

Additionally, the durability of the materials used for insulation is essential for having the ability to deal with varying temperatures in the ambient air and solar radiation (Alyami et al., 2022b). Retrofitting buildings in hot climates also entails considering climate change's impact. With rising temperatures, the challenge of preventing retrofitted buildings from overheating grows, making it necessary to adapt insulation material choices and retrofitting strategies. Zhao (2020) explores the application of rigid polyurethane foam (RPF) to enhance the energy efficiency of coastal buildings through roofing insulation. This study offers a strategy for improving building insulation and contributing to energy conservation in coastal environments.

Al-Homoud (2005) explores the significance of thermal insulation in buildings, emphasizing its role in reducing energy consumption and operational costs. The study emphasizes the importance of thermal insulation in reducing energy consumption in buildings, especially in regions with harsh climate conditions. The study emphasizes that efficient use of thermal insulation not only reduces the annual energy cost and system size required, but also extends the duration of thermal comfort without the need for mechanical air conditioning (Al-Homoud, 2005).

Numerous studies have investigated the optimal insulation thickness for residences in Saudi Arabia, along with the most effective placement of this insulation. A case study based in Riyadh evaluated three distinct wall insulation configurations, each 26mm-thick, positioned internally, centrally, and externally (Al-Sanea and Zedan, 2011). The analysis revealed that walls with multiple insulation layers outperformed those with a single 78-mm-thick insulation layer situated internally, resulting in a 20% reduction in peak cooling and heating transmission loads. In the context of thermal insulation materials in Saudi Arabia, four primary types have been identified: Polyurethane, Polystyrene, Fiberglass, and Mineral fibre. The position and appropriate thickness of thermal insulation in building envelopes enhance energy performance in Saudi Arabian residential buildings. Saleh (1990) conducted a study that demonstrates a marked reduction in cooling loads by placing thermal insulation with a thickness ranging from 50 to 100 mm within the outer layer of the exterior wall. A study by Al-Naimi (1989) explored energy conservation in residential buildings in Dammam, Saudi Arabia, highlighting issues like poor thermal design that lead to high energy consumption from mechanical cooling systems. Through surveying houses and assessing six case studies, a computer model was developed to predict annual energy usage for cooling, suggesting energy savings through building envelope modifications and lower U-values.

In another study examining heat transfer in complex building blocks with cavities, it was found that inserting polystyrene in the cavities reduced the heat rate by 36% (Al-Hazmy, 2006). On a typical hot summer day, solid polystyrene reduced the total daily heat transfer by 25%. Another study by Al-Hadhrami and Ahmad (2009) explored the impact of adding insulation material to bricks, either by mixing it with the brick material or filling brick holes with it, aimed at enhancing thermal resistance. The findings revealed that such additions increased the thermal resistance of clay brick samples by up to 15% indicating a significant positive effect, especially for concrete blocks. Per findings by Al-Tamimi (2021), the optimal thickness of thermal insulation for walls and roofs was explored in a typical villa across three Saudi cities using the DesignBuilder tool. Four insulating materials were selected to evaluate energy savings over 20 years. The analysis showed a direct relation between insulation material cost and energy efficiency, with total energy costs of 7.7, 9.7, and 5.6 $\$/m^2/y$ in Najran, Gazan, and Khamis Mushait respectively. Optimal insulation thicknesses were found to be 2, 6, and 8 cm for these cities respectively. The payback period ranged from 4.7 years in Gazan to 8.8 years in Khamis Mushait, indicating the cost and energy-saving benefits of tailored insulation thickness (Al-Tamimi, 2021). On the other hand, a study found optimal thicknesses of 9 cm for polystyrene, 1 cm for polyurethane board, and 7.6 cm for rock wool insulation under specific test conditions (Al-Sanea et al., 2003). Both studies collectively contribute to a comprehensive understanding of how varying insulation materials and configurations can significantly impact energy conservation and cost efficiency in different climatic and construction contexts (Al-Sanea et al., 2003; Al-Tamimi, 2021). Similarly, another study reinforced this notion by identifying polystyrene as the most cost-effective insulation material across all examined walls and climates, offering the shortest payback period, followed by rock wool and then polyurethane (Al-Sanea et al., 2016).

In summary, external walls' thermal performance and energy efficiency are critical for reducing energy consumption, improving indoor comfort, and reducing building energy costs. By implementing appropriate insulation materials and thicknesses, as well as considering factors such as climate zones, it is possible to enhance the thermal performance and energy efficiency of external walls.

3.6.3. Roofing for Thermal Efficiency

Many studies provide insights into various aspects of roof construction and its influence on energy consumption, and radiation in hot climates like KSA. As outlined in Section 2.62.6 above, the Saudi Building Code Regulations (2018) mentioned that roofs have lower U-values than other building envelope components, including walls. This distinction highlights the critical role roofs play in the thermal performance of buildings, given their direct exposure to high levels of solar irradiance, especially in Saudi Arabia's arid climate.

Taleb and Sharples (2011) present a case study on developing sustainable residential buildings in Saudi Arabia. The study emphasizes the importance of sustainable design strategies, including roof construction, in reducing energy consumption. By incorporating energy-efficient materials and design principles, such as proper insulation and shading, the study demonstrates the potential for significant energy savings in residential buildings. The solar absorbance of a residential roof can vary based on its material, colour, and other design features.

The solar absorbance of a residential roof can vary based on its material, colour, and other design features. Similarly, the solar reflectance of a roof can fluctuate depending on the colour, with lighter colours reflecting more sunlight than darker ones (Akbari et al., 2008). The solar absorbance of a roofing material measures the solar radiation absorbed by the material compared to the total incident solar radiation. It is expressed as a numerical ratio ranging from 0 to 1. A higher solar absorbance value indicates that the material absorbs more solar radiation. This measurement is important for understanding how much heat the roofing material retains, which can impact building energy efficiency and overall temperature regulation. Saber et al. (2019) investigated the performance of cool roofs subjected to Saudi climates. The study evaluates the impact of increasing rooftop solar reflectivity on energy consumption and insulation thickness. It demonstrates that increasing solar reflectivity can lead to significant energy savings and reduce the required insulation thickness in hot climates.

The study by Al-Sanea (2002) examined the thermal performance of six roof structures in Riyadh, Saudi Arabia, under changing climatic conditions. The results showed that in comparison to a reference roof without insulation, using dense concrete foam as a layer significantly reduced the heat-transfer load. In particular, when using lightweight concrete foam, the reference daily average heat-transfer load decreased by 45%. Additionally, when a 5-cm thick insulation layer composed of polystyrene, extruded polystyrene, and polyurethane was utilized, the reductions in the reference daily average heat-transfer load were 32%, 27%, and 22%, respectively (Al-Sanea, 2002).

Coma et al. (2016) conducted a study that examined the thermal evaluation of green roofs as a passive mechanism for conserving energy in buildings by examining their impact on cooling loads and enhancement of thermal comfort. The findings indicate that the implementation of green roofs resulted in a significant reduction of 16.7% in overall electrical energy usage. In Saudi Arabia, the typical roof shape in housing is often flat. Another study conducted in Saudi Arabia demonstrated that green roofs did not exhibit any thermal advantages in comparison with traditional rooftops (Khan and Asif, 2017). However, intensive vegetated roofs were found to effectively mitigate the thermal load Khan and Asif (2017) investigated the efficiency of green roofs in different climates is evident when comparing their performance in Riyadh's hot and dry climate to that in Dhahran's hot and humid conditions. In Riyadh, the green roof demonstrates a slightly higher effectiveness, resulting in a reduction of energy consumption by 6.7%. Similarly, in Dhahran, the green roof proved to be effective, reducing energy consumption by 6.8%.

Nevertheless, the arid climate of Saudi Arabia presents challenges. Sustaining the life of a green roof necessitates a substantial water supply, which is a potential concern in regions with high temperatures. Moreover, the initial expenses associated with installing and maintaining a green roof may aid individuals considering the implementation of this environmentally sustainable feature. It may also require additional upfront costs for structures to be appropriately constructed to guarantee that rainwater can drain away. Despite these challenges, the long-term energy savings and environmental advantages could make green roofs a viable option in Saudi Arabia for promoting urban sustainability while balancing ecological awareness with practical concerns in a harsh climate.

In the context of dust accumulation on building roofs, a study conducted by Algarni and Nutter (2015) revealed that enhancing roof insulation reduces the effects of dust accumulation on building roof systems. Specifically, in Riyadh, a 28% reduction in cooling space is anticipated with a dusty roof. The findings emphasize the importance of employing suitable insulation for energy conservation and appropriate insulation methods for energy preservation. However, it is worth noting that a significant proportion of residential buildings in the Middle East and North Africa region do not meet the necessary construction requirements (Algarni and Nutter, 2015). Over 70% of residential buildings in Saudi Arabia lack insulation, reflecting a significant oversight in energy-saving practices in the region as stated in a study by Algarni and Nutter (2013).

Based on the study conducted by Al-Shaalan et al. (2014b), the maximum allowable overall heat transfer coefficients (U) for various wall and roof constructions, considering their construction types range from 0.251 to 0.564, medium construction has a range of 0.192 to 0.479, and 0.165 to 0.419 for light construction. The data suggests that the construction type and external colour significantly impact the heat transfer coefficients, with lighter/medium colours and heavier construction generally allowing lower heat transfer, contributing to better thermal performance (Al-Shaalan et al., 2014b).

Al-Tamimi (2022a) showcased that combining different retrofitting strategies significantly enhanced energy efficiency in an office building in Najran, Saudi Arabia. Specifically, the combination of various passive design solutions led to a reduction in energy consumption to around 26.8% of the original demand. This holistic approach, which incorporated multiple retrofitting measures, proved to be the ideal solution for maximizing energy efficiency, resulting in substantial energy savings and contributing to a low-carbon economy.

Tables 3.3 and 3.4 highlight a range of insulation options, each with unique properties and effectiveness, combined with strategies for practical application in building design. This approach highlights the necessity of integrating materials with architectural innovations to achieve significant energy savings and contribute to sustainable building practices.

Table 3. 3 Comparative thermal insulation materials for buildings in hot climates. Source: (Nosrati and Berardi, 2018; Koru, 2016)

Insulation Type	**Moisture Resistance**	**Durability**	**Suitability for Hot Climates**
Fiberglass	Moderate	High	Moderate; requires vapour barrier for humidity
Expanded Polystyrene (EPS)	High	Moderate to high	Good; lightweight and easy to install
Extruded Polystyrene (XPS)	Very High	High	Excellent; higher moisture resistance and R-value
Polyurethane Foam (PU)	High	High	Excellent; flexible with a high insulation value
Mineral Wool	Moderate	High	Moderate; high fire resistance but variable moisture resistance
Aerogel	Moderate to high	High	Excellent; superior insulation with minimal thickness
Cellulose	Low	Moderate	Moderate; eco-friendly but requires treatment for fire and pest resistance

Table 3. 4 Material properties and design implications for energy efficiency in roofing.

Roofing Strategy	Description	Benefits	Implementation Challenges	Impact on Energy Efficiency
Dynamic Insulation	Adjusts insulation properties in response to environmental conditions.	Optimizes thermal performance year-round.	Technological complexity and cost.	Significantly reduces energy consumption for heating and cooling.
Solar Photovoltaic (PV) Integration	Installation of PV panels on roofing surfaces to generate electricity.	Reduces reliance on grid energy and lowers operational costs.	Initial investment and roof suitability.	Directly contributes to a building's energy self-sufficiency.
Roof Albedo Management	Regular cleaning and maintenance to maintain high solar reflectance of roof surfaces.	Maintains the effectiveness of reflective roofing materials.	Ongoing maintenance requirements.	Preserve the roof's ability to reflect solar radiation, minimizing heat gain.
Vegetated (Green) Roofs	Use of plants and soil as a living roof layer.	Provides insulation, reduces urban heat island effect, and manages stormwater	Requires maintenance, waterproofing, and structural considerations for weight.	Offering environmental benefits alongside cooling effects.

The reviewed studies show roof systems are crucial to building thermal performance and energy efficiency, especially in hot-dry areas like the Middle East and North Africa. Various studies emphasize selective insulation application and the necessity for improved construction standards to reduce energy. In summary, exploring roofing systems for hot climates, particularly in Saudi Arabia, emphasizes the combined effect of selecting appropriate thermal insulation materials and employing operational strategies to enhance energy efficiency.

3.6.4. Window and Glazing

This section provides an overview of windows and shading in energy conservation within building envelopes. To enhance energy efficiency and comfort within buildings, especially in hot climates, the design and implementation of glazing and shading are crucial. Windows, being one of the weaker links in the building envelope regarding heat gain in summer and heat loss in winter, necessitate thoughtful design to mitigate these effects while also allowing natural light. Specific elements, including window ratio, orientation, and the thermal characteristics of the glass material, determine the influence of windows on the energy performance of buildings. Additionally, shading devices also play a vital role in managing the amount of solar heat gained through windows.

The Solar Heat Gain Coefficient (SHGC) measures the fraction of solar energy transmitted through a window, influencing a building's energy efficiency use based on the window's orientation and climate. Following the Saudi Code, double-paned aluminium windows with a U-value of 2.67 (W/m^2K) and glazing SHGC of 0.25 are required for all locations (SBC, 2018). Additionally, the code refers to a specific standard that limits the window-to-wall ratio (WWR) to no more than 25% of the total exterior surface area of a building. In various climates, managing SHGC is important for maximizing energy consumption (Harrison and Wonderen, 1994).

Figure 3.7 provides a clear comparison of three types of glazing: single, double, and triple pane. Each type offers varying degrees of thermal insulation and light transmission. Single glazing, with the highest U-factor and Solar Heat Gain Coefficient (SHGC), provides less insulation and higher heat gain. In contrast, double and triple pane glazing demonstrate a decrease in both U-factor and SHGC, indicating improved insulation and reduced heat transmission. This makes them more useful for building energy savings. These visual representations underscore the importance of selecting the appropriate glazing type for energy efficiency and thermal comfort in different climates.

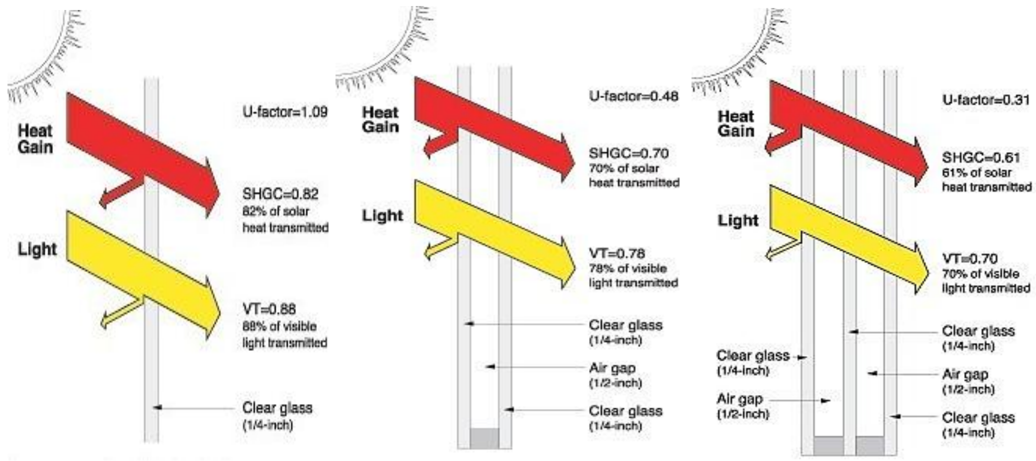


Figure 3. 7 Glazing Types for Thermal Efficiency (Maven, 2017).

Chaiyapinunt et al. (2005), investigated a range of characteristics, including the solar heat gain coefficient (SHGC), visible light transmittance (VLT), and shading coefficient (SC). This study aimed to determine the thermal performance of glass windows and films. It assessed the effects of various glass window types and window coatings on thermal comfort and heat transfer. Furthermore, the research emphasized that the performance of glass windows and films varied depending on their qualities and characteristics. Specifically, the performance of various film types, including low-emissivity (low-E) films, varied in terms of heat transfer and thermal comfort (Chaiyapinunt et al., 2005).

In another study, Jelle et al. (2012) evaluated the performance of low-emissivity (low-E) glass and double-glazed windows, highlighted their ability to reduce heat transfer. This study highlighted how important low-E glass is for improving energy efficiency by reducing heat loss. Furthermore, the study indicated that aerogels, which offer both excellent insulation and improved light transmission qualities, show great potential for future improvements in fenestration (Jelle et al., 2012).

The study by Gasparella et al. (2011) found that while triple glazing offers excellent thermal insulation, its low solar heat gain can potentially increase heating energy needs in colder climates. These characteristics require careful consideration due to potential higher heating demands. According to these findings, Ihm et al. (2012) conducted research in South Korea and recommended favouring double-glazed windows over triple-glazed ones due to their cost-effectiveness and ability to balance economic and thermal performance considerations.

The effective utilization of building and fenestration geometry characteristics, combined with additional fenestration components such as shading devices, energy-efficient glazing, and room geometry, can significantly reduce building energy consumption and enhance overall building performance (Susorova et al., 2013). The study suggested that considering geometry parameters is crucial in the construction of new buildings or the renovation of existing ones. In regions with hot and temperate climates, optimal energy efficiency is achieved when rooms are oriented towards the north and equipped with large windows, whereas rooms with smaller windows are oriented towards the south. Geometrical variables observed average energy savings of 6%, with the highest recorded reduction reaching 14% in such environments (Susorova et al., 2013).

In the research conducted by Al-Homoud (1997), the importance of optimizing glazing was highlighted, emphasizing the necessity for reduced shading coefficients and diminished glass U-values, especially in hotter climates. Specifically, in warmer regions such as Riyadh and Jeddah, findings suggested a preference for limiting glass coverage on the east and west sides of buildings, while providing greater flexibility for south and north-facing exposures.

Another study, conducted in an office building in the hot climate of Aswan, Egypt, examined the impact of different glazing materials, window orientations, and window-to-wall ratios (WWR) on energy usage (Mahmoud, 2022). Some forms of glazing significantly reduced overall yearly energy usage, with savings ranging from 3.66% to 12.71% compared to a single layer of transparent glass. The exact amount saved depends on the glazing type and the orientation of the windows. The study found that incorporating a nanogel layer among two layers of argon and two layers of transparent glass, with a window-to-wall ratio (WWR) of 10%, led to a substantial decrease in overall yearly energy use (Mahmoud, 2022).

According to Aboulnaga (2006), the widespread misuse of glass in the Gulf region can be attributed to a lack of knowledge regarding sustainable design principles. Specifically, Aboulnaga (2006) highlighted the excessive solar heat gain experienced in buildings with Gulf glass systems. The author recommended the use of low-emissivity (low-e) glass, tinted glass, and external shading devices to mitigate heat gain and increase energy efficiency, thereby improving visual comfort for occupants. The author also suggests utilizing double-glazed windows filled with argon gas to improve thermal insulation.

Hence, it's imperative to address glazing techniques and methods to curtail energy consumption and optimize thermal comfort.

Based on a study conducted by Ebrahimpour and Maerefat (2011), the utilization of the most suitable overhang or side fin, as determined for single clear pane glazing, proved to be more beneficial for windows facing any direction as compared to advanced glazing windows like double clear pane glazing or low-E glazing. This evaluation was conducted within the context of typical residential buildings in Tehran, focusing on the impact of advanced glazing and overhangs on the solar energy transmitted through the fenestration areas.

To control the amount of solar heat entering the building through the windows, (Hammad and Abu-Hijleh, 2010) investigated the feasibility of installing extensive external louvres as shading devices in an office building. The results indicated that energy savings from a light-dimming technique ranged from 24.4% to 25.19% across all facade orientations. The savings increased from 28% to 34% when coupled with a dynamic louvres system. However, Al-Sallal (2010) disapproved of using external dynamic shading systems due to the significant maintenance costs associated with keeping them functioning in the extremely dusty climate of the United Arab Emirates. Lai and Wang (2011) conducted research that examined the potential for energy savings in residential buildings in Taiwan using several building envelope designs, including glazing. The researchers conducted simulations to evaluate the impact of window glass and shading techniques on energy consumption. According to the study's findings, selecting appropriate window glass significantly reduced yearly energy costs, with the use of shading devices showing a similar effect. (Lau et al., 2016) focused on high-rise office buildings in Malaysia and found that the use of shading devices on low-e double-glazed facades can result in annual cooling energy savings of 1.0% to 3.4%, with even higher savings when shading devices are applied to all orientations

Aldossary et al. (2014b) carried out multiple case study analyses that focused on the effects of shading devices in investigating patterns of home energy consumption in hot and dry regions. Their study, conducted in the Jeddah region, used large-scale energy models and simulations to assess energy use in a variety of typical homes. The results of the study emphasize the effectiveness of shading devices, which when combined with energy-efficient glass and renewable energy sources showed the ability to reduce energy usage by 21% to 37%. These findings highlight that architectural modifications contribute significantly to energy conservation in dry environments (Aldossary et al., 2014a). Alaidroos and Krarti (2015b) demonstrated that adding shading devices, such as 1.0 m overhangs, could significantly improve energy savings by blocking direct solar irradiation. They reported that advancements in the U-value and solar heat gain coefficient of windows could lead to energy savings of up to 10% compared to buildings that use single-glazed windows and maintain a higher window-to-wall ratio. These insights provide valuable guidance for improving energy efficiency in residential construction within the region, supporting broader sustainable building initiatives (Alaidroos and Krarti, 2015b).

Bahaj et al. (2008) discussed emerging glazing technologies for highly glazed buildings in hot arid climates, such as electrochromic glazing and aerogel glazing, and predicted potential reductions in cooling demand. According to these studies, double glazing and shading strategies are essential in hot climates to reduce cooling loads, and various approaches and technologies show potential for energy savings that comply with the Saudi building code.

3.6.5. Enhancing Building Sustainability via Integration of Renewable Technologies: Applications of Photovoltaic Systems

In 2022, Saudi Arabia ranked as the third-largest producer of crude oil and condensate globally and was the leading exporter of crude oil (EIA, 2023). According to a study by Alarenan et al. (2020), industrial energy consumption in Saudi Arabia markedly increased from 1986 to 2016, establishing it as one of the Kingdom's principal energy use sectors and emphasizing its significant status in global energy consumption. Saudi Vision 2030, introduced in 2016, focuses on expanding the Saudi economy beyond oil dependence. It is anticipated that by 2032, Saudi Arabia will increase its electricity generation capacity to 120 GW (Wada, 2017). The country, endowed with substantial solar and wind energy resources, aspires to install 9.5 GW of renewable energy generation systems through a mix of solar and wind energy as outlined in its Vision 2030 (Poudineh et al., 2020). To this end, investments in renewable energy within the power sector are being ramped up alongside hikes in domestic energy prices to boost efficiency (Poudineh et al., 2020). Under the guidance of Saudi Vision 2030, the National Transformation Program 2020 was initiated with the ambitious goal of achieving 3.45 GW of renewable energy by 2020, constituting 4% of the kingdom's total power consumption. A substantial investment of

109 billion US dollars over the next two decades is planned for solar energy to achieve the 9.5 GW installation target, with solar photovoltaic (PV) systems serving as the focal point. As the global move from fossil fuels to renewable energy progresses, technologies like photovoltaics are becoming increasingly popular. Building Integrated Photovoltaics (BIPV) systems, which integrate photovoltaic elements into building structures like rooftops or facades, present a pathway to reduce electricity costs and fossil fuel use. However, the investigation of installing PV panels on residential rooftops for electricity generation and its consequential impact on energy consumption remains under-explored in Saudi Arabia.

Numerous studies have emphasized the advantages of using photovoltaic (PV) panels for electricity generation in Saudi Arabia, highlighting aspects such as building structure, shading areas, and the expected electricity generation from PV. The flat rooftops common in Saudi Arabian architecture are ideal for PV panel installations, maximizing solar exposure (Aldossary et al., 2017; Asif et al., 2019; Dehwah et al., 2018a). These structures allow for extensive implementation of PV systems, significantly contributing to the country's energy sustainability goals. For instance, a study by Imam et al. (2020) evaluated the techno-economic viability of grid-connected PV systems for residential buildings in Jeddah, indicating that such installations could provide significant residential energy demands while remaining economically feasible. The study found that PV systems had a high performance ratio, suggesting efficient energy production relative to their potential output (Imam et al., 2020).

Additionally, Khan et al. (2017) explored the potential for rooftop solar PV across various cities in Saudi Arabia, estimating that such systems could generate a significant portion of the country's energy demand. This study provided a detailed analysis of the power generation capabilities of rooftop PV installations, further emphasizing the viability of solar energy in addressing national energy consumption needs (Khan et al., 2017). Mandalaki et al. (2012), investigated the energy performance of various configurations of fixed shading devices integrated with photovoltaic (PV) systems. The study found that shading devices offering the highest daylight availability, such as vertical louvers and canopy louvres, led to increased energy consumption for heating and cooling due to greater exposure to reflected solar radiation. In contrast, horizontal Louvers, which allow minimal daylight penetration, were highly efficient in reducing the energy requirements for heating and cooling.

Zhang et al. (2017b) assessed BIPV's performance in terms of electricity generation and energy savings in Hong Kong's climate. Through simulations via EnergyPlus, and considering different orientations, it was concluded that the optimal BIPV installation location for maximizing electricity production was the south facade at a 30-degree angular position, although the study was limited to examining the horizontal configuration.

Asif (2016b) found that the application of PV on building rooftops can meet a significant portion of the energy requirements, such as producing over 16% of the total energy requirements of the King Fahd University of Petroleum and Minerals (KFUPM). Sharples (2013) highlighted the societal benefits of PV integration into buildings in Gulf Cooperation Council (GCC) countries, including savings in capital costs, increased use of exported oil and natural gas, and a reduction in CO_2 emissions. Al-Otaibi et al. (2015) evaluated the performance of PV systems on Kuwaiti schools' rooftops and found that the performance ratio was maintained between 0.74 and 0.85, with an annual average daily yield of 4.5 kWh/kWp/day.

In a study conducted in a Mediterranean climate, a conventional roof was compared to one equipped with photovoltaic panels. The results showed a 6.7% increase in heating loads during winter, while summer saw a 17.8% reduction in cooling loads (Dominguez et al., 2011). The efficiency and payback period of panels are directly influenced by factors such as material, orientation, capacity, tilt, and roofing materials. The payback period can range between 4 and 11 years (Hayat et al., 2017; Buker et al., 2014).

The location and orientation of a building significantly impact both PV production and the building's energy efficiency (Kylili and Fokaides, 2013). Among various climates, hotter climates offer a higher return on investment in PV. A study in Abu Dhabi, which monitored different roof-mounted PV systems' performance, revealed that the systems produced up to 17,465 kWh of energy in May (Emziane and Al Ali, 2015).

3.7. The demand for residential energy retrofitting in Saudi Arabia

Saudi Arabia’s unique climate conditions, characterized by extreme heat and high solar exposure, have made air conditioning a necessity for most homes, accounting for nearly 70% of residential electricity consumption. The residential sector remains a significant energy consumer due to the rapid growth of the housing sector and unsustainable building practices (Alshamrani and Mujeebu, 2016). This energy inefficiency highlights the urgent need for retrofitting to reduce energy consumption and align with national sustainability goals such as Saudi Vision 2030.

Several studies, such as those conducted by Alrashed and Asif (2015a), have documented high Energy Use Index (EUI) values for various housing types in Saudi Arabia, highlighting the critical need for intervention. For example, EUI values for apartments and villas reach up to 150 kWh/m^2/year in the Eastern Province, significantly exceeding global benchmarks. The rapid expansion of the housing sector, coupled with a lack of sustainable construction methods, has resulted in increased energy consumption and economic inefficiencies. This necessitates the retrofitting of existing buildings to enhance energy efficiency and mitigate environmental impact (Alalouch et al., 2019). According to Asif (2016a), energy retrofitting can reduce lifetime energy consumption by 30–80 %, which not only lowers operational costs but also aligns with regional energy goals. Furthermore, retrofitting can enhance energy productivity across the GCC region, emphasizing the need to update existing buildings(Krarti et al., 2019).

Energy-efficient retrofitting of residential buildings has emerged as a crucial strategy across the MENA region, especially in Saudi Arabia. Several studies have outlined potential reductions in energy consumption through prototype models representing buildings. For instance, Krarti and Ihm (2016) assessed the feasibility of achieving net-zero energy consumption in residential buildings across the MENA region. Their findings revealed that modifications to existing design practices could lead to a significant 50% reduction in energy consumption, thereby offering the potential impact of retrofitting in Saudi Arabia.

Given these retrofitting potentials, government support becomes pivotal. Alaidroos & Krarti (2015) and Krarti et al. (2017) demonstrate how retrofitting could reduce residential energy consumption by 40% depending on the city. They further suggest that financial support from the government for retrofitting initiatives could lead to a substantial 36% decrease in energy subsidies, highlighting the importance of government involvement.

In contrast, a study by Ihm and Krarti (2012) in Tunisia provides valuable lessons in integrating various Energy Efficiency Measures (EEMs). Their findings suggest that optimal design modifications could yield 59% energy savings, which could serve as a benchmark for similar retrofitting efforts in Saudi Arabia.

Building on the broader benefits of retrofitting, Alotaibi et al. (2023) specifically focus on improvements in energy efficiency for domestic air conditioning systems in Saudi Arabia. systems. They estimate that, under the Business as Usual (BAU) scenario, energy savings could reach up to 21.4 TWh by 2030, with additional savings of 12.7 TWh achievable through further improvements. This study underscores the importance of enhancing the energy efficiency ratio (EER) of air conditioning units and implementing new refrigerants, which could result in substantial energy savings for Saudi homes

Felimban et al. (2023a) examine the energy-saving potential of several retrofitting techniques for dwellings in Jeddah, Saudi Arabia. Their study assesses the impact of updating windows, wall insulation, and air conditioning units, with models indicating energy savings of 25% to 66%. The study highlights the importance of retrofitting, especially for older buildings that consume high energy due to outdated construction standards.

The study by Al-Saadi et al. (2017) focused on retrofitting residential buildings in Oman, examining strategies such as air conditioning (AC) improvements, insulation, and lighting upgrades. The study concluded that combining these strategies could result in a 42.5% annual energy reduction. However, it primarily focused on technical efficiency improvements without providing a detailed economic analysis. Using DesignBuilder software, the researchers modeled energy performance to identify reductions achievable through enhanced insulation, efficient AC systems, and LED lighting (Al-Saadi et al., 2017).

In contrast, Al-Saadi (2021) expanded this analysis to include institutional buildings in cooling-dominated climates, incorporating a holistic view of energy, thermal, and economic performance. This study emphasized the need for cost-effective retrofitting strategies, assessing not only energy savings but also payback periods and return on investment. it explored advanced HVAC systems, building envelope enhancements, and window optimizations. This focus on institutional buildings reflects the demand for sustainability in larger structures, requiring comprehensive strategies to manage cooling loads, occupant comfort, and economic viability. Findings indicated that such retrofits could reduce energy consumption by up to 56% while maintaining indoor thermal comfort.

Alhaqbani et al. (2023) highlight the importance of institutional initiatives through a case study on energy efficiency projects at Imam Mohammad ibn Saud Islamic University.

Their research shows that such initiatives can reduce energy demand significantly, achieving a 30% reduction in installed photovoltaic (PV) capacity while maintaining energy sustainability. This example highlights the role of government and educational institutions in promoting energy retrofitting for large complexes. Similarly Al-Homoud and Krarti (2021) provide a comprehensive review of Saudi Arabia's residential energy efficiency potential, noting high energy consumption largely due to air conditioning. Their study highlights the economic benefits of retrofitting as well as the benefits of lowering energy demand and CO2 emissions. They propose a roadmap to improve energy efficiency codes, retrofit buildings, and integrate smart technologies. Despite these strategies, the MENA region, including GCC countries, has faced challenges in fully realizing these benefits due to limited regulatory enforcement (Al-Homoud and Krarti, 2021).

Despite these advancements, the insufficient enforcement of standards and codes remains a challenge that policymakers must address (Griffiths, 2017b). Therefore, it is essential to focus on cost-effective solutions that integrate passive and active measures to meet Vision 2030's sustainability goals. While significant research has been conducted on energy retrofitting in Saudi Arabia, there is still a lack of comprehensive studies examining the economic feasibility of these measures, particularly regarding their implementation within the existing policy and regulatory frameworks.

In summary, the literature highlights the benefits of retrofitting residential buildings in Saudi Arabia, both in terms of energy savings and environmental impact. However, many studies lack holistic solutions that integrate technical measures, such as insulation, HVAC upgrades, and solar installations with regulatory and economic considerations. Future research should aim to integrate passive and active measures, including renewable energy, within Saudi Arabia's building code framework. Additionally, long-term economic analyses are needed to support the financial viability of retrofitting for homeowners.

3.8. Energy Simulation Tool

Building Performance Simulation (BPS) tools are now widely available and gaining popularity in engineering and energy fields. These tools allow users to model and analyse the energy consumption and environmental impact of buildings, helping to optimize design for increased efficiency. Additionally, BPS tools can also assist in identifying potential areas for improvement in existing buildings to reduce energy usage and costs. With technological advancements, BPS tools have become more user-friendly, allowing architects and designers to integrate energy modelling into their workflows easily. Many modern methods for energy simulation (IDA-ICE, DesignBuilder, EnergyPlus, TRNSYS, and IES-VE) implement the approach of energy usage in various ways.

One of the most widely used simulation tools is DesignBuilder. It has a well-organized layout with tab views. It can be difficult to modify data, even though it offers several input options and templates. Parametric analyses can be performed with the tool, but the resulting graphics often need to be simpler for architects to understand (Attia and De Herde, 2011).

EnergyPlus is a free program developed by the U.S. Department of Energy in 1996, which dynamically simulates heating, cooling, lighting, ventilation, other energy flows and water use in buildings (Drury et al., 2005). Energy Plus is a thermal simulation software application designed to analyse energy flow and thermal load in buildings. Engineers, constructors, and energy experts utilize it to create energy models (Sousa, 2012). Importantly, Energy Plus does not feature a graphical interface for visualizing and conceptualizing buildings, which makes its technical format more time-consuming for conducting simulations.

Integrated Environmental Solutions-Virtual Environment (IES-VE) is a reputable dynamic energy simulation tool favoured by academics, architects, and engineers for building design and retrofit projects (Shameri et al., 2013a). Known for its professional graphical interface, IES-VE simplifies complex thermal calculations into easy visualizations. It offers a variety of variables for building simulation analysis, as well as a geometric representation feature for building modelling. The tool, with its dynamic thermal simulation component ApacheSim, helps enable detailed analysis and optimization of building systems concerning comfort and energy measures. It's tested to the IES ASHRAE 140 standard, ensuring reliable dynamic modelling in line with the CIBSE classification system (Sousa, 2012). Table 3.5 visualizes the energy simulation tool comparisons.

TRNSYS (Transient System Simulation) is a software tool used to simulate transient systems, specifically those associated with energy and power. It is widely used in the field of renewable energy system design and analysis. The software is capable of modelling complex systems and evaluating their performance over time, making it a valuable tool for researchers and engineers working on energy projects. (Megri, 2014) recommended its use in teaching students about building thermal behaviour.

IDA Indoor Climate and Energy (IDA-ICE) is a simulation tool that calculates heat balance based on user-defined building parameters, HVAC settings, and internal heat loads. It utilizes climate and weather data, including temperature, humidity, wind, and solar radiation, to model building performance (Hilliaho et al., 2015).

The table provides a comprehensive comparison of the features supported by various simulation software tools, specifically Energy Plus, ESP-r, IDAICE, IES, and TRNSYS. Each software is listed as a column header, and the features are enumerated row-wise. These simulation tools have diverse capabilities, with some features being universal across all software, while others are more specialized. This table serves as a valuable resource for professionals and researchers looking to select a simulation tool that best fits their specific needs.

Table 3. 5 Comparisons of energy simulation tools. Source : (Drury et al., 2005; Sousa, 2012).

	Energy Plus	ESP-r	IDA ICE	IES	TRNSYS
Simulation Solution					
Simulation of loads, systems and solutions	X	X	X	X	X
Iterative solution of nonlinear systems	X	X	X	X	X
Duration of Time Calculation					
Variable time intervals per zone for interaction of the HVAC system	X	X			
Simultaneous selection of building systems and user		X	X	X	X
Dynamic variables based in transient solutions	X	X	X		
Complete Geometric Description					
Walls, roofs and floors	X	X	X	X	X
Windows, skylights, doors and external coatings	X	X	X	X	X
Polygons with many faces	X	X	X	X	
Imports of building from CAD programs	X	X	X	X	X
Export Geometry of Buildings for CAD software	X	X	X		
Import / Export of simulation models of programs	X	X	X	X	
Calculation of thermal balance	X	X	X	X	X
Absorption / release of moisture from the building materials	X		X	X	X
Internal thermal mass	X	X	X	X	X
Human thermal comfort	X	X	X	X	X
Solar Analysis	X				X
Analysis of Isolation	X	X	X	X	X
Advanced fenestration	X	X	X	X	X
Calculations of the building in general	X	X		X	X
Surface temperatures of zones	X	X	X	X	X
Airflow through the windows	X	X		X	X
Driving surfaces	X	X	X	X	X
Heat transfer from the soil	X	X	X	X	X
Thermophysical variable			X		
Daylighting and lighting controls	X	X	X	X	
Infiltration of a zone	X	X	X	X	X
Automatic calculation of coefficients of wind pressure				X	
Natural Ventilation	X	X	X		X
Natural and mechanical ventilation				X	X
Control open of windows for natural ventilation	X	X	X		X
Air leaks in multiple zones	X	X	X		X
Renewable Energy Systems					
Solar Energy	X	X		X	X
Trombe Wall	X	X	X	X	X
Photovoltaic panels	X	X		X	X
Hydrogen Systems		X			X
Wind Energy		X			X
Electrical Systems and Equipment					
Energy Production through R.E.	X	X			X
Distribution and management of electric power loads	X	X			X
Electricity generators	X				X
Network connection	X	X			X
HVAC Systems					
HVAC idealized	X	X	X	X	X
Possible configuration of HVAC systems	X	X	X	X	X
Repetitions cycle air	X	X	X	X	X
distribution systems	X	X	X	X	X
Modeling CO_2			X	X	X
Each distribution of air per area	X	X	X	X	X
Forced air unit per zone	X	X	X	X	X
Equipment Unit	X	X		X	X

3.9. Summary

The literature review broadly explores the impact of building envelope design on energy efficiency, particularly focusing on the utilization of glazing, shading, insulation, and PV integration into buildings in various climates. Through a range of studies, the review investigates how different materials and configurations can significantly affect a building's thermal performance and energy consumption. Key insights from different geographical regions provide a comprehensive understanding of the energy-saving potential of optimized envelope designs. The review also highlighted how combinations of different retrofit measures reduce energy consumption and improve thermal comfort in residential buildings, aligning to enhance energy efficiency and sustainability.

This chapter outlined the need for a holistic approach to retrofitting residential buildings in Saudi Arabia, specifically addressing the limitations of previous studies that have not fully explored the integration of both passive and active retrofitting strategies in alignment with the updated Saudi Building Code. By identifying this gap, the research sets the stage for the detailed exploration of sustainable retrofitting methods in subsequent chapters.

Chapter 4

Research Methodology

4.1. Introduction

The methodology section thoroughly provides an overview of the research strategy and methods used to investigate residential building retrofitting. The chapter describes the study objectives and simulation methods used to assess the energy performance and cost-effectiveness of retrofit options in Saudi Arabia. It highlights the research objectives and proves their significance in Saudi residential building retrofitting. The study also intends to investigate the inclusion of renewable energy systems in the retrofit process to further improve energy performance and minimize environmental effects.

Generally, there are three main methods to assess building energy performance: quantitative, qualitative, and mixed-methods data (Welten and Reich, 2023). The quantitative approach utilizes mathematical and computational techniques to simulate and analyse a building's energy performance. Wang et al. (2012) discuss quantitative energy performance assessment methods for existing buildings, using various methods. Their study underlines the importance of organized, data-driven methods for accurate energy evaluation. In contrast, qualitative energy modelling gathers information through surveys, interviews, observations, and feedback from building occupants and stakeholders (Wiese et al., 2018). The research thoroughly addresses the issue by using advanced simulation tools within a quantitative methodological framework.

4.2. Research Design

This study employs quantitative methods to integrate measure sets and simulate a chosen building energy model, offering a fresh perspective on energy-efficient retrofit measures (Peeters et al., 2009). The study aims to establish a comprehensive understanding of current energy-efficient retrofit measures and their implications for building performance. This review covers a diverse range of sources, including research articles and technical reports, to identify best practices and key considerations.

These findings were then integrated into the design of the simulation scenarios to ensure that the retrofit measures considered in this study were current and relevant to the field. Additionally, qualitative research has enhanced quantitative modelling and simulation, leading to a more comprehensive approach to energy-efficient building retrofitting.

The quantitative aspect of this research involves the use of a building energy modelling approach to simulate and evaluate a building's energy efficiency, relying on mathematical and computational methods. Based on numerical data, this approach quantifies various parameters related to the energy consumption, cost benefits, and environmental impacts of various energy retrofit measures of archetype building models in three Saudi Arabian cities: Riyadh, Jeddah, and Dhahran. The results obtained from quantitative energy modelling, typically presented in the form of numerical data, graphs, charts, and statistical analyses, have practical implications for the design and retrofitting of energy-efficient buildings in these cities.

The methodology chapter describes designing low-energy buildings in a series of steps. This structured approach ensures that each phase effectively enhances the building's energy efficiency. Table 4.1 outlines these steps, offering summaries of each phase during the design process to show how they advance the energy efficiency objectives.

Table 4. 1Research methodology breakdown: Phases, Descriptions, and Significance.

Phase	Description	Significance
1. Contextual Analysis	Examine the specific geographical, and climatic context of Saudi Arabia.	Assess the site conditions, including climate, and other environmental factors that could impact the building's energy performance.
2. Goal Definition	Define clear objectives and targets for energy conservation, based on existing standards and research goals.	Provides a clear path for the research, ensuring focused and purpose-driven methodologies.
3. Baseline Model Establishment	Establish a baseline model representing typical residential buildings in Saudi. This model incorporates architectural elements, construction practices, and commonly used energy systems, providing a representative foundation for assessing retrofitting strategies.	Offers a reference point to measure and evaluate the impacts of various EEMs.
4. Identification of EEMs	Thoroughly describe potential Energy Efficiency Measures, considering both their technical specifications and their relevance to the Saudi context.	a comprehensive list of interventions for detailed assessment.
5. Preliminary Simulation	Utilize advanced simulation tools to analyse the energy performance of the baseline model, creating a baseline dataset that captures current consumption patterns.	Provides a baseline dataset against which the effects of EEMs can be measured.
6. EEM Impact Assessment	Implement each EEM in the model and evaluate its individual and collective impacts on energy consumption.	Allows to identify any areas for improvement and ensure ongoing energy efficiency.
7. Optimal EEM Combination	Determine the combination of EEMs that provides the highest energy savings that maximize energy savings by conducting simulations.	An optimized model that has high energy efficiency.
8. Cost Analysis	Conduct a detailed economic evaluation of the proposed EEMs, weighing the initial investment against potential energy savings over time.	Ensures the proposed interventions are energy-efficient and investigates their cost-effectiveness.
9. Recommendations & Future Directions	Offer recommendations for stakeholders and outline potential possibilities for subsequent research.	Enables the real-world application of findings and highlights areas for further exploration.

In the first phase of the research, a base case model of a building was developed using IES-VE simulation software. This model was created by considering the architectural plans, technical specifications, and operational profiles of the building. After developing the base-case model, the validation process involved using actual energy consumption data from the building. This validation step ensures that the simulation model accurately represents the actual building and its performance. The following research phase involved simulating various retrofit scenarios using the validated base-case model. These scenarios, which are significant, included implementing different energy-efficiency measures (EEMs), such as insulation, glazing, HVAC system improvements, shading devices, and photovoltaic systems. The building's energy performance was assessed by evaluating the impact of each strategy. In this study, the quantitative energy model was used to evaluate the building envelope's energy performance through a sensitivity analysis.

The data from these simulations were carefully analysed to evaluate the impact of each Energy Efficiency Measure (EEM) and to identify the most effective combinations of EEMs. This led to the implementation of a comprehensive strategy, demonstrating how modifying the building envelope and other key elements can significantly lower energy consumption. The study aims to provide valuable insights into the degree of compliance and potential areas for further improvement of the minimum requirements (SBC-602). This approach seeks not only to meet but also to exceed SBC standards, providing insights that could inform future strategies for improving energy efficiency and sustainability in line with Saudi Arabia's Vision 2030 goals.

The final part of the analysis involves a cost analysis of the most effective strategies, a calculation of the payback period, and a cost-benefit analysis. Through systematic variation of parameters and analysis of the consequent energy consumption patterns, this study seeks to identify the most effective retrofit strategies. While the emphasis remains on energy savings, the research also provides a cost-benefit analysis to outline the proposed strategy's financial aspects clearly. This approach, ranging from energy modelling to sensitivity analysis, provides a comprehensive overview of the research process. The findings of this research significantly enhance the understanding of sustainable building practices by offering practical recommendations for energy-efficient retrofitting, considering financial feasibility and compliance with regulatory frameworks. Figure 4. 1 represents the flow chart of the research methodology.

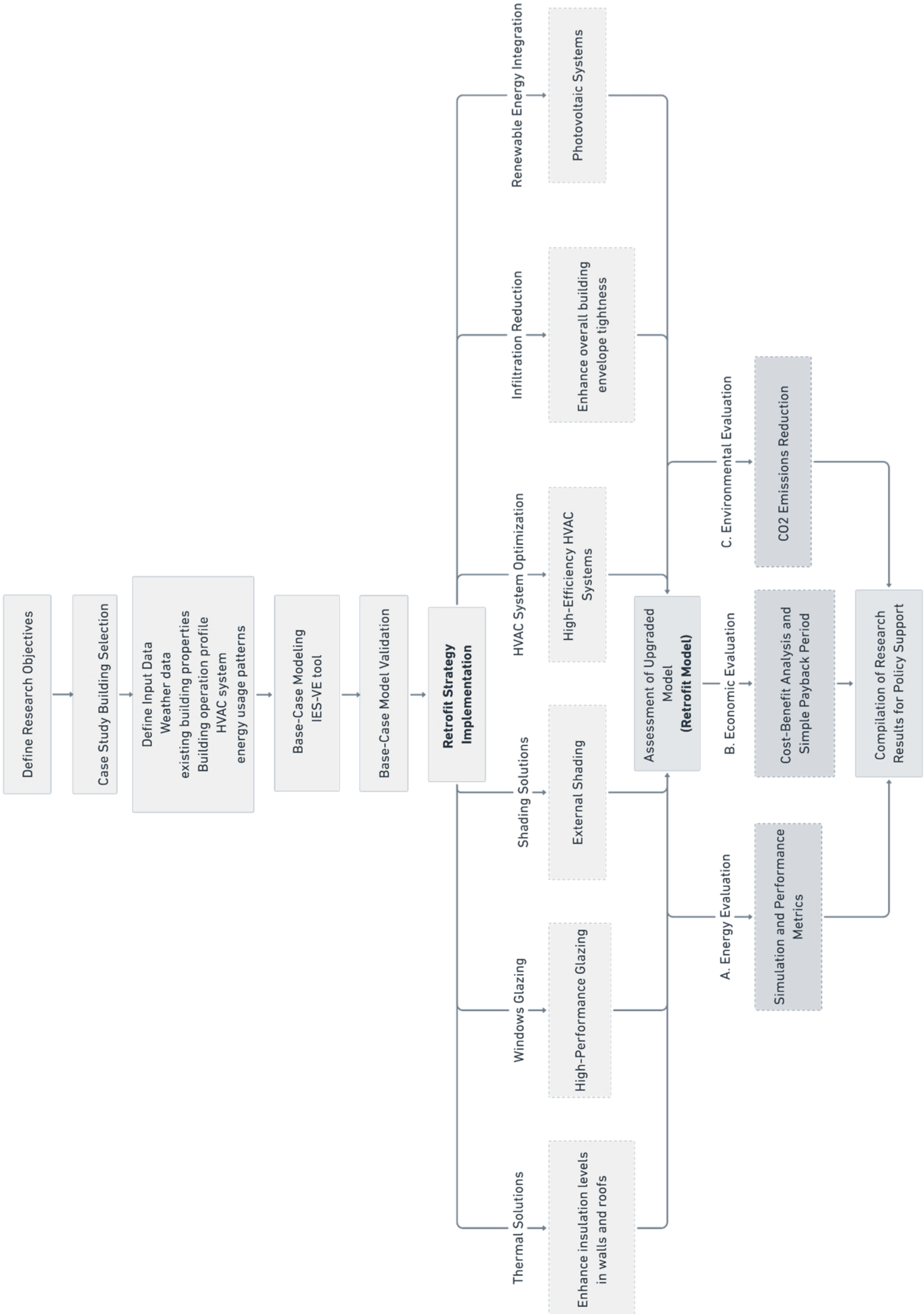


Figure 4. 1 Methodology flowchart

4.3. Energy System Modelling Software

This section explores the selection and utilization of simulation software for energy system modelling and performance evaluation It provides an overview of the chosen software, highlighting its capabilities in simulating building energy performance, analyzing retrofit measures, and integrating renewable energy systems. Several energy software tools, such as EnergyPlus, TRNYS, IES-VE, and DesignBuilders, have adopted diverse approaches to analyse energy efficiency. Comparative reviews of the BPS tools are presented in Section 3.8 above. These are not just performance tools but highly developed ones that can provide extensive information on thermal, energy, and other environmental parameters (Crawley et al., 2008). According to Ibrahim and Zain Ahmed (2006) acknowledged the continuous development and improvement of building energy simulation tools over the past few decades.

Among these tools, Integrated Environmental Solutions Virtual Environment (IES-VE) was selected for this study due to several key factors that align with the research objectives. While EnergyPlus and TRNSYS offer powerful simulation capabilities and detailed control over building energy simulations, IES-VE stands out for its user-friendly graphical interface and ease of use, which are particularly advantageous when analyzing complex retrofit measures. EnergyPlus, though highly flexible and detailed, requires significant programming knowledge, which can increase the complexity and time required in the modeling process. In contrast, IES-VE simplifies complex thermal and environmental calculations, making it more accessible for detailed building performance analysis without extensive programming requirements.

Furthermore, IES-VE offers a comprehensive library of building components and systems, facilitating the evaluation of multiple retrofit option. The software supports energy performance modeling under various scenarios, enabling assessments of building energy efficiency and compliance with carbon emission standards. This comprehensive functionality, combined with seamless integration for renewable energy simulations and HVAC system analysis, makes IES-VE particularly suitable for evaluating Saudi Arabia's retrofit strategies under existing environmental regulations.

The energy modeling software Integrated Environmental Solutions Virtual Environment (IES-VE) was used to simulate the energy performance of the chosen archetypical model. With its robust tools, IES-VE enables a variety of environmental evaluations, producing detailed thermal and energy data outputs. The theoretical foundation of IES-VE lies in dynamic thermal simulation, which enables the detailed analysis of a building's energy use by simulating interactions between various building components. This approach provides insights into how building envelope modifications, insulation, glazing upgrades, and HVAC retrofits affect overall building performance.

IES-VE is a widely used software tool for building energy consumption analysis, favored by architects and engineers due to its user-friendly graphical interface (Attia et al., 2009). This program has been extensively validated and is known for its accuracy and reliability. Its effectiveness in building performance research, especially for retrofit projects, has been demonstrated in numerous studies (Shameri et al., 2013b; Altan and Ozarisoy, 2022; Chen et al., 2022; Kutty et al., 2023). Fundamentally, IES-VE can evaluate energy efficiency and carbon emission compliance of building designs, making it valuable for evaluating and visualizing technical information related to Saudi Arabia's sustainability goals and retrofit strategies.

The building is divided into thermal zones, each with specific occupancy and load settings. IES-VE then performs dynamic thermal simulations over time, calculating heat transfer through conduction, convection, and radiation. These simulations capture seasonal variations, allowing the software to estimate energy consumption, system efficiency, and HVAC performance across thermal zones. Finally, IES-VE provides detailed reports on energy use, temperature, and carbon emissions, helping assess how different retrofits improve energy efficiency and indoor comfort.

IES-VE is based on principles of building physics and thermodynamics to model energy flows accurately. The software divides the building into thermal zones, each with unique occupancy and load characteristics, and performs dynamic thermal simulations to calculate heat transfer through conduction, convection, and radiation. Climate data is incorporated to simulate the effects of external environmental conditions on internal energy performance, a critical feature for accurately modeling buildings in Saudi Arabia, where extreme climate conditions, such as high temperatures and intense solar radiation, substantially impact energy demand.

IES-VE is built upon fundamental principles of building physics and thermodynamics to accurately model energy flows within buildings. The software divides the building into thermal zones, each with specific occupancy and load settings. IES-VE then performs dynamic thermal simulations over time, calculating heat transfer through conduction, convection, and radiation. It incorporates climate data to simulate the effects of external environmental conditions on internal energy performance—a feature that is critical for accurately modeling buildings in Saudi Arabia, where extreme climate conditions, such as high temperatures and intense solar radiation, substantially impact energy demand.

Despite its advantages, IES-VE has several limitations that must be acknowledged. First, while its user-friendly interface makes setting up models easier, it is less flexible than open-source tools like EnergyPlus, which allow for more customization. Users of IES-VE are restricted to the software's built-in parameters and components, which can be limiting for specialized or unique building systems. Additionally, as a commercial software package, IES-VE includes licensing fees that may limit its accessibility for some users, particularly in academic settings.

In conclusion, the selection of IES-VE for this study aligns well with the research objectives. The need to evaluate energy retrofitting measures in Saudi Arabia's residential sector involves assessing both technical efficiency and compliance with local energy regulations, and IES-VE's robust simulation environment supports these goals effectively. Its capacity for integrating various retrofit strategies, such as envelope modifications, HVAC improvements, and renewable energy integration while providing accurate energy performance visualizations makes it a suitable tool for this research. IES-VE also enables effective communication of complex thermal analysis through visual outputs, allowing decision-makers to easily interpret the benefits of proposed retrofits. This feature aligns well with the goal of informing policy and regulatory frameworks for retrofitting, ultimately supporting Saudi Vision 2030's sustainability targets. In this response, this study focuses on the energy analysis features of IES software, as described in Table 4.2.

Table 4. 2 IES-VE software features.

Feature	Function
Model it	Building Geometry Creation: the software allows users to create 3D building models with accurate geometry, including walls, floors, roofs, windows, doors, and other architectural elements.
Building Template Manager	Building materials, construction components, and thermal properties library
Apache	Energy Consumption Analysis: detailed energy consumption analysis by considering factors such as lighting, heating, cooling, ventilation, and equipment usage. Users can input occupancy schedules, lighting controls, and appliance loads to simulate actual energy usage patterns and assess the building's overall energy performance.
Sun cast	assessing solar radiation, shading, and daylighting aspects of building design. This analysis helps identify areas of the building that receive the most solar exposure, allowing for optimized design decisions regarding shading devices, solar panel placement, and glazing properties.
Weather Data	The software incorporates climate data from various sources to accurately model the local climate conditions. Users can input specific weather data or choose from a library of weather files corresponding to different locations worldwide.

4.4. Importance of Sensitivity Analysis

Building design and engineering experts place significant emphasis on enhancing building energy efficiency, including implementing solutions such as more efficient heating and cooling systems, improved insulation, and using renewable energy sources. Integrating sensitivity analysis techniques into building energy simulation software allows for the identification of design variables that significantly impact energy usage. The observed variables were manually assigned to the simulation software. By utilising related element tools, it is possible to effectively manage the parametric tool, aiding in the accurate selection of variables and outputs related to the study. Through thermal simulations, this tool was used to simulate various design scenarios. Apache simulations were run to simulate changes in each parameter combination. The simulation results were then analysed to identify the most efficient approach to achieving the desired outcome.

This research involves performing a sensitivity analysis to identify the parameters with the most significant impact on energy performance. One method for building energy modelling is integrating sensitivity analysis techniques into the building energy simulation software. This approach efficiently identifies design variables that have the most significant impact on energy usage (Sanchez et al., 2014; Tian, 2013). In recent decades, computer simulation software has become a viable method for managing complex technical systems. The integration of suitable sensitivity techniques with building energy modelling software presents a practical and valuable approach for promptly assigning design parameters according to their significance in energy usage (Nguyen and Reiter, 2015). Local sensitivity analysis, also called differential sensitivity analysis, is a one-factor-at-a-time (OFAT) method that is often used in building performance analysis as a sensitivity analysis (Tian, 2013). The one-factor-at-a-time (OFAT) method is effective for determining how different input variables or parameters affect a building's overall energy performance. This method involves adjusting one design variable at a time, such as thermal insulation and efficient glazing systems, while keeping all other parameters constant at their initial values. The sensitivity analysis approach employed provides significant insights into the influence of individual input variables or parameters on the overall energy performance, thereby maintaining the initial settings for all other parameters. This approach, therefore, offers considerable understanding of the influence of individual input variables or parameters on the overall energy performance of a building, making it a well-proven method suitable for a wide range of applications (Heiselberg et al., 2009; Saltelli et al., 2010; Sanchez et al., 2014).

4.5. Base Case Energy Modelling

Base case modelling involves creating a representative model of an archetypical building before implementing retrofitting measures. Once the base case model is established and validated, it serves as a reference for evaluating the impact of different retrofit scenarios on energy consumption and overall building performance. This process includes selecting weather data, building envelope property data, building operation profile, power density of internal gains, lighting and equipment, occupant heat gain, HVAC system configuration, and infiltration rate. By comparing the simulation results of the retrofit scenarios to the base-case, it becomes possible to identify the most effective strategies for achieving energy efficiency and sustainability objectives.

First, the base case model was developed using Model IT in IES-VE, and building parameters were assigned to reflect typical features of the Kingdom's existing housing stock. The model accounts for the features of the Kingdom's existing housing stock using 54 prototypes, defined by three building types (Aldubyan et al., 2021; Krarti et al., 2020). For this study, a medium-sized, single-detached, two-story villa was selected to represent the baseline energy consumption of Saudi residential building.

The base-case energy model is based on recent data sources that have been reviewed by multiple researchers and represents an archetypical villa model (Krarti et al., 2020; Alaidroos and Krarti, 2015b; Aldossary et al., 2014b). The characteristics of the model are defined using data collected in 2018 by the General Authority for Statistics (GAStat) on housing units across different regions of Saudi Arabia, as well as from reported energy audit studies (GAStat, 2018a). This model represents a typical villa by integrating common features such as standardized construction practices, materials, and energy systems found across Saudi Arabia in older buildings that do not comply with recent regulations. Although regional variations exist, the selected prototype reflects baseline characteristics widely shared among these older villas, making it suitable for assessing general energy performance and retrofitting needs across the country's residential sector.

The baseline is in the three most populated regions of the KSA, Riyadh, Dhahran, and Jeddah, owing to their geographic diversity, climate variations, population, and regional importance, as discussed in Section 3.2. The surrounding terrain within the model was determined to be a city in all regions. The villa archetype is designed for a medium-sized family of six members, which is the average Saudi family size. It consists of a central living room, three bedrooms, bathrooms, and a kitchen with a height of 7 m^2 and a flooring area of 525 m^2. The kitchen, guest room, dining room, living room, and hallway are on the first level. The second floor has mainly three bedrooms and an upper-level hallway. Archetypal floor plans are shown in Figure 4.2 (Ahmad, 2004).

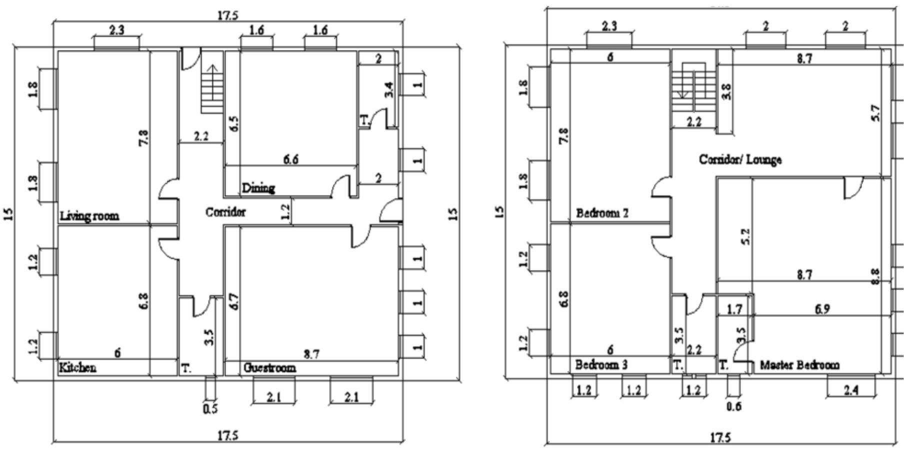


Figure 4. 2 The layout of the archetypical villa: (a) ground floor and (b) first floor.

4.6. Input Data and Preprocessing; Define Baseline Model

Establishing the input data for the baseline is crucial for laying the groundwork for simulation analysis. This includes defining the building characteristics, location, weather data, construction details, occupancy patterns, equipment loads, and other energy-related elements. This section details the necessary data used for energy simulation and analysis. Ensuring consistency, accuracy, and compatibility with the simulation program is imperative. In this phase, input data is essential for the simulation model to accurately predict energy usage.

4.6.1. Weather Data

Accurate weather data is essential for realistic building-energy simulations. Weather data were collected from reliable sources and represented the typical climatic conditions at the building's location. When analysing buildings' energy efficiency and thermal performance, it is essential to use accurate and representative weather files. These are the bases for simulating how the built environment and climate interact, allowing for the estimation of energy consumption. Therefore, selecting appropriate weather files is crucial for ensuring the reliability and validity of building energy simulations.

For this study, weather data was sourced from EnergyPlus Weather Data Sets (EPW) provided by the U.S. Department of Energy (DOE). These files, frequently used in building energy modeling, are typically based on a Typical Meteorological Year (TMY), which compiles representative data from multiple years to reflect typical weather patterns for a specific location. This approach enhances modeling accuracy by providing realistic climatic conditions (Wang et al., 2021). The DOE collects, analyzes, and verifies the quality of weather data from numerous meteorological stations to provide complete weather files, known as EnergyPlus Weather (EPW) files (Candanedo et al., 2013). These files include hourly weather data such as temperature, humidity, wind speed, and solar radiation values, averaged over a minimum of 10 years. For this study, the weather data used is based on historical records from the past 20 -30 years, ensuring the model reflects typical regional climate patterns and improving simulation reliability.

EPW files are compatible with a range of building energy simulation tools, including IES-VE, which supports EPW files as acceptable weather data sources. This compatibility allows for consistent and accurate energy performance evaluations across different locations. By using these weather files, the study examines how climate impacts energy consumption, identifying opportunities for improving energy efficiency.

One limitation of using Typical Meteorological Year (TMY) data in EPW files is the lack of urban microclimate considerations, especially the Urban Heat Island (UHI) effect (Pyrgou et al., 2017). TMY data is typically collected from stations in less densely populated areas, such as airports, and may not fully capture the unique conditions of urban environments. Urban areas experience distinct microclimates due to factors like dense building layouts and high population density, which increase temperatures, particularly during summer, as buildings absorb and retain heat.

Location selection for the case study:

Weather data in Saudi Arabia show a wide range of climates, from hot and dry in the centre to milder along the coasts in the west and east. In this study, Riyadh, Jeddah, and Dhahran were chosen as the primary locations for several reasons, including climate variation, urban development, and the representativeness of different regions in Saudi Arabia. According to Saudi Building Energy Conservation Code 602, the selected cities are in climate zone 1 (SBC, 2018).

Riyadh, the capital city, represents the central region of Saudi Arabia and is characterized by hot and arid climatic conditions with high temperatures and low humidity (Aldossary et al., 2014c). In Riyadh, the average temperature ranges from 15°C to 37°C, with the highest temperatures occurring during summer (Al-Ghamdi and Moore, 2014). In contrast, Jeddah is located on the western coast and experiences a hot and humid climate with daily maximum temperatures typically exceeding 35°C during the hot season. July is the hottest month, with average temperatures of 38°C and 30°C (Hegazy and Qurnfulah, 2020; Alghamdi et al., 2014). In the Eastern Province, Dhahran has a hot-humid climate with high temperatures over 45°C in summer and mild winters. This data captures critical parameters that directly influence building energy performance, such as the dry bulb temperature, wet bulb temperature, and global radiation levels. Figure 4.3 illustrates climatic parameters for the three cities under study. The dry bulb temperature serves as an indicator of the ambient air temperature, while the wet bulb temperature offers a perspective on the air's relative humidity and cooling potential. Additionally, the global radiation levels depicted in the figure highlight the prospects for employing solar energy, an essential factor when considering incorporating renewable energy solutions in buildings. Further climate diagrams from the Meteoblue Climate Database were created using a 30-year hourly weather model (Meteoblue, 2022). Detailed climate information is provided in Appendix A, Table A.1.

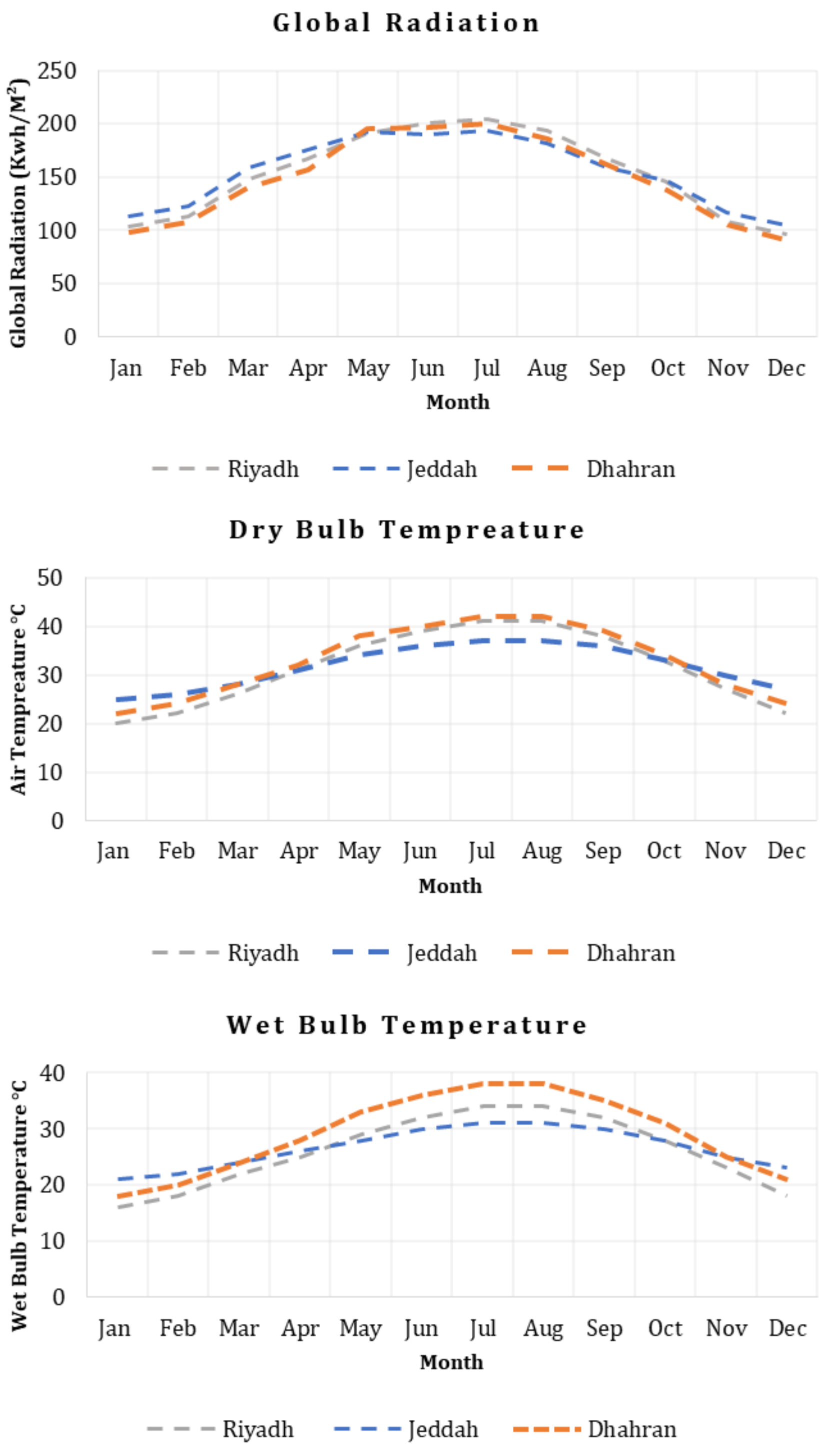


Figure 4. 3 Climatic Parameters: Dry Bulb Temperature, Wet Bulb Temperature, and Global Radiation Levels for Jeddah, Riyadh, and Dhahran

This study included three cities with common climatic conditions across different parts of Saudi Arabia to ensure an analysis of the energy performance of residential buildings in diverse climates. Each city's annual cooling and heating degree days were calculated to represent the total cooling required based on outdoor temperatures. The equation provided below was used, and each city's meteorological database, containing up to ten years of historical weather data, was used to determine the CDD values.

Cooling Degree Days (CDD):

$$CDD = \sum_{i=1}^{n} (Tavg,i - Tbase) \quad \text{(Equation 4. 1)}$$

$$HDD = \sum_{i=1}^{n} (Tbase - Tavg,i) \quad \text{(Equation 4. 2)}$$

Where:

- n is the number of days.
- Tbase is the heating/cooling base temperature (usually 18.3°C).
- Tavg,i is the daily average outdoor temperature for day i.

Cooling degree days (CDD) indicate the amount of energy required to cool. Riyadh experiences high CDD levels every year, reflecting hot summer conditions. Jeddah has the highest CDD among the three cities, driven by a hot and humid climate. In contrast, the heating degree days (HDD) are relatively low in all the cities. This degree-day analysis highlights the cooling-dominated energy use across Saudi Arabia owing to the prevalent hot climate. See Figure 4. 4 CDD/HDD in the three regions of study.

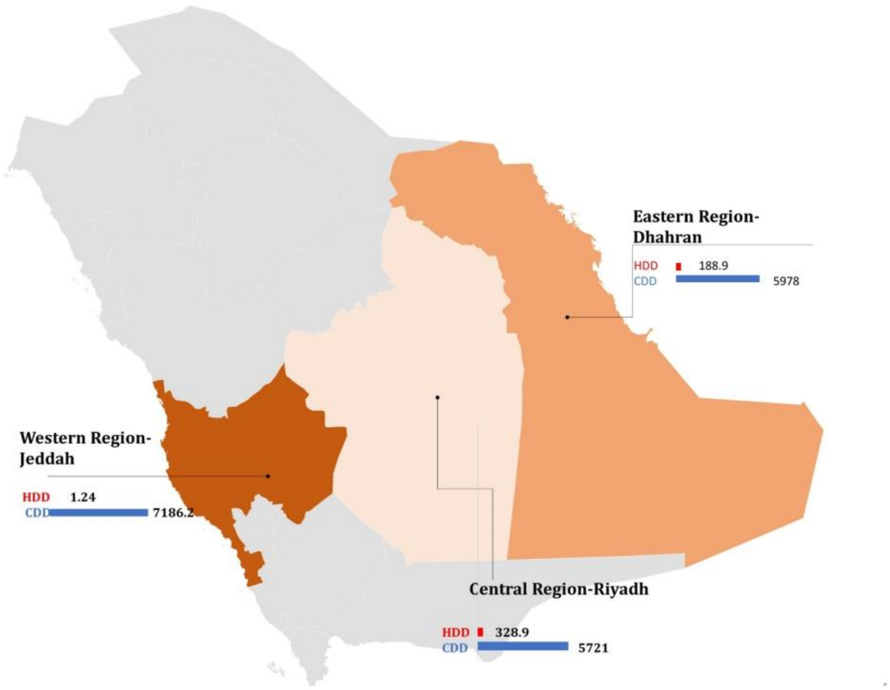


Figure 4. 4 CDD/HDD in the selected study cities. Source: Author's Calculation, (EPW files, meteorological databases).

Additionally, the choice of these cities was affected by their urban growth and population density. Riyadh, the largest city in Saudi Arabia, is a highly urbanized and densely populated area that serves as the country's administrative and economic hub. Jeddah is distinguished by its thriving economic and tourism sectors, consisting of urban and neighbouring regions. Meanwhile, Dhahran is characterized by its association with a major oil company and related infrastructure. Urban development in these cities directly affects energy consumption and building characteristics. As urban areas continue to expand, the demand for energy in residential buildings increases, driven by population growth, increased household size, and changing lifestyles. By studying these cities, this study can assess the energy performance of buildings in different stages of urban development and explore the potential for energy-efficient interventions in existing and new construction. These cities represent critical economic factors that make energy performance and efficiency crucial to the broader context of sustainable development in Saudi Arabia.

In conclusion, the selection of Riyadh, Jeddah, and Dhahran as study locations is based on climatic variation, population density, and the representation of different regions in Saudi Arabia. This selection enables a comprehensive analysis of energy performance and thermal characteristics, considering the diverse challenges faced by residential buildings across various climatic and urban contexts. Including major cities in three distinct climate zones will allow for an examination of how building envelope systems perform under hot, arid, and hot coastal conditions. By conducting research in various locations, the study can identify any factors unique to these areas that may affect the amount of energy used in residential spaces. This supports the assessment of efficiency opportunities in the building sector of Saudi Arabia.

4.6.2. Energy Model's Elements Specifications

A building envelope consists of all the elements that separate the indoor and outdoor environments, including walls, roofs, windows, doors, and floors. Property data on the building envelope includes characteristics such as the materials used, insulation levels, thermal conductivity, and other relevant properties. These data help understand how heat transfer occurs through the building envelope and affects energy consumption. As outlined in Section 4.5, the baseline energy model is based on a typical villa design in Saudi Arabia. The model's features are determined using data from KSA housing units collected in 2018 by the General Authority for Statistics (GAStat), as well as insights from energy audit studies (GAStat, 2018a; Krarti et al., 2020).

In Saudi Arabia, residential building roofs are typically flat and constructed with reinforced concrete frames and slabs. Residential buildings commonly use concrete blocks as the primary construction material for exterior walls due to their durability and thermal insulation properties. Many buildings in Saudi Arabia feature external cladding for aesthetic and functional purposes. Common cladding materials include stones and external plasters, which can enhance the appearance of buildings. The construction materials utilized in the selected archetypical baseline building, with U-values obtained through IES-VE, were considered equivalent to non-insulated construction, as outlined in Table 4.3.

Table 4. 3 The characteristics of the archetypical baseline (villas) in the KSA.

Building Elements & Construction Parameters	**Description**
No. of Stories	2
Building height	7 m
Total floor area	525 m^2
Window-to-Wall Ratio (WWR)	13%
No. of Occupants	6
Shading devices	No external shading devices
HVAC system	Split DX is a Typical mini-split system which is the most desirable type in a Villa.
Energy-efficiency (EER)	Low EER /COP 2.3
Cooling set point	23 °C
Infiltration rate	0.8 Air change per hour (assumed) (Krarti et al., 2020)
Lighting power density	4 W/m^2
Equipment power density	3.5 W/m^2
Air relative humidity	Min 30%, Max 60% based on ASHRAE, 2009 and complies with SBC-602 (Alaidroos and Krarti, 2015a)
Flowrate	The minimum flow rate for a mini-split system is 8 1/s per person (Manufacturer).

Parameters	**Description**	**U Values (W/m^2K)**	
	Base case	**BC (IES-VE)**	**SBC (Zone 1)**
External wall	20 mm plaster outside + 200 mm L.W hollow concrete block + 20 mm plaster	1.9	0.34
Roof	10 mm built-up roofing 200 mm concrete roof slab13 mm plaster inside	2.4	0.20
Glazing	Single glazed window	5.7 (SHGC) 0.52	2.67 (SHG) 0.25

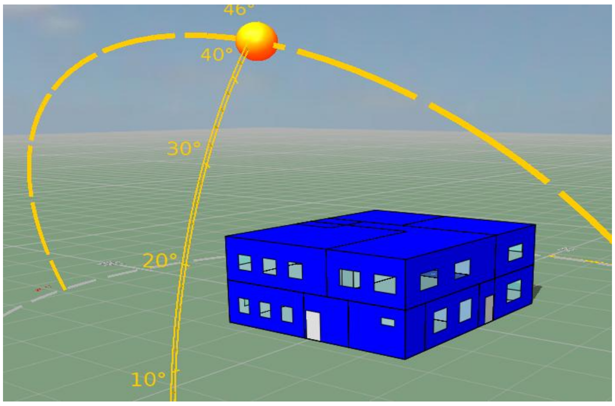


Figure 4. 5 3D Model. Prototypical villa axonometric view (IES-VE).

Building structures, ranging in age from 10 to 20 years, must adhere to the Saudi Building Code (SBC) despite being constructed before the code was implemented. As previously mentioned, all building features failed to meet SBC minimal standards because the base-case model was uninsulated, and the windows were single-glazed, which is very common in residential construction. Based on a survey conducted by Al-Saadi (2006), the primary construction material used for walls in Saudi Arabia is concrete, with 83% of buildings utilizing uninsulated hollow concrete blocks. Therefore, envelope parameters were examined after defining the acceptable retrofit options. The selected studies for this analysis were located in climate zone 1, as defined by the Saudi building code. Although the building code does not mandate specific materials or insulation thicknesses, it outlines the minimum required U-values for exterior walls and roofs according to the climate and location, as outlined in Table 4. 4. Accordingly, the optimal envelope thermal insulation layers were investigated for baseline.

The U-values specified in the Saudi Building Code are generally higher than those in the CIBSE Guide and UK standards, reflecting a regional adaptation to Saudi Arabia's hot and arid climate. While the UK's standards aim for lower U-values to enhance insulation against cold, Saudi regulations are adjusted to balance insulation needs against cooling requirements in its hot and arid climate with intense solar radiation. In Saudi Arabia, the primary concern in building design is to prevent excessive heat gain from the hot exterior, which would increase the demand for air conditioning and cooling. The focus is more on shading and reflecting solar radiation away from buildings. While insulation is essential the emphasis is on keeping the interior cool, which is a different approach than in colder climates.

Table 4. 4 The Saudi Building Code requirements for building envelopes (Saudi Building Code, 2018).

Saudi building code requirements for the building envelope (SBC-602)				
Climate Zone	**U-value (W/m²K)**			
	Wall	Roof	Glazing	Door
Zone 1 Riyadh, Makkah, Madinah, Najran, Jazan, Bisha, Eastern region	0.34	0.20	2.66	2.83
Zone 2 Gassim, Hail, Tabuk, Al-Jouf, Assir, Al-Taif, Al-Baha, Northern area	0.39	0.23	2.66	2.83
Zone 3 Abha, Khamis Moshet, Guriat, Tarif	0.45	0.27	2.66	2.83

4.6.3. Building operation profile

A building's operation profile refers to its schedule and energy use patterns. This includes occupancy patterns, lighting schedules, equipment usage, and other factors that influence energy consumption on a daily and weekly basis. The internal heat gain from occupants, lighting, and appliances significantly affects the overall heat load and, consequently, the energy consumption of a building. Therefore, it is critical to define the residents' activities and schedules, as well as the lighting and equipment operation profiles, for an accurate simulation model. Building occupants' occupancy patterns and behaviors are essential factors that contribute to energy use. The profiles for people, lighting, and equipment were considered to capture the operational parameters and schedules of the selected case, accounting for variations in usage on weekdays and weekends. Based on the available data on building occupancy, it was determined that, on average, the case building accommodated six occupants. Occupancy behaviour directly affects energy consumption by influencing the operation of building systems (Picard et al., 2020; Yan et al., 2015).

The operation profiles for lighting, occupancy, and equipment heat gain are critical factors that affect energy consumption in buildings. These profiles represent the timing and duration of the system's operation and were adopted in this study to reflect the typical conditions found in residential buildings. The frequency of occupancy, lighting, and equipment profiles for weekdays and weekends was established based on previous studies conducted on residential buildings (Alaidroos and Krarti, 2015b; Krarti et al., 2020).Therefore, the operation profiles were assigned to align with the original building's profiles, as illustrated in Figure 4. 6.

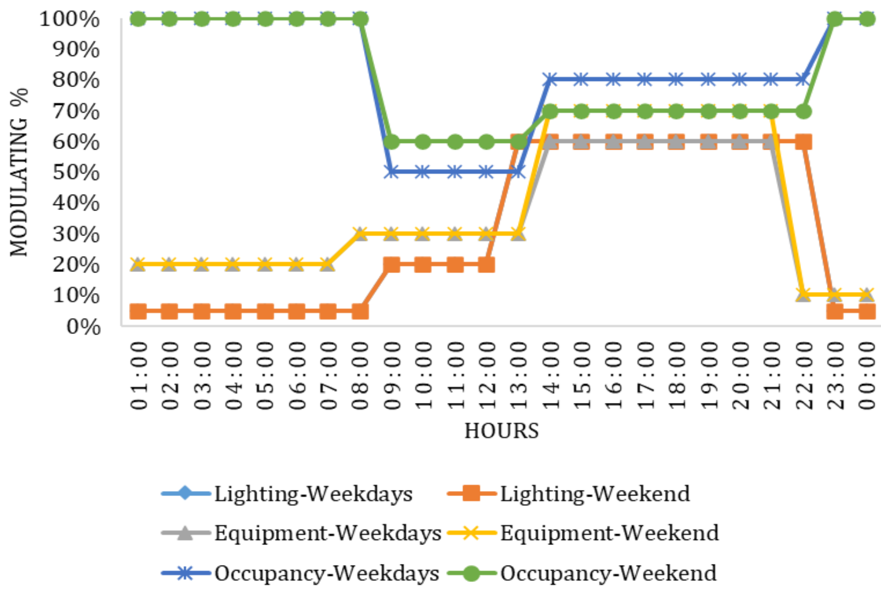


Figure 4. 6 Scheduling of selected cases (lighting, equipment, and occupancy).

4.6.4. Power Density of the base case model (Heating gains, Lighting, and Equipment)

Power density is an important factor in energy modelling for accurately estimating and forecasting building energy use. The power density is the amount of energy utilized per unit area, generally given in watts per square meter (W/ m^2). It offers valuable insights into the distribution and intensity of the energy-consuming components within a building. This includes the power density of the internal gains (e.g., heat generated by occupants, lighting, and equipment). These data help estimate the internal heat load and its contribution to energy consumption. The heat produced by different internal sources, such as people and appliances, is referred to as internal gain. Equipment power density refers to the power used by various building equipment, whereas lighting power density refers to the electrical power used by the lighting systems.

Certain assumptions were established in this study to assist in analysing and modelling internal gains, lighting, and equipment. The values of equipment power density vary among researchers, ranging from 9 to 3.5 W/m^2. Lighting heat gain is the amount of heat transmitted into space by lighting applications. These procedures were occasionally performed differently in previous studies. In a recent study, the lighting power density was 4 W/m^2 (Krarti et al., 2020).

Therefore, the heat gain data used in this study are based on a recent study of Saudi housing energy modelling, which represents typical values observed in the Saudi housing stock (Krarti et al., 2020; Alaidroos and Krarti, 2015b). Due to the limitations and difficulties in obtaining data for individual buildings, power density assumptions have become necessary. Since the referenced study focuses on Saudi Arabia, using the same power density assumptions ensures that the research remains contextually relevant. The referenced study established a baseline understanding of the energy consumption patterns and retrofit potential of residential buildings in Saudi Arabia. By using the same power density assumptions, this research builds on the existing knowledge and investigates further aspects within the established framework. This approach allows for a consistent comparison and enhances the analysis. This allows for deeper analysis and evaluation of different scenarios, providing valuable insights for energy policymaking and decision-making processes. Accordingly, the power density values used in this study were 4 W/m^2 for lighting and 3.5 W/m^2 for equipment.

4.6.5. Occupants' heat gain

The heat generated by building occupants is essential in building energy simulations because it significantly affects overall energy consumption. The heat gain depends on the number of occupants, their activities, and the duration of occupancy. Accurate data on the heat gain of the occupants is essential for realistic energy performance predictions.

ASHRAE, the American Society of heating, refrigeration, and air conditioning, provides comprehensive guidelines and standards for estimating occupant heat gain based on various activities and space types. These guidelines consider factors such as activity level, clothing insulation, metabolic rate, and environmental conditions to determine the specific values of occupant heat gain. The ASHRAE standards address both sensible heat (measured in watts) and latent heat, which represents the total heat gain from occupants. These standards serve as valuable references for assessing thermal loads associated with occupants in different settings, including residential spaces. The ASHRAE Handbook of Fundamentals (2009), an approved source of the national building code for Saudi Arabia, provided the sensible heat gain values for different room types in this study, as shown in Table 4.5 (ASHRAE, 2009). Occupancy within a building can have a significant impact on the overall thermal energy balance, particularly in terms of how much latent heat gain. This latent heat gain arises from the metabolic processes and moisture production of the building's occupants, which can contribute substantially to the cooling load required to maintain thermal comfort (Sajjad et al., 2020). The average latent heat gain per person in a residential setting, based on ASHRAE guidelines, is typically around 60–65 watts. This value reflects moderate residential activities. By adhering to ASHRAE standards, the energy model incorporates realistic occupant heat gains, providing a solid basis for evaluating and optimizing the energy performance of residential buildings in Saudi Arabia.

Table 4. 5 Sensible Heat Gain (W/person)

Room Type	**Sensible Heat Gain (W/person)**
Bedroom	40
Living Room	65
Kitchen	80
Multipurpose Room	70

4.6.6. HVAC System

The heating, ventilation, and air conditioning (HVAC) system configuration includes information on the type of HVAC system installed in the building and its capacity, efficiency, and control strategies. The HVAC system significantly affects energy consumption and indoor comfort.

According to the housing survey data in 2018, the number of AC units in residential buildings varies across housing types in most Saudi provinces (GAStat, 2018b). Villas were observed to have an average of seven AC units, indicating a higher demand for cooling due to their larger size and increased thermal load. However, traditional houses typically have four AC units, while apartments have three units on average (GAStat, 2018b). The variations in the number of AC units reflect different requirements for maintaining occupant comfort and indoor temperatures in various types of housing. The survey data emphasized the importance of having enough AC units to meet household cooling needs. On average, five AC units per household were necessary to achieve and maintain a comfortable indoor environment. This suggests that larger residential spaces require additional units for adequate cooling. In Saudi Arabia, split AC systems have become standard HVAC systems in residential buildings due to their affordability, availability, and ease of installation. However, it is widely recognized that split AC systems generally have lower energy efficiency ratios compared to more advanced and energy-efficient systems. For this study, the split AC units selected for the base model represented the majority of residential buildings in Saudi Arabia. Thus, the base model assumes the use of split units with low-star efficiency labels based on the SASO efficiency rating (SASO, 2021).

For the simulation analysis, a cooling set point of 23°C was chosen as the reference temperature for the base-case model. This aligns with other recent studies that also used 23°C as the baseline set point for their simulation analysis (Krarti et al., 2020). Consequently, an investigation was conducted to assess the impact of adjusting the set-point temperature on annual energy consumption, and simulations were conducted to determine the effect of increasing the Energy Efficiency Ratio (EER) of the HVAC system on the building's energy consumption and cooling load. In Saudi Arabia, the Coefficient of Performance (COP) of air conditioning (AC) systems varies widely, depending on the type of cooling unit, its age, and Energy efficiency ratio (EER). Generally, newer AC models in the Saudi market have higher COP values due to improvements in technology and energy efficiency regulations, as detailed in Section 5.3.5 below.

However, it's common to find less efficient AC systems in older buildings, primarily because these buildings were either constructed before the implementation of Building energy standards or because cost considerations led to the installation of cheaper, less efficient units. Using the split AC system allows for an accurate representation of the existing building stock. It establishes a foundation for evaluating and quantifying the energy savings and improvements attained through retrofit scenarios involving more energy-efficient HVAC systems. The objective is to compare the energy performance of the base case model, which represents the current state of residential buildings, with retrofit scenarios that involve more energy-efficient HVAC systems. This comparative analysis provides valuable insights into the potential energy savings and benefits of retrofit programs that enhance HVAC systems in Saudi Arabian dwellings.

4.6.7. Infiltration rate

Infiltration refers to unintentional air leakage into and out of a building via gaps, cracks, and openings in the building envelope. The infiltration rate measures this air leakage and affects the building's energy efficiency, thermal performance, cooling loads, and occupant comfort. When evaluating the energy efficiency of residential buildings, it is important to consider the infiltration rate as a crucial factor. A variety of variables, including construction materials and climate conditions, influence the infiltration rate, measured in air changes per hour (ACH) (Jones and Powell, 2005).

Due to practical constraints and the diverse range of building types in Saudi Arabia, accurately determining the infiltration rate in residential housing is difficult. As direct measurements are not readily available, an assumed infiltration rate was adopted for the base case model. Notably, this assumption is derived from previous studies and common assumptions in the field. Studies by Krarti et al. (2020); (Alaidroos and Krarti, 2016), frequently use an infiltration rate of 0.8 ACH for housing. With the limited availability of local data on infiltration rates specific to Saudi Arabia, this assumed value has been widely accepted within the field to provide a baseline understanding of energy usage patterns and the potential for energy conservation.

However, it is worth noting that the Saudi Building Code (SBC, 2018) specifies an infiltration rate requirement of 0.25 ACH for residential buildings. This requirement signifies the importance of minimizing the infiltration rate and ensuring energy efficiency in building construction. The specified infiltration rate requirement in the Saudi Building Code (SBC) differs significantly from the assumed value of 0.8 ACH used in previous studies. This discrepancy implies that the SBC requirement may be more applicable to the construction of energy-efficient buildings. Given the limited availability of local data on infiltration rates specific to Saudi Arabia, the assumed value has been widely accepted within the field as a baseline understanding of energy usage patterns and the potential for energy conservation.

The study aims to evaluate the effectiveness of applying (SBC-602) standards related to infiltration rates for enhancing energy efficiency in residential buildings in Saudi Arabia. It involves comparing energy savings under baseline conditions with those achieved through retrofit scenarios focused on improved air tightness. This includes a sensitivity analysis to examine the effects of varying infiltration rates. By conducting this analysis and addressing the discrepancies between assumed values and SBC requirements, the research seeks to identify the potential energy savings achievable.

The findings of this study will contribute to a deeper understanding of the energy performance of residential buildings in Saudi Arabia and guide the implementation of sustainable and energy-efficient practices in construction and retrofitting processes. This will contribute to developing sustainable building practices and support SBC's goals of promoting energy-efficient and comfortable residential environments.

4.7. Model Validation

Model validation is a critical step in ensuring the accuracy and reliability of the simulation results. This section discusses the procedures and methodologies used to validate the simulation model against reported data. The reliability of building energy simulation models is highly dependent on the quality of the input data. Several key input categories must be accurately defined to produce valid results that represent actual building performance, as discussed in Section 4.4. These categories include physical characteristics, geometry, construction materials, HVAC systems, equipment efficiencies, and operating schedules (Ryan and Sanquist, 2012; Reddy et al., 2006).

The validation of the base-case model compares simulated monthly electricity consumption results with actual energy consumption data from an existing model of Saudi residential buildings developed in a recent study by Krarti et al. (2020). This comparison provides essential insights into a residential building stock model customized for evaluating energy retrofit initiatives in Saudi Arabia, calibrated using national utility data from 2018. The reported data serve as a benchmark to verify the base case model's accuracy in predicting energy consumption and overall building performance.

Electricity consumption is a significant factor in residential buildings, and accurate prediction is essential for evaluating energy efficiency measures. To determine the accuracy of the model, the monthly electricity consumption of the baseline model was verified against the reported energy consumption data from the study by Krarti et al. (2020). The assessment of the base case model's accuracy involves applying statistical metrics to compare the actual reported data (energy bill) with the predicted data from the base case model simulations. This study utilizes ASHRAE metrics, namely the Normalized Mean Bias Error (NMBE) and Coefficient of Variation of the Root Mean Square Error

(CVRMSE), to evaluate the model's error rate (ASHRAE, 2002). Table 4.5 displays the recommended calibration criteria from ASHRAE Guideline 14 for the energy model's monthly and hourly calibration.

Table 4. 6 ASHRAE Guideline 14 for monthly and hourly calibration of energy models.

Data Type	Index	ASHRAE Guideline 14
Calibration Criteria		
Monthly criteria %	NMBE	±5
	CV (RMSE)	15
Hourly criteria %	NMBE	±10
	CV (RMSE)	30
Model Recommendation		
R^2		>0.75

The Normalized Mean Bias Error (NMBE) measures the average percentage bias between the observed and predicted values, as given by the following equation 4.3. To meet the ASHRAE standard, NMBE should be within 5% of the monthly calibration data. A positive NMBE indicates that the model overpredicts, on average, while a negative NMBE indicates underprediction.

1. Equation 4.3 determines the Normalized Mean Bias Error (NMBE).

$$NMBE = \left(\frac{1}{n}\right) * \sum_{i=0}^{n} \left[\frac{(yi - \hat{y}i)}{yi}\right] * 100\% \qquad \textit{(Equation 4. 3)}$$

Where:

- n = Numbers of data points. (12 months)
- yi = Observed values; reported data values.
- $\hat{y}i$ = Simulation predicted value.

Additionally, the Coefficient of Variation of the Root Mean Square Error (CVRMSE), given by equations 4.4 and 4.5, is used to assess the model's precision The CVRMSE should be within 15% of the monthly calibration data to comply with the ASHRAE standard.

2. The coefficient of Variation of the Root Mean Square Error is determined.

$$CVRMSE = \left(\frac{RMSE}{\bar{y}i}\right) \times 100\% \qquad \text{(Equation 4. 4)}$$

$\bar{y}$ = mean of the reported values yi

$$RMSE = \sqrt{\left[\left(\frac{1}{n}\right)\sum_{i=1}^{n}(yi - \hat{y}i)^2\right]} \qquad \text{(Equation 4. 5)}$$

3. Coefficient of Determination R^2.

$$R^2 = 1 - \frac{\sum(y_i - \hat{y}_i)^2}{\sum(y_i - \bar{y})^2} \qquad \text{(Equation 4. 6)}$$

The Normalized Mean Bias Error (NMBE) and Coefficient of Variation of Root Mean Square Error (CVRMSE) were used as references and evaluation measures to validate the simulation results. Table 4. 5 presents the (NMBE) and (CVRMSE) calculated using the simulated model with the reported data to show the variability of the errors between them. Based on ASHRAE Guideline 14, a negative (NMBE) of -0.38% indicates that the simulated values closely match the observed data. In contrast, a CVRMSE of 1.358% indicates that the model's predictions are relatively close to the observed data. According to these findings, energy consumption patterns can be accurately captured with reasonable accuracy. Overall, the accuracy metrics indicated a high level of agreement between the simulations of the base case model and the reported data, demonstrating the accuracy and reliability of the model.

Table 4. 7 Calculations for validating the model by applying the NMBE and CVRMSE equations.

Month	Reported Data (Energy Bill) KWh- yi	Simulated Model (IESVE) KWh- ŷi	Differences yi − ŷi
Jan	4,453	4815	-362.4
Feb	4,383	3967.8	415.2
Mar	5,738	4660.9	1077.1
Apr	8,312	9351	-1039.4
May	13,524	13892	-368.2
Jun	15,871	15596	275.1
Jul	16,131	17074	-943.4
Aug	17,399	17013	385.6
Sep	13,631	13605	25.7
Oct	9,942	9619	323.3
Nov	5,239	4260	978.7
Dec	4,972	5290	-318.4
Total	119,595	119146	
NMBE%		-0.38%	
CV(RMSE) %		1.358%	
Mean of the Reported data		9966.3	

Furthermore, the coefficient of determination (R^2) assesses the model's fit and indicates how well the two data sets (yi , $\hat{y}$) are calibrated. It is a useful tool for understanding the relationships between variables and assessing regression models. R^2 ranges between 0 and 1. The coefficient of determination R^2 in this study was 0.982%, as shown in Figure 4.7. A higher R^2 value indicates a superior model fit to the data. This indicates that the model's predictions correspond well with the actual observed values. According to ASHRAE Handbook recommendations, R^2 should be greater than 0.75. $squared\ is$an essential instrument for determining the accuracy of a regression model and comparing different regression models by following equation 4.6. In addition, it is used to evaluate the model's overall efficacy and identify potential enhancement areas.

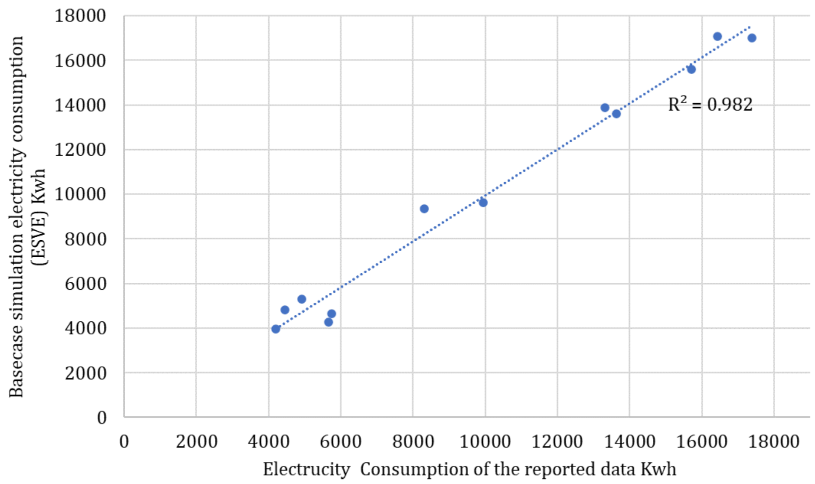


Figure 4. 7 A chart represents the coefficient of determination between the reported data and the simulated values.

According to ASHRAE standards, they are used as guidelines to determine whether base-case model predictions are acceptable by utilizing the statistical metrics provided to effectively evaluate the accuracy of the data. Comparing the simulation results with the stated data offers valuable insights into the performance of the base-case model. This enhances its credibility for accurately predicting energy consumption and optimizing building performance. Moreover, they ensure that the data is valid for future energy performance analyses and retrofit scenarios.

4.8. Simulation Process; Defining Retrofit Measures for Simulation

The simulation was initiated after establishing the defined parameters. This simulation process was repeated in diverse settings to ensure a thorough examination. Each simulation was executed by modifying a single factor at a time. This method of adjusting one factor at a time represents a systematic approach employed in the simulation process, where each variable is modified while all other factors are held constant. Within the context of this study, a crucial comparative analysis of different Energy Efficiency Measures (EEMs) was conducted. This approach allowed for a precise assessment and comparison of the impact of each variable on energy efficiency. This methodical strategy ensures a clear understanding of how each factor contributes to the overall building energy performance, underscoring the significance of the study.

Retrofitting existing buildings to make them more energy-efficient is seen as an effective way to achieve the goals of reducing energy use and promoting sustainable development. After setting up and validating the baseline case, the defined input parameters were assigned to the IES-VE to perform a full performance evaluation. To determine the most energy-efficient measures and evaluate their effectiveness in the baseline model and in meeting the requirements of the Saudi Building Code 602, a comprehensive load analysis was performed using ApacheSim. The Elements Tool within the simulation software helps define and set specific input parameters for parametric analysis. This generates distinct models that may subsequently be evaluated to determine energy efficiency. The comparative outcomes were used to identify the most efficient retrofitting options. This strategic development, based on the simulation results, underscores the practical application of the study in real-world scenarios.

Table 4. 8 Configuration and Calibration Parameters Used in Energy Simulation (Klarić et al., 2016).

Parameters (Variables)	Calibration Range	Calibration Tool	Upgraded Model Parameter Values	Justification
SEER kW/kW = CoP	2.3–3.5	Manually	3.5	Based on local industry standards; aligns with HVAC best practices.
Cooling Setpoint	20–25	Element	25°C	Complies with SBC Code; optimizes comfort and efficiency.
Air Exchanges - Infiltration	0.2–1	Element	0.25 ACH	Adjusted to comply with SBC Code; affects air quality and energy consumption.
Constructions - Roof U-Value	0.2–2.4	Manually	0.201	Low U-value enhances thermal performance and energy efficiency.
External Wall U-Value	0.3-1.9	Manually	0.32	Improve the wall insulation level to comply with the minimum requirement of the Saudi building code and reduce energy consumption for heating and cooling
Windows U-Value	1.6–5.0	Manually	2.3	Chosen to reflect the best practice for energy-efficient glazing in the region.
PV Roof System	20%-30%-40% coverage	Manually	40% of the accessible roof area	Maximizes renewable energy generation potential, contributing significantly to sustainability goals under Vision 2030.
Windows shading (Overhang + side fins +louver)	.2-1	Manually	louvres	Louvres were chosen to enhance control over solar gains and reduce cooling loads.

4.9. Cost-benefit and payback calculation

After investigating and assessing the suggested strategies, cost-benefit and payback calculations were conducted to determine the economic viability of each retrofit measure.

This evaluation focused on estimating direct material and equipment costs, derived from local market data, and calculating the associated energy savings.

Labor costs were excluded to focus on fixed material expenses, providing a simplified financial view; however, future research could include labour cost for a more comprehensive assessment. Only basic economic indicators (payback period, NPV, and discount rate) were used, providing a preliminary assessment of each measure's financial feasibility in light of Saudi Electricity Company's tariff. This offers an initial perspective on economic viability. Additionally, costs are based on current local market, with the assumption of stable market conditions. This approach aligns with the study's goal of establishing a clear baseline for material costs, serving as an essential first step in evaluating economic feasibility.

Equations 4.7, 4.8, and 4.9 were used to calculate the expected cost savings from reduced energy consumption, allowing for an analysis of the potential payback period and long-term value of each retrofitting measure. By analyzing these savings against the initial investment, this research offers insights into the potential economic payback and long-term value of retrofitting measures for homeowners in Saudi Arabia. The detailed costs, savings, and implications of each measure are discussed in the Results and Discussion chapter, including their potential impact on energy efficiency in alignment with Saudi Arabia's energy goals.

Annual energy savings: Energy savings measured in kilowatts per hour (kWh) were determined as the difference in energy consumption between the baseline and retrofit measures.

$$ES = EC\ Baseline - EC\ Retrofit \quad \textit{(Equation 4. 7)}$$

Where:

- $EC\ Baseline$, the energy consumption of a building without retrofitting.
- $EC\ Retrofit$, the energy consumption of a building with a retrofit.

Annual Energy Cost Savings: To convert energy savings into financial terms, the applicable electricity rate was considered.

$$CS = ES * ET \quad \textit{(Equation 4. 8)}$$

Where:

- ET, Saudi Company's Electricity Tariff (SEC). Depending on the local energy costs of electricity, the cost is 0.18 SR/kWh from the national grid or 0.39 SR/kWh from generators.

Cost-benefit analysis: This step identifies the cost of the proposed retrofit measures, including initial costs, maintenance costs, and the expected cost savings over the lifecycle for the implemented retrofits.

Payback Period: This step specifies the number of years it will be recovered through savings to equal the initial investment. It's calculated by dividing the initial cost by the annual energy cost savings from the retrofit.

$$Payback\ Period\ (Years) = \frac{\text{Total Retrofit Cost}}{\text{Annual Energy Cost Savings}}$$ *(Equation 4. 9)*

Net Present Value (NPV): is a financial metric to evaluate the profitability of an investment over time. It calculates the difference between the present value of cash inflows and the present value of cash outflows over a period by using Equation 4. 10.

Net Present Value (NPV)

$$\text{NPV} = \sum_{t=1}^{n} \left(\frac{C_t}{(1+r)^t} \right) - C_0$$

(Equation 4. 10)

Where:

C_t = Cash inflow during the period t

r = Discount rate (4%)

t = Time period

n = The lifespan of the measure (25 years)

C_0 = Initial investment

NPV helps determine the value of an investment by converting future cash flows into their value today (present value) and then comparing it to the initial investment. A positive NPV indicates that the projected earnings exceed the anticipated costs, making the investment profitable. This makes NPV a critical tool in assessing the financial return of energy retrofitting projects.

4.10. Environmental Analysis (CO_2)

In addition to energy savings, reducing carbon emissions (CO_2) from buildings is a strong motivation for implementing energy-efficient retrofits. This includes calculating the reduction in CO_2 resulting from the lower energy consumption of the proposed retrofit measures. The proposed upgrade model was evaluated for CO_2 emissions as part of the environmental analysis. CO_2 emissions were calculated based on fuel type and corresponding emission factors. Equation 4.12 illustrates the general equation for calculating the CO_2 emissions from energy consumption.

$$CO^2\ Emissions = (Ei \times EFi) \qquad \text{(Equation 4. 11)}$$

Where:

- *Ei* is the energy consumption for a particular fuel type *I* (such as electricity or natural gas, usually measured in (kWh).
- *EFi* is the emission factor for fuel type *i*, measured in (kg CO_2/kWh).

Equation 4.13 for quantifying the emission savings for both the baseline and retrofit scenarios.

CO_2 savings= CO_2 Emissions-baseline− CO_2 Emissions-retrofit (*Equation 4. 12)*

4.11. Summary

The methodology chapter describes the strategy used to examine several retrofitting alternatives in the three Saudi Arabian cities. The parameters were specified and calibrated according to industry standards and the Saudi Building Code using the IES-VE software for energy simulations. Several retrofitting options, including window adjustment, wall and roof insulation, shading, and renewable energy use. This organised method provides a foundation for future research and discussions on energy performance and sustainability in residential structures.

Chapter 5

Analysis of Base Case and Individual Energy Efficiency Measures

5.1. Introduction

The first part of this chapter examines the baseline model, utilizing a dynamic energy simulation tool to evaluate the energy consumption patterns within the buildings. This process aims to provide a foundational understanding of the fundamental energy dynamics within typical residential structures. After the base case analysis, the chapter transitions to a detailed investigation of each Energy Efficiency Measure (EEM) in isolation. By employing a variety of assessment techniques, including sensitivity, the study illustrates the individual effectiveness of these EEMs. This approach not only highlights the elements with the most substantial influence on the energy performance of the base-case model but also provides a clear picture of how each EEM can contribute to overall energy efficiency when applied independently.

The simulation outcomes are then presented and evaluated to direct decision-makers toward effective measures for improving energy efficiency. This study is significant in determining the most beneficial retrofitting options, as it elaborates on the practical implications of the outcomes for retrofitting decisions.

5.2. Analysis of Base Case Model

This section analyses the model's energy performance using the IES-VE simulation software and the previously defined parameters. The simulation results reveal significant energy savings for the retrofit scenarios compared to the base-case study building and the minimum SBC requirements. Following that, the results of the energy simulation study are then used to evaluate the building's performance and identify areas for improvement. Finally, the simulation results are used to inform decisions regarding the implementation of energy-efficient retrofitting strategies.

5.2.1 Energy end-use

Understanding energy end-use is essential for analysing how different sectors contribute to overall energy consumption within a region. This section provides a breakdown of energy end-use categories, highlighting the distribution of energy consumption across various applications such as cooling, heating, lighting, and equipment.

Tables 5.1, 5.2, and 5.3 present the monthly energy consumption breakdowns for the base cases in Jeddah, Riyadh, and Dhahran. The percentage values represent the proportion of each energy consumption category relative to total energy consumption. The analysis of the base-case model for energy consumption in these cities revealed significant cooling load percentage trends. Cooling load refers to the total amount of heat energy that must be removed from a building to maintain comfortable indoor temperatures. It includes various factors such as internal heat gains from occupants and equipment, and the building’s insulation. Each city's cooling load percentage is determined by averaging its monthly cooling consumption percentages throughout the year.

Jeddah has the most significant cooling load, accounting for 78.04% of the total energy consumption, reflecting the city's reliance on cooling systems due to its extremely hot environment. This high percentage is influenced by factors like high solar radiation, extensive use of air conditioning, and building designs that may not sufficiently moderate heat gains. Dhahran comes in second with a cooling load percentage of 62.40%, demonstrating a considerable dependence on cooling to counteract its warm climate and energy demands. Riyadh has the lowest cooling load percentage of the three cities at 56.20%; however, cooling still accounts for the majority of overall energy use. This variation is impacted by regional climate differences, building designs, and cooling system.

Table 5. 1 Simulated monthly energy consumption breakdown for the base case model in Jeddah.

Months	**Interior Lighting (MWh)**	**Room Electricity (MWh)**	**Space Heating (MWh)**	**DHW (Electricity) (MWh)**	**Space Cooling (MWh)**
Jan	0.4782	1.7241	0.04	0.3583	4.6013
Feb	0.4319	1.5572	0	0.3237	4.4302
Mar	0.4782	1.7241	0	0.3583	6.4346
Apr	0.4628	1.6685	0	0.3468	9.6829
May	0.4782	1.7241	0	0.3583	12.178
Jun	0.4628	1.6685	0	0.3468	13.720
Jul	0.4782	1.7241	0	0.3583	14.617
Aug	0.4782	1.7241	0	0.3583	15.166
Sep	0.4628	1.6685	0	0.3468	13.510
Oct	0.4782	1.7241	0.	0.3583	12.939
Nov	0.4628	1.6685	0.05	0.3468	8.8833
Dec	0.4782	1.7241	0.09	0.3583	5.741
Total	5.6305	20.2997	0.18	4.2191	121.906
Percentage %	3.70%	13.35%	0.1%	2.78%	80.16%
Total energy consumption (MWh)			152.056		
(EUI) in kWh/m^2/year			286		

Table 5. 2 Simulated monthly energy consumption breakdown for the base case model in Riyadh.

Months	**Interior Lighting (MWh)**	**Equipment (MWh)**	**Space Heating (MWh)**	**Water Heating (MWh)**	**Space Cooling (MWh)**
Jan	0.4782	1.7241	2.1192	0.3583	0.1356
Feb	0.4319	1.5572	1.0797	0.3237	0.5753
Mar	0.4782	1.7241	0.294	0.3583	1.8063
Apr	0.4628	1.6685	0.0536	0.3468	6.8198
May	0.4782	1.7241	0.038	0.3583	11.293
Jun	0.4628	1.6685	0.1273	0.3468	12.990
Jul	0.4782	1.7241	0.1345	0.3583	14.379
Aug	0.4782	1.7241	0.0292	0.3583	14.423
Sep	0.4628	1.6685	0.0684	0.3468	11.058
Oct	0.4782	1.7241	0.0578	0.3583	7.0002
Nov	0.4628	1.6685	0.1252	0.3468	1.657
Dec	0.4782	1.7241	2.4197	0.3583	0.3101
Total	5.6305	20.2997	6.5466	4.2191	82.4495
Percentage %	4.73%	17.04%	5.49%	3.54%	69.20%
Total energy consumption (MWh)				119.1454	
(EUI) in $kWh/m^2/year$				226	

Table 5. 3 Simulated monthly energy consumption breakdown for the base case model in Dhahran.

Months	Interior Lighting (MWh)	Equipment (MWh)	Space Heating (MWh)	Water Heating (MWh)	Space Cooling (MWh)
Jan	0.4782	1.7241	1.5434	0.3583	0.2897
Feb	0.4319	1.5572	0.5805	0.3237	0.6007
Mar	0.4782	1.7241	0.0174	0.3583	2.2454
Apr	0.4628	1.6685	0.0039	0.3468	7.0661
May	0.4782	1.7241	0	0.3583	12.877
Jun	0.4628	1.6685	0	0.3468	14.067
Jul	0.4782	1.7241	0	0.3583	17.025
Aug	0.4782	1.7241	0	0.3583	17.3997
Sep	0.4628	1.6685	0	0.3468	13.718
Oct	0.4782	1.7241	0	0.3583	10.9651
Nov	0.4628	1.6685	0.0028	0.3468	3.288
Dec	0.4782	1.7241	0.4108	0.3583	1.0514
Total	5.6305	20.2997	2.5587	4.2191	100.59
Percentage %	4.22%	15.22%	1.92%	3.54%	75.47%
Total energy consumption (MWh)				133.3023	
(EUI) in kWh/m²/year				251	

According to meteorological data, Riyadh experiences high temperatures for most of the year, with average monthly temperatures reaching 30 °C and often exceeding 40 °C from May to September—the hottest period of the year. These high temperatures, coupled with intense solar radiation, exacerbate the challenge of cooling indoor spaces. Figures 5.1 and 5.2 demonstrate that Riyadh allocates nearly 69.20% of its produced electricity to cooling.

In contrast, Jeddah is hot and humid throughout the year, with temperatures from June to August well above 40 °C due to its coastal location. This climate further increases discomfort and the demand for space conditioning, resulting in space cooling accounting for 80.16% of Jeddah's total energy consumption higher than that of Riyadh.

Temperatures in Dhahran are comparable to those in Riyadh, averaging 34.6 °C in June and 35.2 °C in August, with summer temperatures often exceeding 40 °C. Consequently, cooling consumes 75.47% of the total energy used in Dhahran.

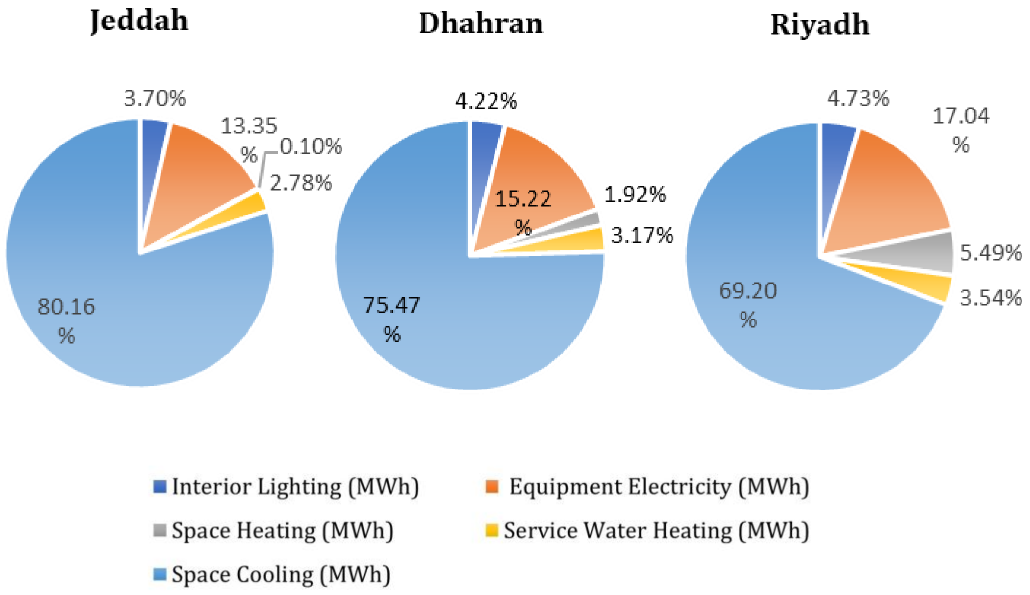


Figure 5. 1 Annual breakdown of energy use.

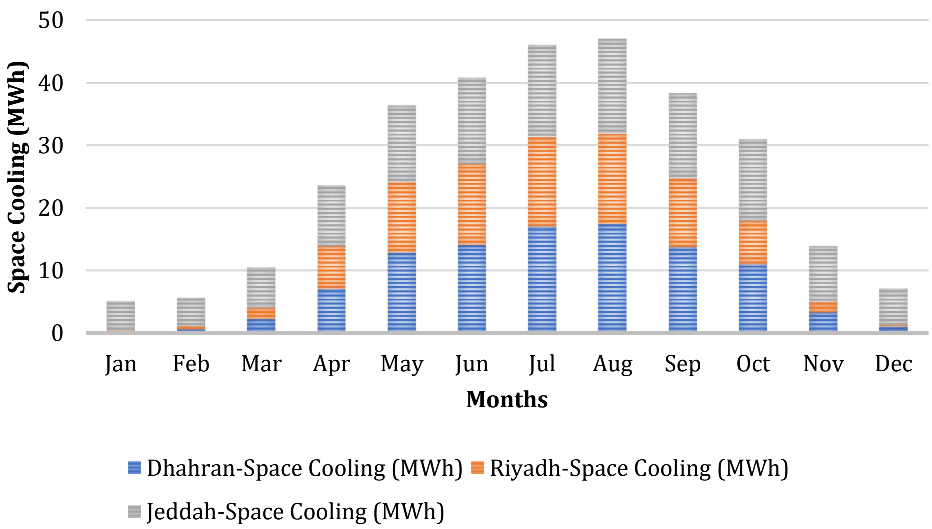


Figure 5. 2 Cooling load of the three cities.

5.2.2 Conduction gain

Building envelopes constantly interact with outdoor environments and play a significant role in regulating heat transmission. This relationship is vital for influencing the quantity of heat that a structure gains from the outdoors. Conduction gains, which quantify the heat transfer through different building components, substantially impact the indoor thermal environment and, consequently, the energy needed for space conditioning

(Sadineni et al., 2011). Roofs directly exposed to the sun play a significant role, and their materials affect their heat-absorption rates. Depending on their position and construction type, walls absorb or reflect heat. Even when windows are necessary for light, they can be sources of heat gain, depending on factors such as the glass type and shade. Notably, the infiltration gain, which occurs when heat enters the building through cracks and holes, contributes to the overall heat balance.

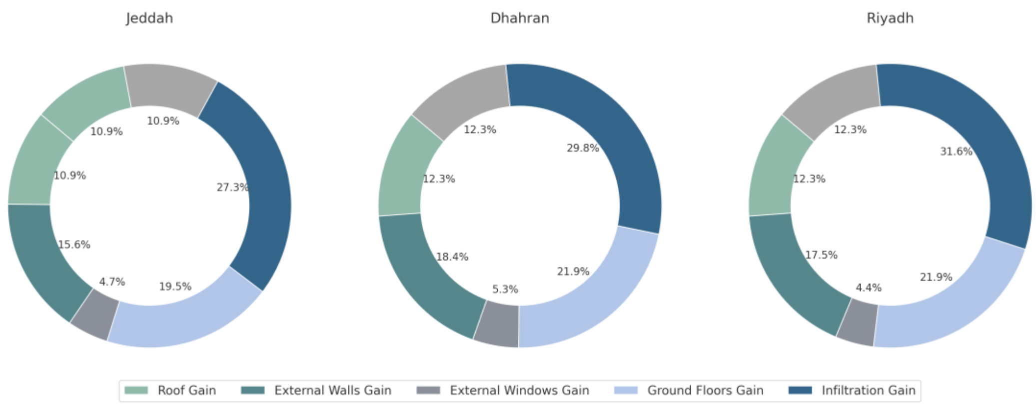


Figure 5. 3 External conduction gain

Figure 5.3 reveals a critical insight: roofs, acting as significant heat conductors, are a common feature in all three cities, reflecting the intensity of solar radiation. In the hot and arid conditions of Riyadh, rooftops alone contributed to 36% of the overall conduction gains. This data highlights the importance of effective rooftop insulation, particularly in the coastal city of Jeddah and the dynamic climate of Dhahran, where conduction gains are also primarily influenced by roofs. While variations were observed in other components, the impact of rooftops on conduction gains remained consistent across all cities. Notably, the thermal conduction gains from the external walls in Jeddah recorded the highest value at 24.86%, followed by Dhahran at 24.97% and Riyadh at 25.48%. This data further emphasizes the significant and consistent impact of external walls on the thermal performance of buildings in these cities.

5.2.3 Climatic Conditions: Temperature Distribution and Degree Day Analysis

Understanding the local climate is crucial for assessing the energy performance of buildings. External temperature significantly influences a structure's need for heating or cooling, impacting occupant comfort, energy use patterns, and the efficiency measures required to maintain desirable indoor conditions. This study selected Riyadh, Jeddah, and Dhahran to investigate the relationship between climatic factors and building energy performance. This section outlines the temperature distributions and degree-day analyses for these cities, resulting in varied energy demand and subsequent evaluation of energy-saving measures. Figure 5.4 represents the air temperature distribution charts for Riyadh, Jeddah, and Dhahran.

In Jeddah, average temperatures are primarily warm, with notable frequencies ranging from 22°C to 35°C, indicating a hot climate influenced by its proximity to the Red Sea coastline. Dhahran demonstrates a variety of temperatures, with the most frequent occurrences seen in the range of 28-34°C. Riyadh has a notable variation in temperature, ranging from a minimum of 4°C to a maximum of 42°C, with a noticeable increase in temperatures above 40°C. These climatic patterns result in extremely hot summers and comparatively mild winters.

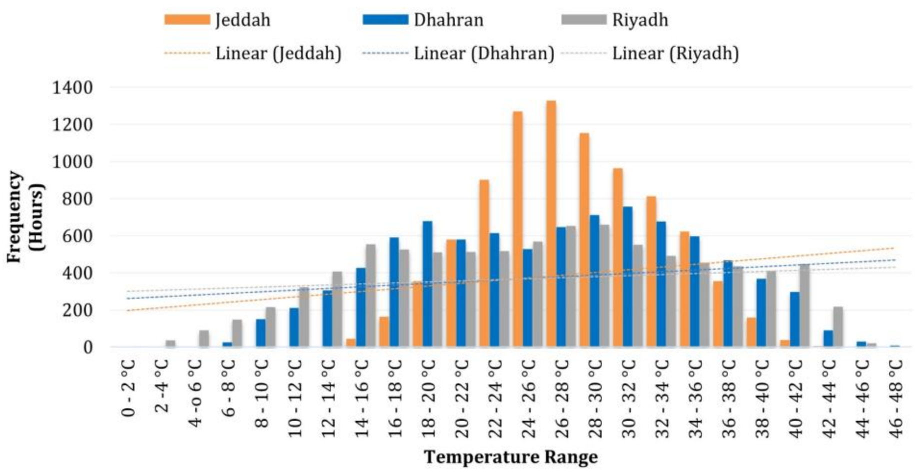


Figure 5. 4 Air temperature distribution in Jeddah, Dhahran, and Riyadh.

Heating degree days (HDD) and cooling degree days (CDD) are measurements used to quantify the demand for energy needed to heat or cool buildings. The Saudi Building Code Energy Conservation Requirements, based on international standards, including the International Energy Conservation Code (IECC) defined a base temperature of 18.3°C for various locations in Saudi Arabia (Indraganti and Boussaa, 2016; Al-Hadhrami, 2013). The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) guidelines guide the calculation of these values, which are based on a base temperature of 18.3 °C (65 °F).

Owing to the higher temperatures in Riyadh, Jeddah, and Dhahran, it is essential to identify the cooling requirements for buildings. Figures 5.5, which represents the sum of degrees by which the daily average temperature is either above (CDD) or below (HDD) a specific base temperature, effectively measures the deviation of daily temperatures from a comfort baseline and estimates energy needs. The cities of Jeddah, Dhahran, and Riyadh exhibit distinctive trends in their cooling degree days, indicating variations in the duration of their cooling requirements. Due to its humid coastal climate, Jeddah consistently exhibits the highest CDD values throughout the year, indicating a constant demand for cooling. Dhahran, also located along the coast, shows a marginally lower CDD than Jeddah, suggesting that coastal regions may moderately impact cooling demand. Riyadh's CDD pattern is characterized by a significant increase in demand during the hot summer months, peaking between May and August. This highlights Riyadh's considerable need for cooling, primarily due to its hot desert climate.

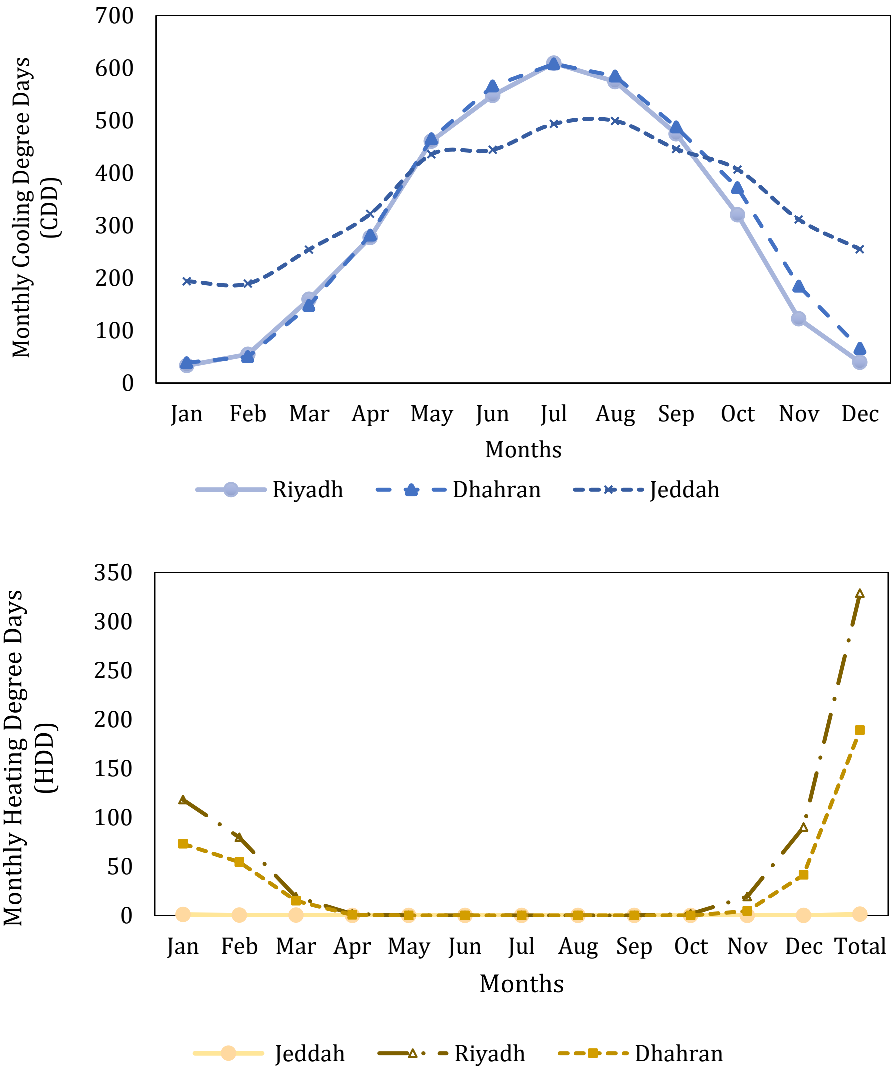


Figure 5. 5 Monthly (CDD) and (HDD) for Jeddah, Dhahran, and Riyadh.

To further characterise the climate, the annual cooling and heating degree days were analysed. The cooling degree days (CDD) indicate the amount of energy required to cool. Riyadh experiences high CDD levels every year, reflecting its hot summer conditions. Jeddah has the highest CDD among the three cities because of its hot and humid climate. In contrast, the (HDD) was relatively low in all cities. This degree-day analysis highlights cooling-dominated energy use throughout Saudi Arabia because of its hot climate. In conclusion, the high temperatures and high solar radiation levels experienced in Riyadh, Jeddah, and Dhahran contributed to the significant need for space cooling. Consequently, any energy efficiency measure implemented in these cities should enhance buildings' energy efficiency, which could lead to considerable energy savings.

5.3 Performance evaluation of individual Energy Efficiency Measures (EEMs) for Building Retrofits

This section outlines various simulation analyses that can be conducted on (EEMs). Retrofitting existing residential buildings involves improving the building envelope through various methods. This section discusses an array of retrofit energy efficiency measures to reduce the cooling load. These measures include modifications to exterior walls and roofs, improvements to HVAC systems, shading devices and glazing, and the potential benefits of installing rooftop photovoltaic (PV) systems. These parameters were chosen due to their significant impact on the overall energy efficiency of residential structures. Retrofit options were assessed using a prototypical Saudi residential building model. Each measure was adjusted independently in separate scenarios while all other variables remained constant. This systematic approach allows for evaluating the individual and cumulative effects of these measures on building energy performance. By implementing these measures, Saudi Arabia can progress towards achieving the environmental goals outlined in Vision 2030 while enhancing sustainability.

5.3.1 EEMs 1 External Wall Insulation

External wall insulation in Saudi Arabia is an effective way to increase thermal efficiency and reduce cooling energy consumption. Insulation is used to prevent heat gain through the walls of a building, maintaining the interior at a comfortable temperature. As previously stated in Section 4.5, most residential buildings in Saudi Arabia lack insulation, which significantly affects their energy efficiency and internal temperature. External insulation is recommended to improve the thermal efficiency of buildings in Saudi Arabia as it is up to 50% more effective than interior insulation (Alghamdi, 2019; Alsaqabi et al., 2023). Additionally, the insulation material should meet specific requirements for each climate zone in Saudi Arabia to ensure optimal energy efficiency. The Saudi Energy Conservation Code (SBC-602) establishes maximum overall heat transfer coefficients and thermal conductivity for each different kind of material, and divides Saudi Arabia into three different climate zones (Alfaraidy and Azzam, 2019; Felimban et al., 2023a). The selection of an insulation material and its thermal properties, such as thermal conductivity, can have a substantial influence on a building's energy efficiency (Alyami et al., 2022a). Furthermore, the insulation costs can also be considered. Table 5.4 shows a comparison of the most common insulating materials based on their performance and physical properties to improve thermal performance, reduce cooling energy use, and meet the Saudi Building Code (SBC-602).

Table 5. 4 An overview of selected Insulation Materials.

Insulation Type	**Thermal Conductivity (W/m·K)**	**Density (Kg/m^3)**	**General Affordability**	**Energy Saving & Performance**
Glass Fiber	0.033 - 0.040	10 - 48	Most Affordable. Commonly used and typically one of the more affordable options.	Good - Suitable for general applications.
Insulation Board	0.030 - 0.038	45-64	Affordable. Widely used and offers a good balance between cost and performance.	Good - Offers decent thermal resistance.
Extruded Polystyrene (XPS)	0.025-0.038	26-35	Mid-range terms of cost.	Very Good - Effective for most applications with balanced cost.
Polyurethane board	0.023 - 0.032	28-35	Slightly Expensive. Cost varies based on density and additives.	Very Good - Provides excellent thermal resistance.
Aerogel	0.013 - 0.020	10	Most Expensive. Advanced technology and superior insulating properties make it more expensive.	Excellent - Superior insulating properties with minimal thickness.

In terms of thermal insulation, the choice of material plays a crucial role in determining the overall efficiency of a building or structure. The thermal conductivity of aerogel insulation is significantly influenced by its unique structure and composition (Koebel et al., 2016). The low thermal conductivity of aerogel insulation results from its absorbent structure, which leads to high absorbencies and substantial inner surface areas (Siegmann and Hirayama, 2008). According to various sources, the thermal conductivity of silica aerogels which are one of the most used types of aerogels, can range from 0.013 W/m·K (Bostanci and Sola, 2018; Buratti et al., 2014). On the other hand, XPS polystyrene, polyurethane board, and glass fibre also offer effective thermal insulation properties. XPS polystyrene, also known as extruded polystyrene, is a rigid foam material commonly used in building construction and is known for its durability and moisture resistance (Asadi et al., 2019). It has a thermal conductivity coefficient ranging from 0.028 to 0.035 W/m·K. Thus, it is a suitable option for thermal insulation in various applications. Polyurethane board, another popular insulation material, has a thermal conductivity coefficient of approximately 0.022–0.032 W/m·K, making it a viable alternative to aerogel insulation. This section examines different insulating materials for evaluation, from advanced options, such as aerogels, to more traditional insulation materials, such as polystyrene and polyurethane. It also illustrates the placement of the five thermal insulation types on the exterior surfaces of the building envelope along with their corresponding additional thicknesses. This approach provided insights into how the choice of material, its thickness, and the specific climate of a city can influence energy savings. See Table 5. 5.

Table 5. 5 External wall insulation types and thicknesses for simulation.

(EEMs1) Code	Insulation Type	Thickness (mm)	U Value (W/m^{2}K
EW1	Aerogel	20	0.44
EW2	Aerogel	30	0.32
EW3	XPS Polystyrene	50	0.43
EW4	XPS Polystyrene	75	0.32
EW5	XPS Polystyrene	100	0.27
EW6	Polyurethane Board	50	0.50
EW7	Polyurethane Board	75	0.41
EW8	Polyurethane Board	100	0.33
EW9	Glass Fiber	50	0.52
EW10	Glass Fiber	75	0.38
EW11	Glass Fiber	100	0.30
EW12	Insulation Board	50	0.51
EW13	Insulation Board	75	0.44
EW14	Insulation Board	100	0.35

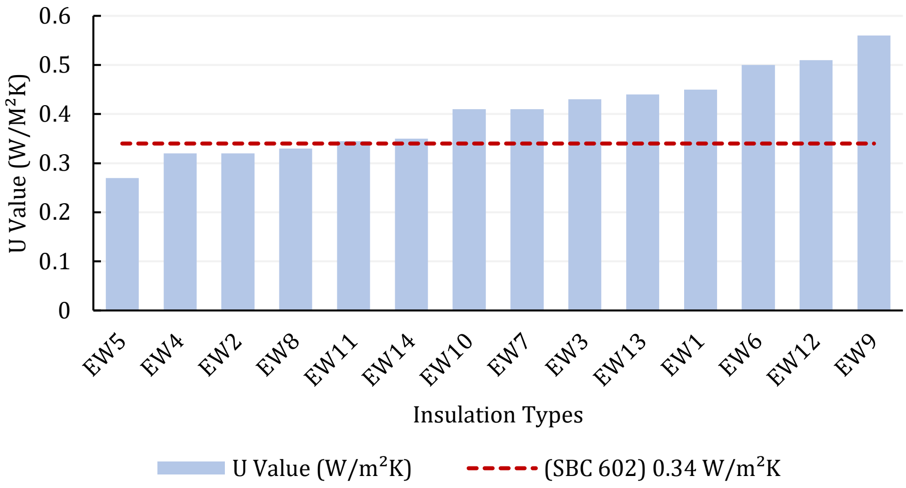


Figure 5. 6 External wall insulation U-value.

Figure 5.6 illustrates the U-values, which represent the thermal transmittance and a relationship between the U-value and the total annual energy consumption for three cities in Saudi Arabia: Riyadh, Jeddah, and Dhahran, for different insulation types and thicknesses. The visualization plots the regression lines against the data points for each city. As the thickness increased from 20 to 100 mm, the U-value steadily decreased, indicating better insulation. The base case represents an uninsulated wall with the highest U-value, indicating the least insulating performance of all the options presented. As the chart's horizontal axis progresses, there is a comparable decrease in the U Values, which signifies enhancements in insulation efficiency across various materials and thicknesses.

The Saudi Building Code (SBC) 602 sets a minimum U-value of 0.34 W/m^2K for wall insulation to enhance energy efficiency. After reviewing different insulation materials, it is evident that each type offers varying degrees of thermal resistance. For instance, XPS polystyrene at 100 mm thickness achieves a U-value of 0.27 W/m^2K, surpassing the SBC requirement and demonstrating its high efficiency in thermal insulation. Similarly, aerogel insulation at 30 mm effectively meets the requirements with a U-value of 0.32 W/m^2K, showcasing its exceptional insulative properties even at thinner thicknesses than traditional materials due to its low thermal conductivity. On the other hand, materials like glass fibre and Insulation Board, both at 100 mm, slightly exceed the SBC's threshold with U-values of 0.35 W/m^2K, indicating a shortfall in meeting the code. This comparative analysis underscores the critical role of material choice and thickness in achieving SBC

602 compliance. Notably, materials like XPS polystyrene and Aerogel provide superior insulation with less material, potentially saving construction space.

To determine the energy-saving percentage, the following equation is used:

$$Energy\ saving\ \% = \frac{(Base\ Case\ Energy\ Consumption - Insulated\ Case\ Energy\ Consumption) \times 100}{Base\ Case\ Energy\ Consumption}$$

(*Equation 5. 1)*

The findings of this study provide valuable insights for building engineers, architects, and construction professionals. In Riyadh, 20mm and 30mm aerogel insulation achieved the highest energy savings across all three cities, with a maximum saving of 12.9% for the 30 mm thickness compared to the base case. XPS polystyrene also performs well, showing a gradual increase in savings as thickness increases, reaching up to a 10.53% reduction. Other materials, such as polyurethane boards, glass fibres, and insulation boards, achieved moderate to low savings, ranging from 8.04% to 9.94%. In both Jeddah and Dhahran, the trends are consistent with Riyadh's. Aerogel remains the top-performing material, achieving up to 10.9% and 12% reductions in Jeddah and Dhahran, respectively. XPS polystyrene follows closely, while other materials demonstrate varied performance, as illustrated in Table 5. 6 and Figure 5. 7. Riyadh generally exhibits higher energy-saving percentages than Jeddah and Dhahran for the same insulation types. The best-performing insulation, on average across all cities, is the aerogel insulation, with a thickness of 30mm and an average efficiency of 11.9%. XPS polystyrene, at a thickness of 100mm, closely follows with an average efficiency of 9.73%. The least-performing insulation is the insulation board, with a thickness of 50mm, providing an average efficiency of 7.37%. Insulation generally performs similarly across cities, with the average performance being a representative metric.

Figure 5.8 illustrates the varying energy-saving percentages for the same insulation type and thickness across different cities. While some insulation materials consistently perform well in all locations.

Table 5. 6 Total annual energy consumption for different wall insulations

(EEM1) Code	Total annual energy Consumption (MWh)		
	Riyadh	Jeddah	Dhahran
BC-W	119.145	152.0555	133.3024
EW1	104.213	135.817	117.859
EW2	103.793	135.433	117.363
EW3	108.2319	140.800	121.901
EW4	107.4656	139.400	120.808
EW5	105.1970	136.976	118.857
EW6	108.645	141.221	122.428
EW7	107.788	140.419	121.586
EW8	107.300	138.721	121.381
EW9	109.090	141.66	122.868
EW10	108.138	140.798	121.932
EW11	107.587	140.278	121.392
EW12	109.573	142.075	123.342
EW13	108.539	141.156	122.323
EW14	107.920	140.532	121.720

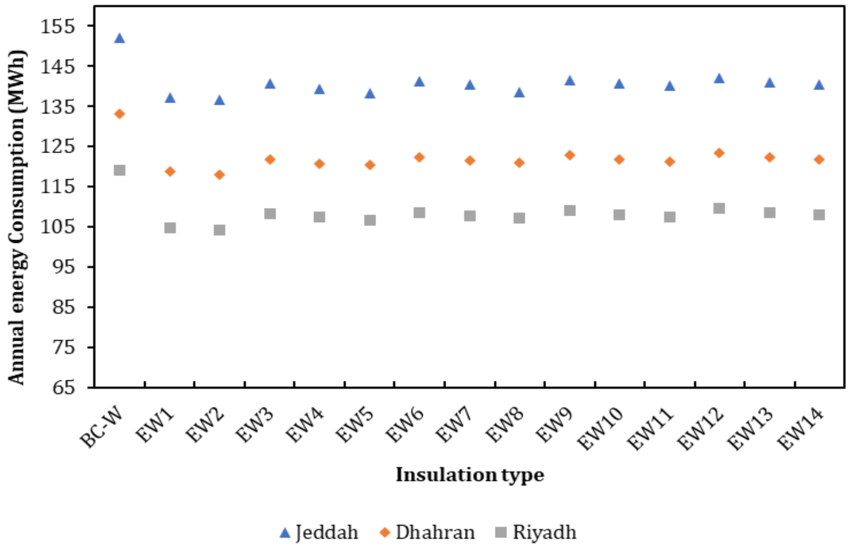


Figure 5. 7 Total annual energy consumption for different wall insulations.

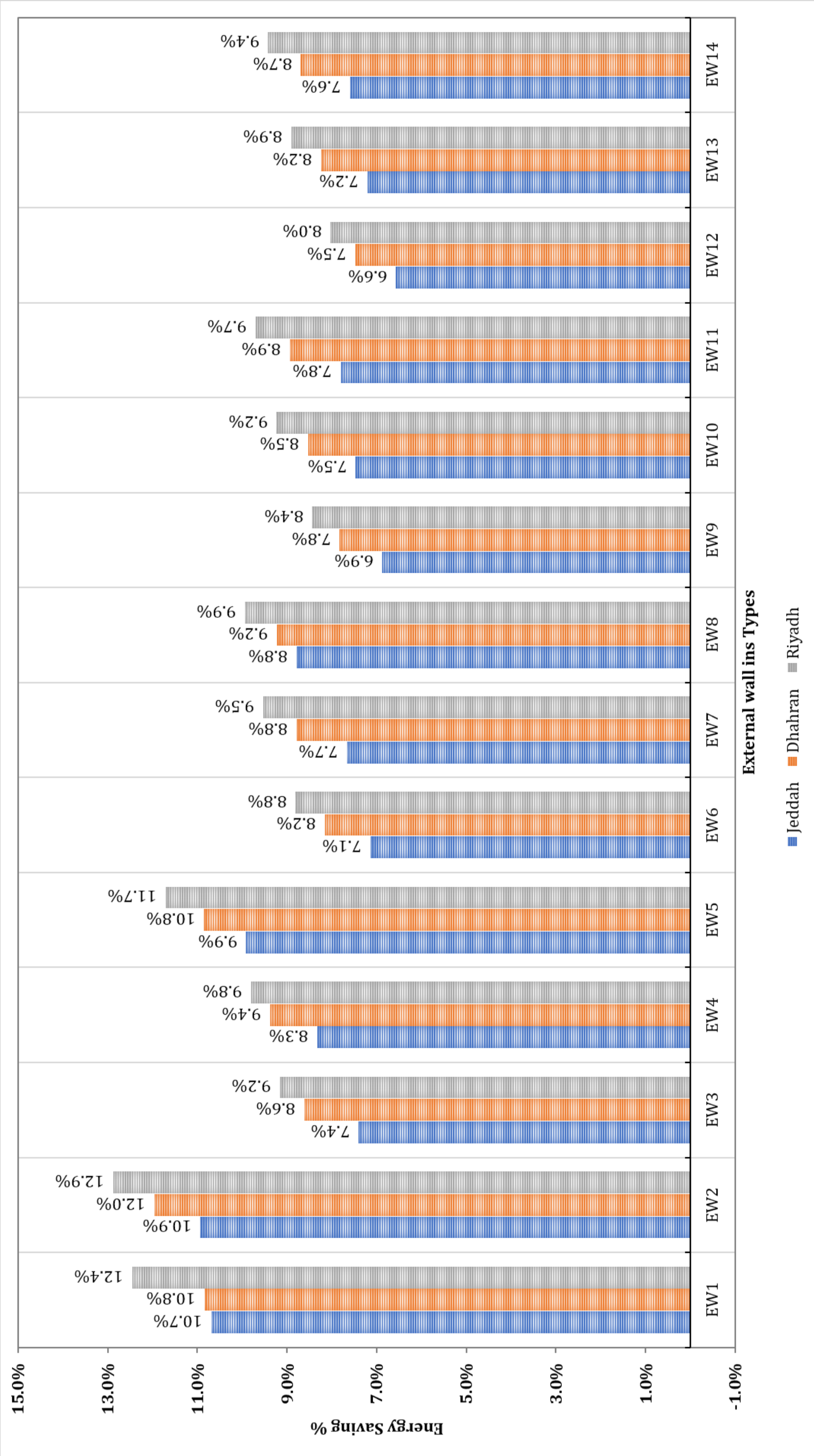


Figure 5. 8 Energy savings for different wall insulations.

5.3.2 EEMs 2 Roof Insulation

In Saudi Arabia, a prevalent issue exists with old buildings, particularly those in the residential sector, that lack proper roof insulation. The base case model is uninsulated with a U-value of 2.4 W/m^2K. As per the findings of Al-Qahtani and Elgizawi (2020), approximately 70% of the buildings in the country are not well insulated. This lack of insulation significantly contributes to increased energy consumption and reduced thermal comfort for the occupants. However, addressing this issue and ensuring proper insulation of all building components can reduce energy consumption and enhance the comfort of the occupants. In the construction of residential and commercial buildings in Saudi Arabia, insulating only the outer walls and windows is common while neglecting other building components, such as the roof (Al-Abduljabbar et al., 2023a). The study found that the roof is the major contributor to the thermal load of a building, followed closely by columns and slabs, which account for 44.2% of the overall cooling load (Al-Abduljabbar et al., 2023b).

This study suggests that an optimum selection of insulators for building components can lead to lower energy consumption and maximum savings in energy and installation costs. In Saudi Arabia, especially in the residential sector, old buildings often lack proper insulation, leading to increased energy consumption and reduced thermal comfort. Improving the insulation of building components, including roofs, can significantly reduce energy consumption and create more comfortable living spaces.

The most common structure of a residential building with a flat roof in the KSA is reinforced concrete, owing to its affordability, availability, and durability. The construction of the skeleton structure follows specific procedures from the foundation to the roof slab, which typically consists of several components: a concrete slab with a thickness ranging from 100 mm t o150 mm, gravel or stones, waterproofing, and gypsum plaster. As a direct consequence, one of the enhancements to the flat roof was installing a thermal insulation layer. This significant upgrade in thermal insulation effectively helps maintain a comfortable temperature inside the building while minimizing the reliance on cooling systems. The proposed roof improvements involved considering various insulation types and thicknesses to enhance the baseline model, as presented in Table 5. 7. By evaluating different options, it was possible to determine the most suitable insulation materials and thicknesses to optimize energy efficiency and overall performance.

Table 5. 7 Roof insulation types and thicknesses for simulation.

(EEM2) Code	Insulation Type	Thickness (mm)	U Value (W/m^2K)
R1	Aerogel	20	0.38
R2	Aerogel	30	0.205
R3	XPS Polystyrene	50	0.41
R4	XPS Polystyrene	75	0.29
R5	XPS Polystyrene	100	0.21
R6	Polyurethane Board	50	0.47
R7	Polyurethane Board	75	0.34
R8	Polyurethane Board	100	0.26
R9	Glass Fiber	50	0.51
R10	Glass Fiber	75	0.40
R11	Glass Fiber	100	0.31
R12	Insulation Board	50	0.54
R13	Insulation Board	75	0.44
R14	Insulation Board	100	0.36

Figure 5.9 effectively visualizes the U-values of various wall insulation materials and their thicknesses against the SBC standard. The Saudi Building Code (SBC) 602 specifies a target U-value of 0.202 W/m^2K for roof insulation. Evaluating various insulation materials against this standard reveals significant differences in their effectiveness and thickness requirements. Aerogel blanket, with its superior insulative properties, meets a U-value of 0.20 W/m^2K. This directly aligns with the SBC requirements, demonstrating that Aerogel provides high-level insulation, making it an excellent choice for applications where space is limited. On the other hand, traditional materials like XPS polystyrene and polyurethane board, while effective, require thicker layers to approach the SBC standard. For instance, 100 mm of XPS Polystyrene achieves a U-value of 0.21 W/m^2K, just slightly above the SBC requirement, while polyurethane board at the same thickness reaches a U-value of 0.26 W/m^2K. A higher U-value indicates insufficient insulation, leading to greater energy consumption to maintain a comfortable indoor temperature. Materials such as glass fibre and insulation board, even at 100 mm, do not meet the SBC target for roof, with U-values of 0.31 W/m^2K and 0.36 W/m^2K, respectively. To comply with the SBC 602 U-value requirements, these materials would require greater thickness.

This comparison highlights Aerogel's advanced performance in meeting energy efficiency criteria with less material usage compared to more traditional insulation types. This makes Aerogel particularly advantageous for new construction and retrofitting projects aiming to meet or exceed SBC 602 standards while maintaining a slim profile for the roofing structure.

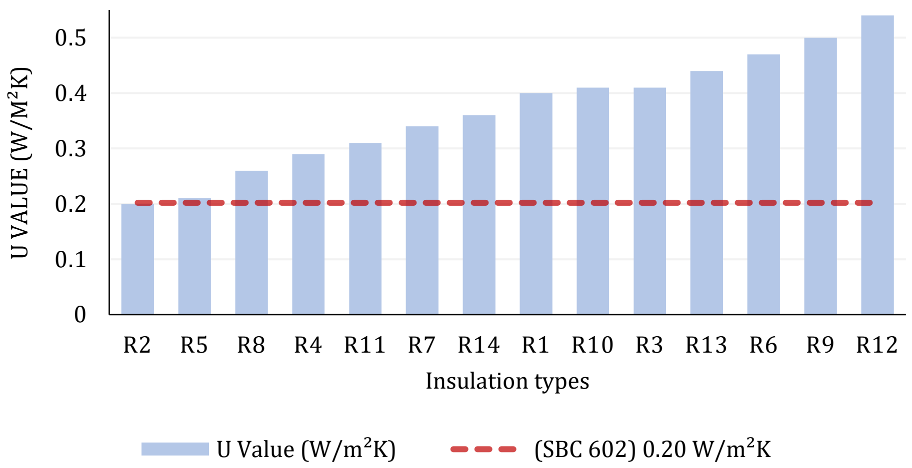


Figure 5. 9 External roof insulation U- Value

The energy-saving efficiencies across three significant Saudi Arabian cities, Riyadh, Jeddah, and Dhahran, indicate that the insulation type and thickness are important factors in determining energy conservation. As shown in Figure 5.11 aerogel, with its advanced insulating properties, offers substantial savings with a thickness of 40 mm, achieving 12.53%, 10.16%, and 11.40% in Riyadh, Jeddah, and Dhahran, respectively. XPS polystyrene and Polyurethane board also present notable reductions in energy consumption. For example, 100 mm XPS polystyrene garners reduced energy consumption by approximately 10.53% in Riyadh, 9.11% in Jeddah, and 9.60% in Dhahran. Glass fibre and insulation boards offer slightly lower savings in comparison. Across all insulation types, there is a discernible trend: as the insulation's effectiveness (lower U-value, which indicates better insulation) increases, there is a proportional increase in energy-saving percentages. This insight underscores the importance of selecting the appropriate insulation type and thickness, particularly when considering the specific climatic conditions of a city. In summary, across all three cities, aerogel insulation, especially at 30mm thickness, consistently offers the most significant energy savings. In contrast, the insulation board, particularly at 50mm, tends to provide the slightest reduction in energy consumption among the tested insulation types and thicknesses. See Figure 5.10 and Table 5.8.

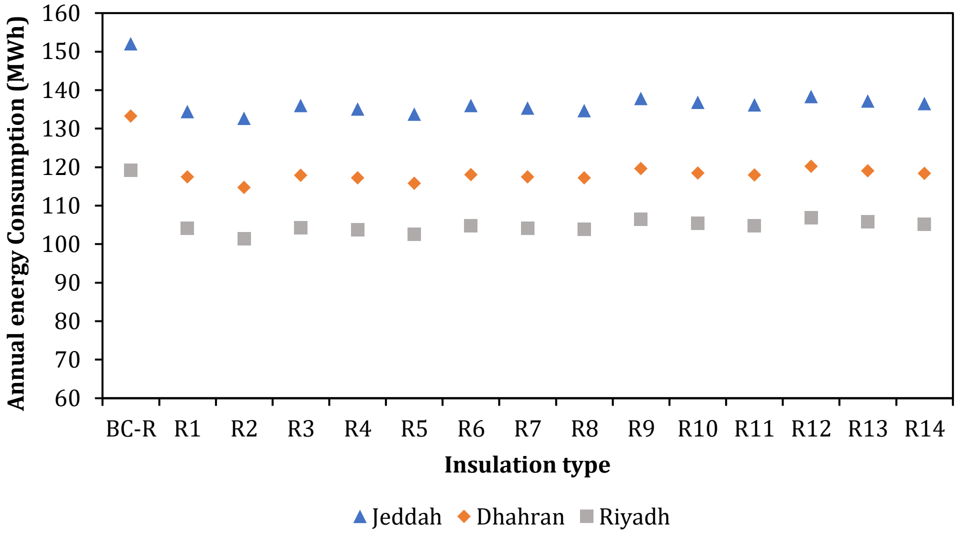


Figure 5. 10 Annual energy consumption for different types of roof insulation.

Table 5. 8 Total annual energy consumption for different roof insulations

(EEM2) Code	**Total annual energy consumption (MWh)**		
	Riyadh	Jeddah	Dhahran
BC-R	119.145	152.055	133.3024
R1	104.180	134.400	117.580
R2	101.549	132.790	114.724
R3	104.369	136.010	117.969
R4	103.892	135.130	117.22
R5	102.479	133.990	115.852
R6	104.449	136.031	118.096
R7	104.217	135.309	117.496
R8	103.931	134.722	117.211
R9	106.463	137.878	119.615
R10	105.421	136.820	118.522
R11	104.804	136.209	117.993
R12	106.902	138.311	120.2043
R13	105.841	137.282	119.0335
R14	105.191	136.569	118.3557

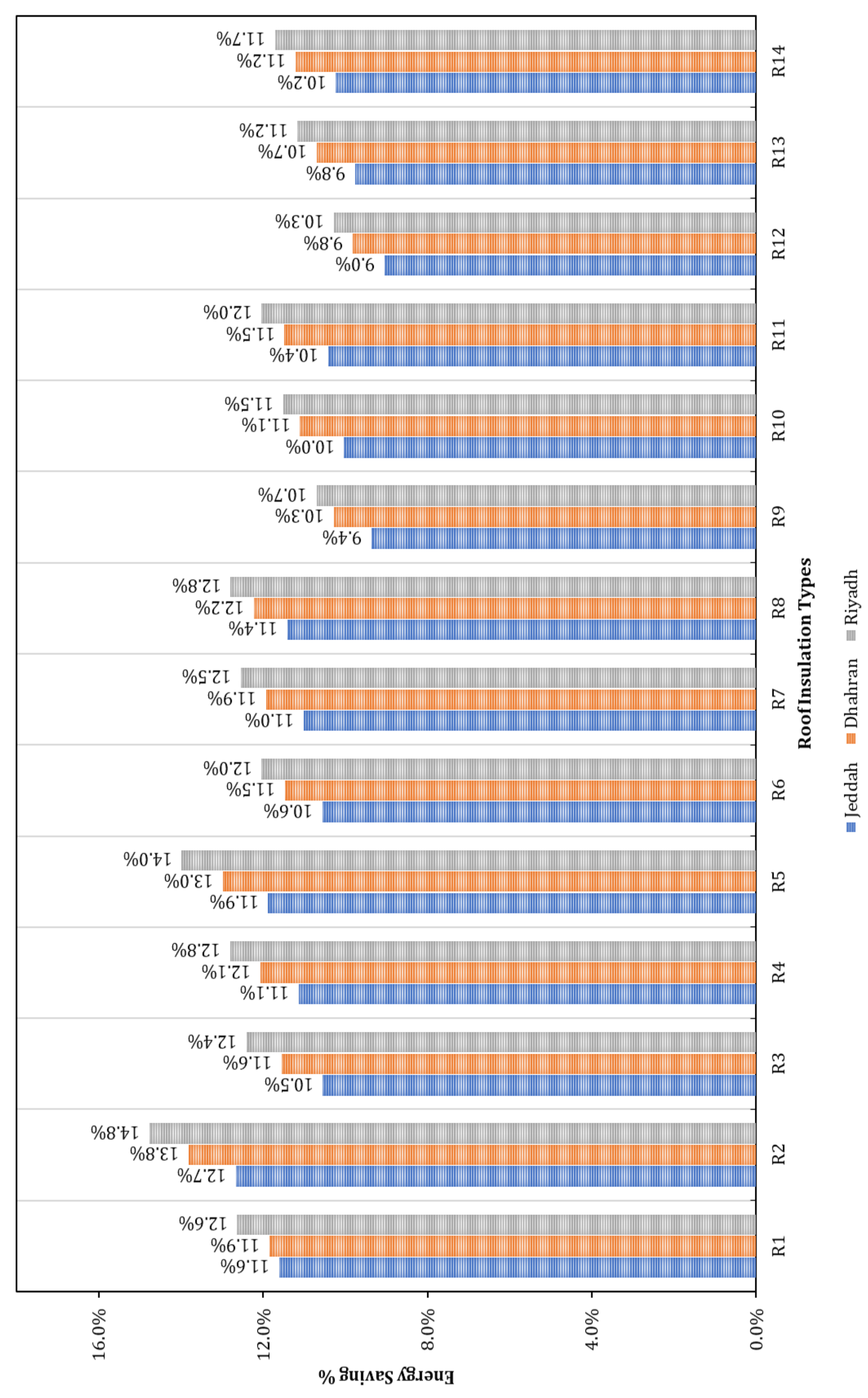


Figure 5. 11 Energy saving of various roof insulation scenarios.

There have been several studies that examine the effects of building envelope systems on residential energy consumption in hot and dry environments, where cooling requirements are high. The insulation of external walls and roofs is one of the most important factors in reducing energy consumption in Saudi Arabia, thereby improving energy efficiency (Saleh, 1990; Al-Tamimi, 2021).

In a different study, thermal insulation types and thickness were evaluated for the energy reduction of a sample prototype building located in three Saudi cities. Results showed that external wall or roof insulation could increase energy conservation by 30% (Al-Tamimi, 2021). According to a study by Al-Tamimi (2021), insulation can reduce residential building energy consumption by up to 77%, depending on the type of insulation used. For the climate of Saudi Arabia, the optimum thickness of thermal insulation applied to the outer surface of an external wall was 5 to 10 cm (Alwetaishi and Taki, 2019). The study also indicated that enhanced fabrications could decrease the total cooling energy demand by 30 to 45%. Additionally, external insulation is more appropriate in areas with consistent cooling needs.

As a result, external wall and roof insulation play a significant role in Saudi Arabia's energy reduction. In a comprehensive review of the literature, it becomes evident that the results obtained from previous studies closely correspond with the findings presented in this section. Nevertheless, it is crucial to acknowledge that various elements, such as the type of insulation selected, its thickness, and the building's characteristics and surroundings, influence the insulation performance. Consequently, when retrofitting buildings, while insulation can notably enhance energy savings, it is beneficial to consider these factors during the planning and implementation of insulation strategies (Zhao, 2020).

5.3.3 EEMs 3 Glazing

Glazing in buildings, particularly in residential environments, is significant for energy efficiency. The selection of glass substantially impacts a building's thermal comfort, quality of natural illumination, and total energy usage. The need for glazing is particularly emphasised in regions with distinct seasonal variations or high amounts of solar radiation, such as Saudi Arabia. Implementing retrofitted glazing in residential structures in Saudi Arabia is a crucial approach aimed at mitigating energy consumption and enhancing the overall performance of existing housing (Aldabesh et al., 2021).

This study examined various types of glazing and assessed their suitability and potential for energy conservation in retrofitting residential buildings in Saudi Arabia. The following sections provide results for each individually examined glazing type, offering an essential understanding of their potential for energy conservation. In the context of retrofitting in Saudi Arabia, several glazing options require careful consideration, as presented in Table 5.9. One such option is low-emissivity (low-E) glass, which features a thin metallic coating that reflects heat while allowing natural light to pass through it. This helps minimise the amount of thermal energy that enters buildings in regions with high temperatures, such as Saudi Arabia. Double or triple glazing involves using two or three layers of glass with a gas-filled space between them. This configuration reduces the amount of heat transmitted. Reflective glazing is a type of glass designed to have reflective properties. It has a special coating that effectively reflects and absorbs a significant amount of solar radiation, thereby reducing the heat entering the structure.

Table 5. 9 Glazing types for simulation.

(EEM3) Code	Glazing Type	U-Value (w/m^{2}k)	SHGC
BC-G	Single clear	5.72	0.47
G1	Double clear 6mm/12mm Arg	2.61	0.78
G2	Double clear 6mm/12mm Air	2.80	0.78
G4	Double LoE 6mm/12mm Arg	1.72	0.56
G5	Double LoE 6mm/12mm Air	2.0	0.56
G6	Double Reflective 6mm/12mm Arg	2.31	0.22
G7	Double Reflective 6mm/12mm Air	2.46	0.22
G8	Double blue 6mm/12mm Arg	2.82	0.57
G9	Double blue 6mm/12mm Air	2.94	0.58
G10	Trible clear 6mm/12mm Arg	2.14	0.72
G11	Trible clear 6mm/12mm Air	2.24	0.72
G12	Trible LoE 6mm/6mm Argon	1.61	0.45
G13	Trible LoE 6mm/6mm Air	1.93	0.45

Figure 5.12 provides a visualization of the performance of various glazing types across the three primary cities of Saudi Arabia: Riyadh, Jeddah, and Dhahran. This performance is determined by the U-values and the resulting annual energy consumption. The glazing types range from basic single clear 6 mm glass, called the base case glazing (BC-G), to the more advanced triple low-emissivity coated glazing with argon gas filling. BC-G has the

highest U-Value of 5.7 W/m²K, which signifies low performance, while G6, a double-reflective glazing with an argon gap, shows the lowest U-Value at 2.31 W/m²K. This progression in U-values, paired with the observed energy consumption metrics, highlights a vital trend: enhanced insulation characteristics, signified by a drop in U-value, corresponding to a reduction in energy consumption. For example, buildings in Riyadh with G6 glazing consumed an estimated 113.81 MWh, which marking visible difference compared to the energy consumption of the base-case (BC-G). This trend is also consistent across Jeddah and Dhahran. See Table 5.10.

Table 5. 10 Total annual energy consumption for different glazing types.

(EEM3) code	**Total annual energy Consumption (MWh)**		
	Riyadh	Jeddah	Dhahran
G1	117.443	149.716	131.1021
G2	117.662	149.918	131.365
G3	115.441	146.492	128.621
G5	115.722	146.779	128.903
G6	113.816	144.3212	127.209
G7	114.387	145.160	127.952
G8	116.261	147.232	129.743
G9	116.350	147.281	129.844
G10	115.576	148.409	128.924
G11	115.765	148.731	129.190
G12	114.722	146.554	128.232
G13	115.032	146.302	128.544

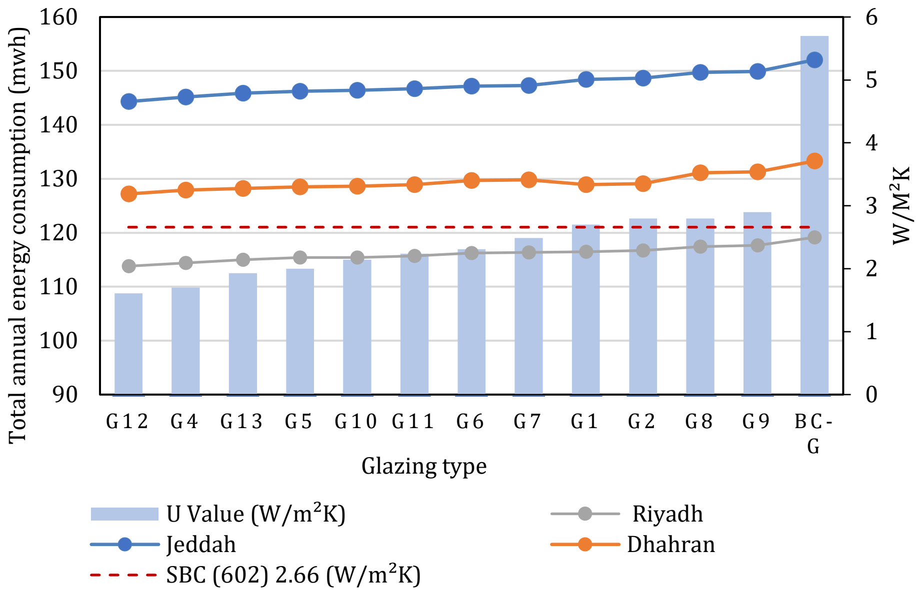


Figure 5. 12 Total annual energy consumption for different glazing types.

The various glazing options include a variety of choices, including double-clear glasses, reflective glazing, tinted glazing, and triple-layered glazing. These options can be further distinguished by the type of gas fill used: argon or air. Upon analysis of the energy savings percentages, it is evident that the double-reflective 6 mm/12 mm with argon gas filled displays the most significant energy savings across all cities, as presented in Figure 5. 13. This glazing option achieves energy savings of 4.5% in Riyadh and 4.6% in Dhahran, reaching its highest efficiency of 5.0% in Jeddah. In contrast, the double-clear glass options provide a reduction of 1.4% in energy consumption for the argon-filled form in Jeddah. Notably, adding another layer of triple-clear glass does not necessarily provide comparable increases in energy savings. For example, Triple Low-Emissivity (LoE) 6 mm/6 mm glass with argon gas filled in Jeddah provides a 3.5% reduction in energy consumption, higher than the 3.1% reduction achieved with air-filled glass.

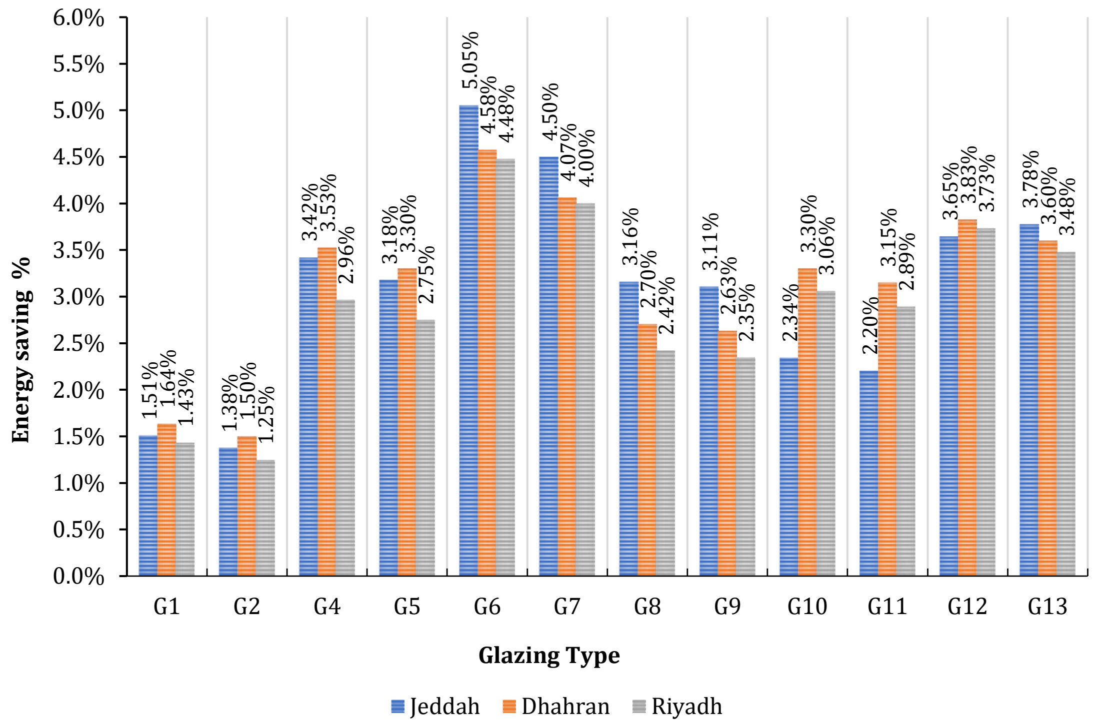


Figure 5. 13 Energy saving of various glazing types.

When evaluating the energy efficiency of several glazing types, (G6), Double Reflective 6 mm/12 mm with Argon filled, stands out as a particularly efficient option. Notably, its U-value of 2.31 W/m^{2}K approximately complies with the Saudi Building Code (SBC602) requirement, established at 2.668 W/m^{2}K. Furthermore, established retrofitting trends in residential structures favour double-glazing options due to a balance of cost-effectiveness, performance, and practicality, even if triple-glazing provides better energy savings. Although the total annual energy reduction provides insights into the performance of various glazing options, it is essential to investigate their behaviour under extreme conditions, especially during peak days, which represent the harshest summer and winter conditions. Peak days play a pivotal role in understanding the highest demands on a building's thermal energy, especially in the intense climatic conditions in Saudi Arabia. Solar gain, also known as solar heat gain, refers to additional heat in a space that is generated by sunlight. As the sun's rays enter a building, the interior spaces can warm up significantly, especially if building components, such as windows, are not designed to mitigate this effect. Efficient glazing solutions can reduce the amount of heat entering a building, reducing the demand for air conditioning and lowering overall energy consumption. In the context of this analysis, identifying the solar gain implications of different glazing options can provide insights into their performance, particularly in regions with high solar exposure, such as Saudi Arabia. By evaluating solar gain, the effectiveness of these glazing options in mitigating unwanted heat entry can lead to energy savings and enhanced occupant comfort. Figure 5.14 shows the total solar gain for different glazing options in the peak summer and winter days. The results indicate that the selected glazing options substantially reduce solar gain in all three cities.

Compared to the base case model featuring single clear glazing, the (G6) referred to as Double Reflective Glazing 6mm +12mm Arg, the city of Dhahran had a substantial decrease in solar gain, with a decline of more than 75%. Both Jeddah and Riyadh experienced decreases of more than 61%, demonstrating the efficacy of these glazing solutions in mitigating undesired solar heat absorption. The decrease in solar gain has the potential to reduce cooling loads, leading to potential energy savings, particularly in hot climates such as those observed in the investigated cities of Saudi Arabia.

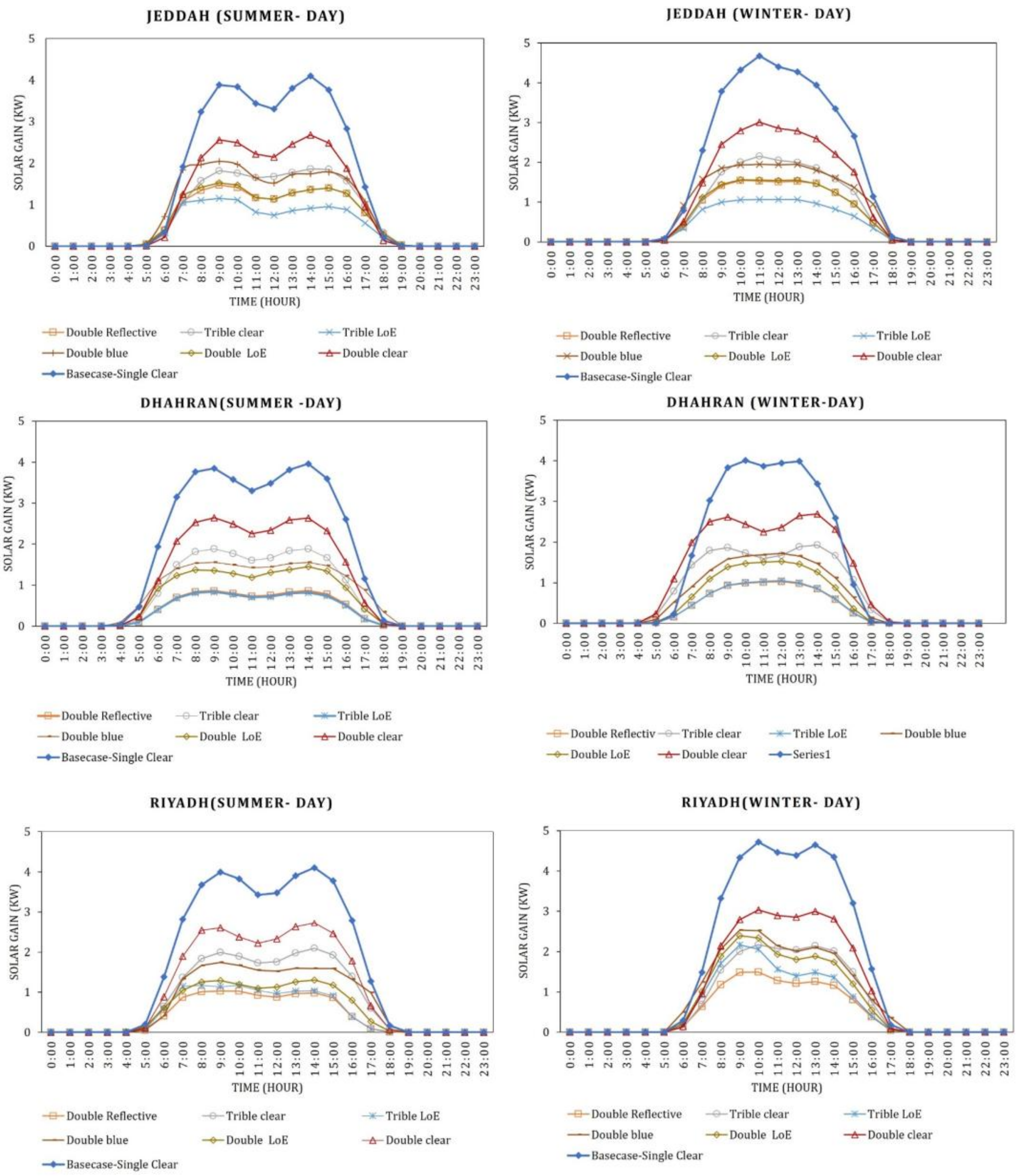


Figure 5. 14 Solar gain implications of different glazing options on summer day and winter day.

The evaluation in this section examined the effects of various glazing types on annual energy reduction and solar gain. Implementing double-glazed windows reduced yearly energy usage by as much as 4%. Multiple studies have been carried out to investigate the thermal and energy efficiency of innovative glazing systems in Saudi Arabia. An investigation was conducted to examine the influence of various glazing types on energy performance in a hot, arid climate. Double low-emissivity (low-E) glazing is a highly effective solution for mitigating heat conduction in regions characterised by high outside air temperatures, such as desert climates like those of Saudi Arabia(Qahtan, 2023; Al-Tamimi, 2022b). The double low-E glazing consists of two layers of glass with a thin metallic coating that reflects heat, preventing it from entering the building. This helps to reduce the need for excessive air conditioning, resulting in energy savings and improved comfort in hot climates. A recent study provides further evidence for the advantages of upgrading glazing technology from a double transparent layer to a reflective coating, resulting in improved energy efficiency and a reduction in energy usage by 22.7% (Al-Tamimi, 2022a).

In summary, this discrepancy can be attributed to differences in environmental conditions, building characteristics, and modelling assumptions. Various factors, including building type and orientation, window ratio to wall, and HVAC systems, can significantly impact the level of energy conservation. In summary, whereas residential construction may exhibit reduced solar gain compared to buildings featuring large windows, the presence of glass remains an essential factor in improving both energy efficiency and occupant comfort in regions characterized by high solar exposure, such as Saudi Arabia.

5.3.4 EEMs 4 External Shading

External shading devices can serve as effective passive design solutions for energy-efficient structures in Saudi Arabia. In countries where the sun is particularly intense, such as Saudi Arabia, external shading is necessary for reasons beyond aesthetics and energy conservation. Given Saudi Arabia's hot and humid climate, external shading devices can effectively control solar radiation on building surfaces and reduce heat gain. Several studies have been conducted on shading devices in Saudi Arabia, including using fixed external shade devices such as horizontal, egg-crate, and overhang types (Babaizadeh et al., 2015; Shahdan et al., 2018). Investigations have shown that external shading devices not only lead to a substantial decrease in energy consumption but also result in an improved distribution of internal sunlight within the building and overall building energy efficiency and the effectiveness of various shading methods in controlling solar radiation (Alwetaishi et al., 2021; Waheeb, 2005).

This section discusses the benefits of implementing external shading on overall energy consumption and solar gain. An analysis was conducted to determine the impact of external shading devices, taking into account the position of the sun during the summer solstice. The goal was to prevent direct solar radiation from penetrating the building during daytime hours. The effect on the output values was investigated by evaluating the implementation of various types and lengths of external shading elements individually, such as overhangs, side fins, and louvres, as shown in Figure 5.15 and Table 5.11.

Figure 5. 15 Shading types.

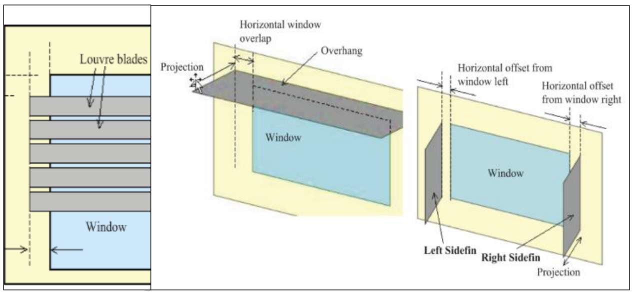


Table 5. 11 External shading type and length

(EEM4) Code	Glazing Type
S1	Overhang projection 0.2m
S2	Overhang projection 0.5m
S3	Overhang projection 1m
S4	Overhang + side fins 0.2m
S5	Overhang + side fins 0.5m
S7	Overhang + side fins 1m
S7	Louvres

SunCast was used to analyse the base case's sun shading. This demonstrated the amount of solar radiation on each facade throughout the year, helping to determine when shading was most desirable and necessary. Figure 5.16 displays the incident solar radiation (kWh/m^2) for each orientation of the base case. The findings revealed that the south facade had the highest incident solar flux values; however, the east and west facades also received significant solar radiation during the mornings and afternoons, emphasising the importance of shading facades.

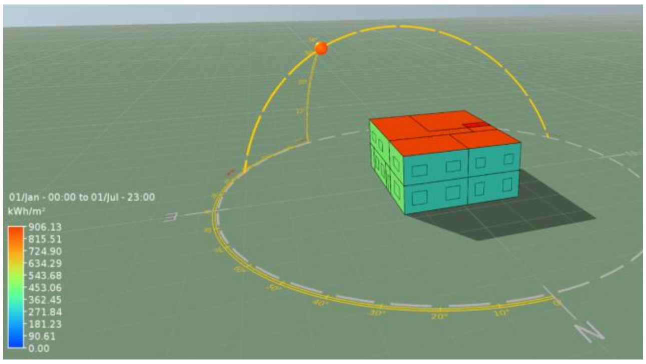


Figure 5. 16 Solar radiation on each facade of the base-case source: Source: IESVE, SUNCAST.

According to Robinson and Selkowitz (2013) state that equations 5.2 and 5.3 calculate the horizontal and vertical (HSA) shadow angles (VSA) for shading solutions to the desired shading period, determining the required depth of the vertical fins *(Dv)* and overhangs *(Do)* based on the orientation and size of the window.. Figure 5.17 shows the sun shading angle used to control solar heat gain through different shading devices' windows.

$$Dv = \frac{w}{Tan(HSA)} \quad \text{(Equation 5. 2)}$$

$$Do = \frac{L}{Tan(VSA)} \quad \textit{(Equation 5. 3)}$$

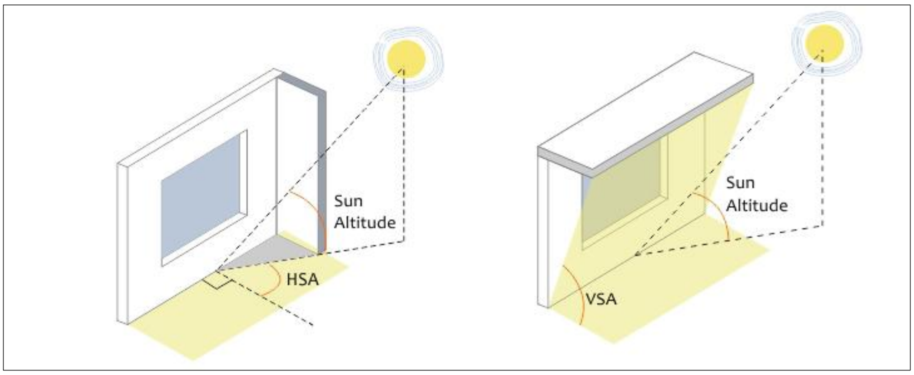


Figure 5. 17 Horizontal Shadow Angle (HSA) and Vertical Shadow Angle (VSA). Source: Shading-NZEB (2020).

Shaded solutions were found to be effective at reducing solar radiation. Dynamic simulations were performed for 0.2 m, 0.5 m, and 1 m deep horizontal overhangs, vertical fins, and louvres. Even though longer shading devices offer enhanced sun protection, they can overshadow a building's aesthetics. Given this, calculations that suggested a shading device depth exceeding one meter were not considered. An overview of the total annual energy consumption for various shading device configurations is shown in Table 5.12.

Table 5. 12 Total annual energy consumption for different configurations of shading devices.

(EEMs 4) code	**Total annual energy Consumption (MWh)**		
	Riyadh	Jeddah	Dhahran
S1	119.1452	152.0521	133.3024
S2	115.256	146.539	128.684
S3	115.1818	146.419	128.561
S4	115.113	146.247	128.441
S5	114.789	146.098	128.187
S6	114.672	145.623	127.926
S7	114.591	145.621	127.890

Figures 5.18 and 5.19 showcase the energy-saving potential of different external shading devices on the annual energy consumption and solar gain in Jeddah and Dhahran. In all three cities, the louvres have the highest solar gain-saving potential, with reductions of 81.8%, 65.3%, and 81.3% in Riyadh, Jeddah, and Dhahran, respectively. This is followed by the combination of an overhang and 1m side fins, offering reductions of 32.6% in Riyadh, 28.8% in Jeddah, and 30.4% in Dhahran. As the depths of the overhangs and side fins increased, the energy-saving potential improved. When it comes to specific energy savings, the louvres consistently offer up to 4% savings across cities. However, the overhangs combined with side fins, depending on their depth, ranged between 3.7% and 4.2% energy savings.

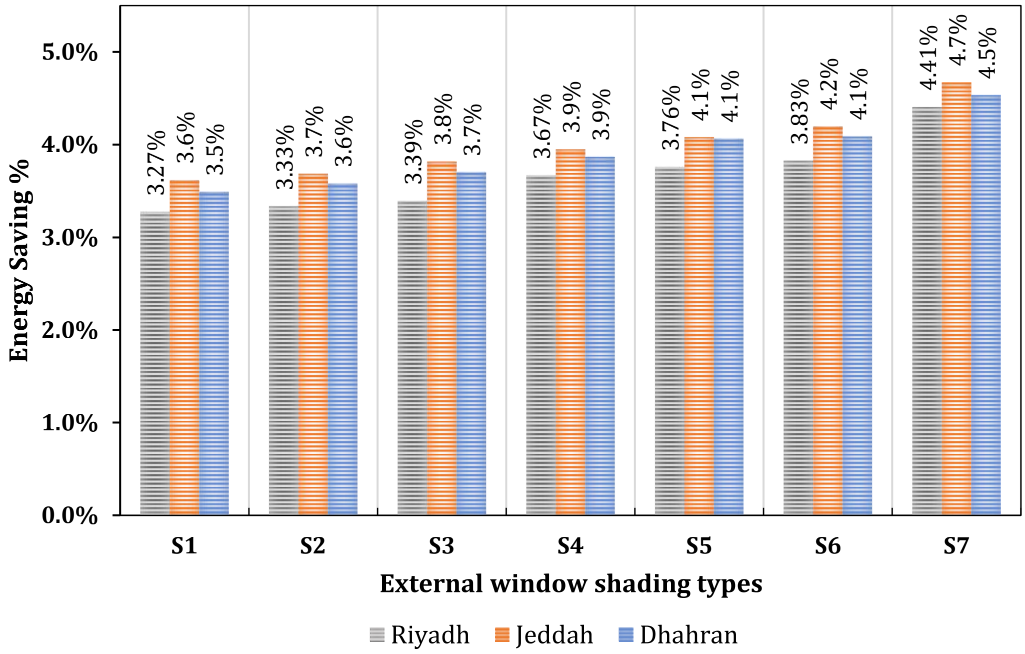
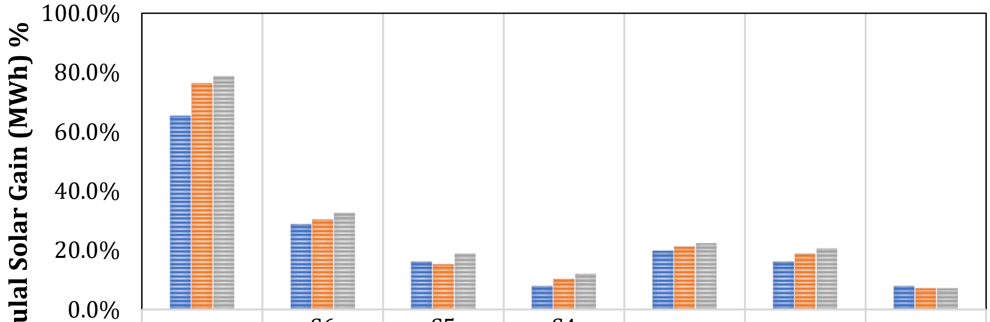


Figure 5. 18 The impact of applying external shading on total annual electricity consumption.



	S7 Louver	S6 Overhang +side fins 1m	S5 Overhang +Side fins 0.5m	S4 Overhang +Side fins 0.2m	S3 Overhang 1m	S2 Overhang 0.5m	S1 Overhang 0.2m
Jeddah	65.3%	28.8%	16.1%	7.9%	19.8%	16.1%	7.9%
Dhahran	76.3%	30.4%	15.2%	10.2%	21.2%	18.9%	7.2%
Riyadh	78.8%	32.6%	18.9%	12.0%	22.4%	20.6%	7.1%

Jeddah Dhahran Riyadh

Figure 5. 19 Effects of applying external shading devices on solar gain.

In conclusion, fixed shading devices are external shading devices commonly used in residential buildings that are permanently installed on the building's façade, such as fixed louvres, overhangs, and canopies (Alhuwayil et al., 2019). These devices effectively reduce solar heat gain and allow maintenance of a more desirable indoor temperature.

The findings indicate that the implementation of shading devices on building envelopes has the potential to decrease the cooling load by over 4%. In contrast, the implementation of shading devices to mitigate solar heat gain during peak summer days has the potential to yield energy savings ranging from 20% to 31%, depending upon the window-to-wall ratio (WWR) (Bellia et al., 2013; Alshamrani and Mujeebu, 2016; Krarti, 2022). According to ASHRAE (2017), shading devices significantly reduce solar heat gain by up to 80%. These findings highlight the importance of selecting the right shading device to optimize energy savings in residential buildings. Louvres are the most effective shading option tested in the cities of Riyadh, Jeddah, and Dhahran for minimizing solar and cooling gains.

5.3.5 EEMs 5 HVAC improvement: Upgrades and Cooling Set Point Adjustments

In energy conservation and efficient building practices, room cooling setpoints are pivotal in dictating electricity consumption, particularly in regions with high temperatures, such as Saudi Arabia. Although these setpoints can significantly impact overall energy usage, they must be balanced with occupant comfort. The Saudi Building Code (SBC, 2019) and the Saudi Energy Efficiency Centre (SEEC, 2018) recommend maintaining the setpoint temperature (SPT) for room cooling within the range of 23 °C to 25 °C. The Saudi Building Code (SBC, 2019) and the Saudi Energy Efficiency Centre (SEEC), suggested that the (SPT) for room cooling be kept within the range of 23 °C to 25 °C (SEEC, 2018). Nevertheless, a survey conducted has revealed that most residential properties in Saudi Arabia are equipped with air conditioning systems that are set to lower temperatures, reaching as low as 18 °C (Krarti and Howarth, 2020; Alshahrani, 2019).

A distinct pattern was observed when total electricity consumption was examined. For instance, when the cooling setpoint is adjusted to 18 °C, the energy consumption rises to 212.49 MWh in Jeddah, reflecting an increase of 39.1%; 189.15 MWh in Dhahran, marking an increase of 41.9%; and 162.83 MWh in Riyadh, also showing an increase of 41.9%. This is compared to the base-case setpoint of 23 °C, which results in energy consumption of 152.06 MWh in Jeddah, 133.30 MWh in Dhahran, and 119.15 MWh in Riyadh. Alternatively, increasing the setpoint temperature from 23°C to 25°C aligns with the upper limit of SEEC's recommendations and falls within the human thermal comfort zone, resulting in a consumption of 128.02 MWh in Jeddah, indicating a reduction of 16.2%; 116.07 MWh in Dhahran, a decrease of 12.9%; and 106.26 MWh in Riyadh, a reduction of 11%. See Figures 5. 20 and 5.21.

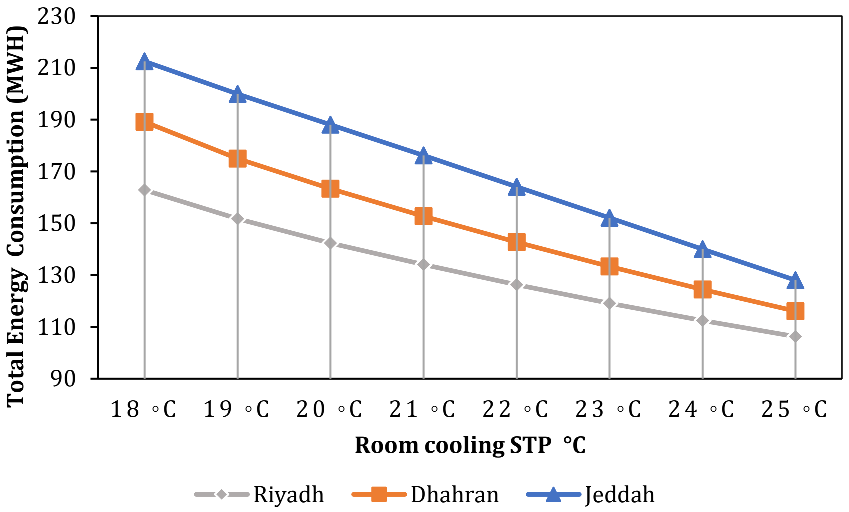


Figure 5. 20 Effect of cooling set point on energy consumption.

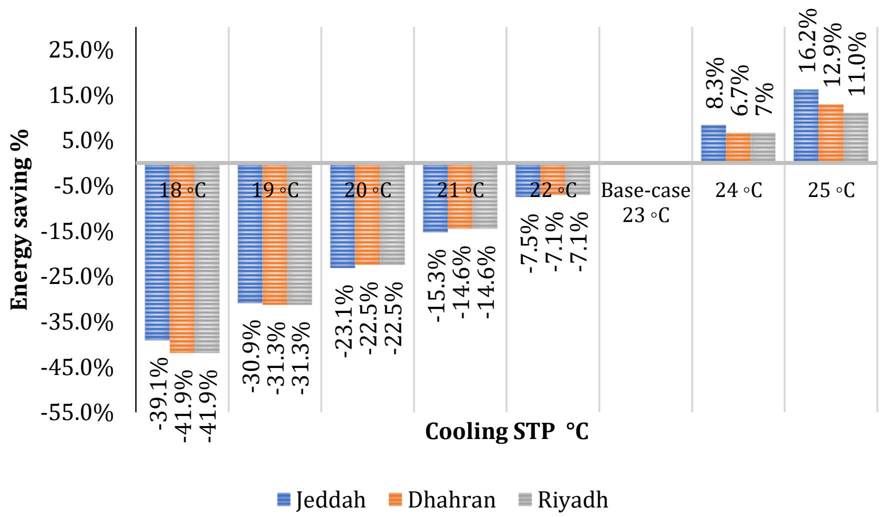


Figure 5. 21 The impact of varying cooling set points in the base case model vs. Energy savings

The second investigation in this section focuses on improving residential HVAC (Heating, Ventilation, and Air Conditioning) systems through the adoption of energy-efficient HVAC. In Saudi Arabia, with its hot and arid climate, enhancing the SEER (Seasonal Energy Efficiency Ratio) or Coefficient of Performance (COP) of cooling systems in residential buildings can bring substantial energy savings (Schiller et al.). The SEER, which measures the cooling efficiency of an air conditioner, and the COP, which measures the heating efficiency, are crucial indicators of energy efficiency. See Table 5.13: Seasonal Energy Efficiency (SEER) Classification.

The AC systems available in the Saudi market today, especially those complying with the latest Saudi Standards, Metrology and Quality Organization (SASO) regulations, typically have a higher Energy Efficiency Ratio (EER) (Howarth et al., 2020). n older buildings, AC systems are often less efficient because they were installed prior to the implementation of stringent energy efficiency standards or due to a preference for lower-cost, less efficient options. The COP of these older systems can be significantly lower, often ranging between 2.0 and 3.0. As a result, the Saudi Standards, Metrology, and Quality Organization (SASO) has introduced new air conditioner requirements. These standards are intended to improve the energy efficiency and overall performance of air conditioning systems in residential establishments.

The Saudi Energy Efficiency Centre (SEEC) has successfully enhanced split air conditioners' Minimum Energy Performance Standards (MEPS). From 2007 to 2018, the MEPS for these units increased by 57%, with the Energy Efficiency Ratio (EER) improving from 7.5 to 11.8. This achievement aligns with the strategic objectives of reducing energy consumption across various sectors, particularly in residential buildings, where air conditioning is a significant energy consumer (Howarth et al., 2020).

The SEEC also developed the standards for energy efficiency labels for air conditioners, which specify the unit's cooling capacity and energy efficiency ratio. A star rating, where a higher rating indicates more energy efficiency, is also included on the label. This has resulted in a decrease in energy consumption and emissions. Furthermore, the new MEPS helps reduce consumers' electricity costs. The label also includes a star rating, with more stars signifying greater energy efficiency.

Table 5.13 (SEER) Classification.

Bar colour	Energy class	SEER limits (Rated value)
Dark green	A	SEER ≥ 18.0
Green	B	18.0 > SEER ≥ 15.0
Light green	C	15.0 > SEER ≥ 12.5
Yellow	D	12.5 > SEER ≥ 10.0
Orange	E	10.0 > SEER ≥ 9.0
Red	F	9.0 > SEER ≥ 8.0

According to ASHRAE 90.1-2004, EER measures the efficiency of an air conditioner or heat pump. It is commonly used to compare the efficiency of different models of air conditioners and heat pumps. The higher the EER, the more efficient the system. The calculation for this measure is expressed in equation 5.4.

$$EER = COP * 3.41 \qquad \text{(Equation 5.4)}$$

By adopting a minimum Energy Efficiency Ratio (EER) ≈of approximately 12, which measures the cooling output of an air conditioner divided by the energy it uses, and roughly corresponds to a Seasonal Energy Efficiency Ratio (SEER) value of 14, a measure of the cooling output during a typical cooling season divided by the total electric energy input during the same period, the base-case air conditioning (AC) system can be enhanced to align with this required EER standard, corresponding to a (COP) of 3.5. Consequently, annual energy consumption can be reduced by between 23% and 27% across all three cities and cooling load savings of up to 33% can be realised as illustrated in Figure 5.22. Due to its coastal location, Jeddah saves more energy when upgrading the air conditioning system, as it experiences a humid climate compared to the more arid climates of Riyadh and Dhahran. Thus, it experiences a humid climate compared to the more arid climates of Riyadh and Dhahran. The combination of heat and humidity means air conditioning systems in Jeddah often must work harder to provide comfortable indoor conditions, leading to higher energy consumption in the base scenario. Thus, implementing energy-efficient measures in such environments will lead to a significant reduction in energy consumption. Even minor adjustments to the cooling setpoint and EER can impact a building's energy consumption.

The results validate the importance of the recommendations the SBC and SEEC set forth, highlighting the necessity of strategic and informed decision-making in building operations. Incorporating efficient air conditioning for a more energy-efficient future in

Saudi Arabia aligns with its sustainability goals. This transition has been established by government regulations, increased awareness of energy conservation, and an acknowledgement of the long-term economic benefits of energy-efficient appliances.

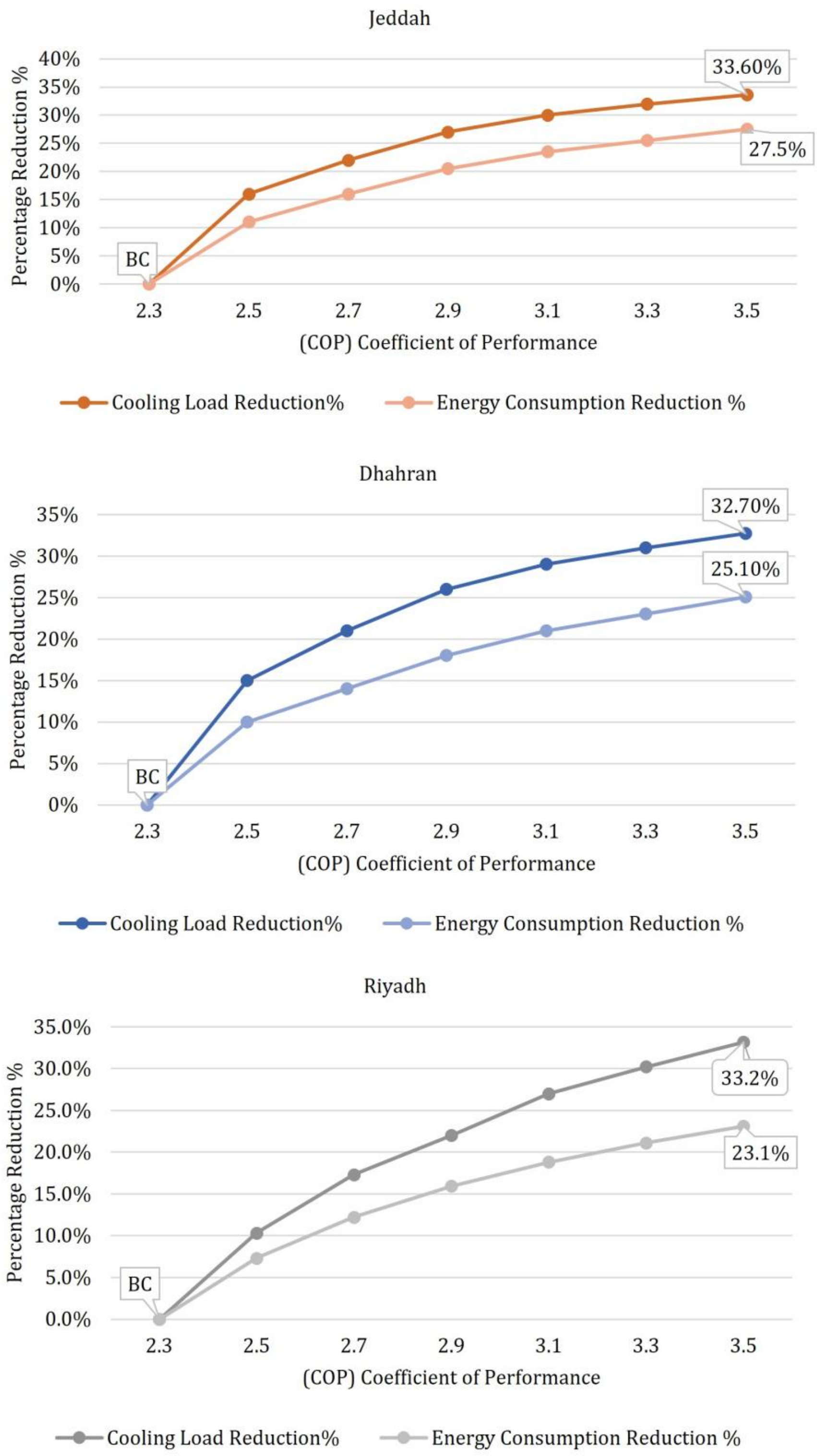


Figure 5. 22 Cooling load reduction and energy consumption Vs. COP.

In conclusion, optimising the cooling set point in air conditioning systems can significantly improve energy efficiency. It has been proven that increasing the temperature set point by two °C can result in an average cooling energy savings of 29%. However, the impact varies based on several factors, including the air conditioning units used, building insulation, and occupants' behaviours. Since its establishment in 2010, the Saudi Energy Efficiency Centre (SEEC) has raised the minimum Energy Efficiency Ratio (EER) requirements for air conditioning units. For instance, Al-Shaalan (2012) highlights efforts to enhance the EER for room air conditioners in Saudi Arabia, aligning with national energy efficiency standards. Notably, the minimum EER for split-type air conditioning units has increased from 7.5 to 11.8, indicating a significant improvement in their energy efficiency rating (Howarth et al., 2020). The results suggest that enhancing the cooling system's energy efficiency ratio to 11.8, which meets the minimum requirements set by the SEEC, can reduce average energy consumption by up to 25%.

The study by Alabdulkarem and Almutairi (2019) provides valuable insights into the importance of adhering to Minimum Energy Performance Standards (MEPS) for air conditioners. It emphasizes how older split-type air conditioners generally operate at only about 68% of the efficiency of newer models. Moreover, they found that replacing old compressors leads to significant performance improvements, reinforcing that upgrading older split-type air conditioners can result in energy savings and CO_2 emissions reductions. This evidence strongly supports the importance of applying MEPS to achieve better energy efficiency in residential and commercial buildings.

Furthermore, Alotaibi et al. (2023) explore the potential energy savings and CO_2 emission reductions achievable through various improvements in the Energy Efficiency Ratio (EER) of new air conditioner stocks in Saudi Arabia up to 2030. Their analysis highlights the critical importance of advancing air conditioner efficiency within the framework of the country's energy conservation strategies (Alotaibi et al., 2023).

5.3.6 EEMs 6 Influence of Air Infiltration

A building's energy efficacy is significantly affected by air infiltration, which is the uncontrolled airflow into a building through cracks, gaps, and openings. Uncontrolled air leaks can be unnecessary, affecting the surrounding air temperature and increasing the HVAC system load. Proper insulation and sealing in these areas can help reduce energy consumption and improve heat gain or loss. This leads to higher energy usage and lower comfort levels for the occupants. However, ensuring proper sealing can substantially reduce the negative effects of air infiltration, creating a more energy-efficient and comfortable environment. The infiltration rate, often measured in air changes per hour can significantly impact the cooling and heating needs of a building, due to the air exchange between indoor and outdoor environments (Mattsson, 2006).

Analysing energy consumption at different infiltration rates provides valuable insights into the correlation between infiltration rates and energy efficiency. The Saudi Building Code specifies a standard infiltration rate of 0.25 ACH, emphasizing the significance of maintaining airtight building envelopes to reduce energy usage. With a baseline infiltration rate of 0.8 ACH, the energy consumption rates are 152.055 MWh in Jeddah, 133.30 MWh in Dhahran, and 119.145 MWh in Riyadh. It is important to consider the energy implications of adjusting this rate. When the ACH is decreased to the recommended 0.25 ACH, Jeddah records an energy consumption of 135.94 MWh, showcasing a 10.6% decrease compared to the baseline. Dhahran and Riyadh registered a 7.8% decrease and a 6% decrease, respectively, as illustrated in Figure 5.23. However, as ACH increases beyond the base case, energy consumption rises, highlighting a contradictory relationship between ACH and energy efficiency, as shown in Figure 5.24. Due to localized factors and climates, each city uniquely responds to changes in ACH. Still, energy consumption consistently rises beyond the recommended standard in all cities, emphasizing the importance of adhering to building code guidelines.

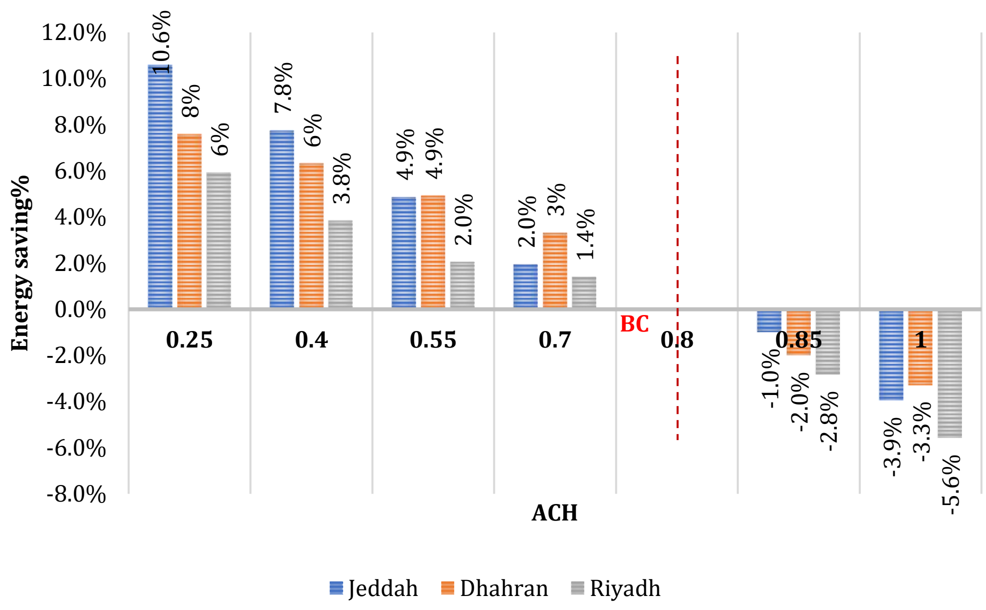


Figure 5. 23 Percentage change in Energy Consumption vs. ACH

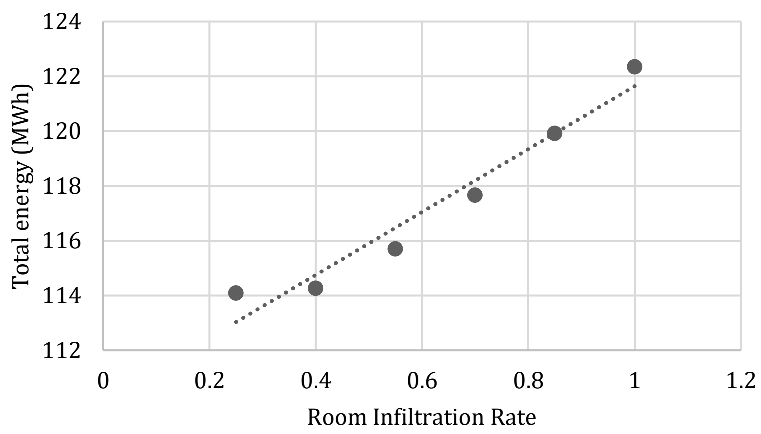


Figure 5. 24 Room Infiltration Rate vs. Total energy (MWh) appears highly correlated.

The findings highlight the significance of managing infiltration rates. By enhancing air tightness to the 0.25 ACH standard as recommended by SBC-602, an average annual energy savings of 8% can be achieved. Buildings in these cities benefit significantly from adopting measures that align with the recommended infiltration rate of the Saudi Building Code. This can be achieved through superior sealing, advanced materials, or controlled ventilation systems, paving the way for a sustainable and energy-efficient future in Saudi

Arabia. A study conducted by Said and Al-Hammad (1993), demonstrated that implementing energy conservation strategies, like wall and roof insulation, and reducing the infiltration rate on a typical two-story residential building in Saudi Arabia, resulted in a significant 27% reduction in annual energy consumption. Another study by Almarzouq and Sakhrieh (2019) in Amman, Jordan, found that reducing the infiltration rate by 50% can save 19.4% of the energy consumed.

The results of this study are consistent with previous research conducted in the field. This objective can be accomplished through various strategies, including implementing measures such as sealing gaps and cracks, installing energy-efficient windows and doors, and insulating the building envelope in a hot and humid temperate climate (Mechouet et al., 2018; Zečević et al., 2018; Fard et al., 2019; Tombarević et al., 2023; Alardhi et al., 2020).

5.3.7 EEMs 7 PV Roof Integration

This section examines the feasibility of integrating photovoltaic (PV) systems on building rooftops. PV technology was selected over other renewable options for several compelling reasons. Saudi Arabia's high solar radiation levels, coupled with strong governmental support for solar energy under Saudi Vision 2030, make PV an optimal choice for residential energy generation. Subsidies may be offered to offset the initial installation costs of PV systems. Additionally, special tariffs for PV-generated electricity encourage adoption by offering favourable rates compared to standard electricity prices. Compared to other renewable sources like wind or biomass, PV systems are better suited for residential use because they can be easily installed on rooftops without requiring large areas or complex infrastructure. This makes them especially practical in urban settings, where space is limited, and energy demands are high.

The monocrystalline silicon module is chosen for this case because it's the most popular type of PV system for the residential sector. In addition, it's the most efficient type in the kingdom's market since it uses a higher grade of silicon (Alshahrani, 2018). Saudi Arabia's expanding population and rising energy needs highlight the urgent need for sustainable energy sources. The Kingdom has responded by announcing significant projects such as the National Renewable Energy Program (NREP). The NREP is a program dedicated to reducing Saudi Arabia's dependence on fossil fuels and its significantly increasing its growth in renewable energy. The Ministry of Energy, Industry, and Mineral

Resources (MEIM) directs it, in line with Vision 2030. By the year 2030, NREP plans to add 54 GW of renewable power capacity to the Kingdom, which would be 20% of the total energy output of Saudi Arabia (Alghamdi et al., 2017).

The country's geographical advantage makes solar power essential. The Saudi solar radiation atlas project, a collaboration between the KACST Energy Research Institute and the US National Renewable Energy Laboratory, offers valuable insights into solar radiation levels. Solar power's feasibility as a primary energy source is evidenced by its successful implementation in energizing the Kingdom (Ajlouni and Alsamamra, 2019). The NREP has launched 13 projects with a total capacity of 4,870 MW, comprising 4,470 MW from solar energy and 400 MW from wind energy (GAStat, 2020).

Considering these developments, this study investigates the potential of photovoltaic (PV) panels to enhance national power generation capacity. It explores the benefits of managing peak electricity demands and transitioning energy consumers into energy producers. Adopting solar photovoltaics (PV) is not just an energy strategy; it's a transformative step towards developing sustainable buildings. PV technologies can be an excellent source of on-site energy generation and cost savings. As a result, the Saudi government recently announced the beginning of a program for installing small-scale solar PV systems and linking them to the transmission system of KSA's national electricity grid (AlOtaibi et al., 2020).

In 2019, the Electricity & Cogeneration Regulatory Authority (ECRA) issued a report outlining the regulatory criteria for small PV solar systems linked to the distribution grid in Saudi Arabia (ECRA, 2019). The ECRA has set the export tariff for surplus energy produced by PV systems in the residential sector at 0.07 SR (0.019 $/kW), as detailed in Table 5.14. In contrast, the residential electricity rate in Saudi Arabia varies from 0.18 SR/kWh (0.048 $) for the first 6000 kWh consumed to 0.30 SR/kWh (around 0.08 $) for higher usage (SEC), as shown in Table 5.15. This program was launched in January 2018 following the government's strategy to subsidize energy use, offering significant financial benefits to consumers.

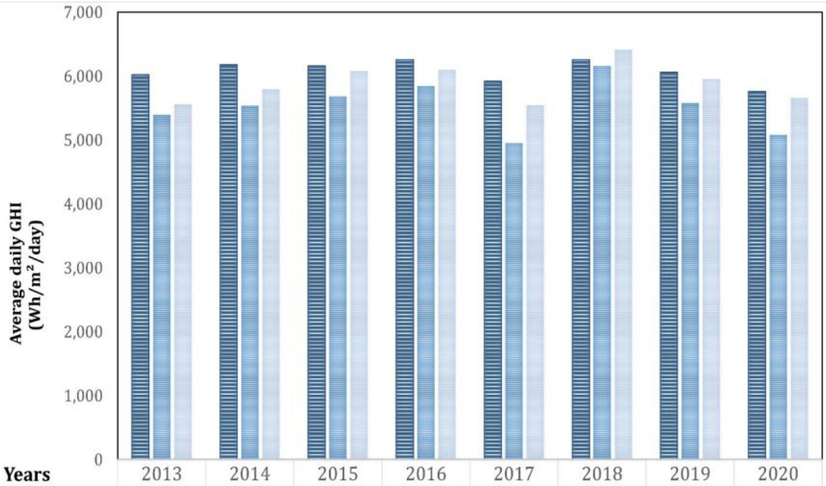
Table 5. 14 Feed-In Tariff for surplus energy of photovoltaic systems in the residential sector, source (ECRA, 2019)

Sector FI	($/kWh)
Residential sector	0.019

Table 5. 15 Energy consumption tariffs in Saudi Arabia (SEC, 2021).

Saudi Arabia's Electricity prices	Consumption Category	($/kWh)
Residential Sector	Up to 6000 kWh	$0.048
	Above 6000 KWH	$ 0.08

In this study, a grid-connected PV system on a building's rooftop was simulated. Photovoltaic (PV) cells directly convert solar energy into electricity. Multiple solar panels work together to convert global horizontal irradiance (GHI) into electricity. Figure 5. 26 displays the average global horizontal irradiance (GHI) across the three regions over eight years. The Central Region experienced an average GHI of approximately 6,080 $Wh/m^2/day$. The Eastern Region had an average closer to 5,530 $Wh/m^2/day$, while the Western Region had a slightly higher average GHI of approximately 5,894 $Wh/m^2/day$. The average daily global horizontal irradiance (GHI) across the three regions from 2013 to 2020, is illustrated in Figure 5.25. The GHI of the Central Region varied between a low of 5,763 $Wh/m^2/day$ in 2020 and a peak of 6,261 $Wh/m^2/day$ in 2018. In the Eastern Region, the values ranged from a noticeable drop to 4,953 $Wh/m^2/day$ in 2017 to a high of 6,159 $Wh/m^2/day$ in 2018. The Western Region exhibited the most consistent rise in GHI, starting at 5,560 $Wh/m^2/day$ in 2013 and reaching a height of 6,416 $Wh/m^2/day$ in 2018. This trend closely mirrors the GHI findings in the study by (Almushaikah and Almasri, 2020a). These ranges highlight the variability of solar irradiance across years and regions, reflecting the influence of local climatic and atmospheric conditions on solar energy potential.



Years	2013	2014	2015	2016	2017	2018	2019	2020
Average daily Irradiance in Central Region	6,022	6,181	6,166	6,258	5,924	6,261	6,066	5,763
Average daily Irradiance in Eastern Region	5,395	5,537	5,682	5,847	4,953	6,159	5,582	5,085
Average daily Irradiance in Western Region	5,560	5,796	6,081	6,099	5,545	6,416	5,954	5,658

Figure 5. 25 Average Daily global horizontal irradiances (GHI) from 2013-2020. Source: GAS.

It is important to understand that various factors influence GHI values, including atmospheric conditions, geographical location, and seasonal variations. Changes in these factors can be attributed to the observed variations in GHI over the years. Given the high solar irradiance, particularly in the Western and Central Regions, there is significant potential for utilizing solar energy in these areas.

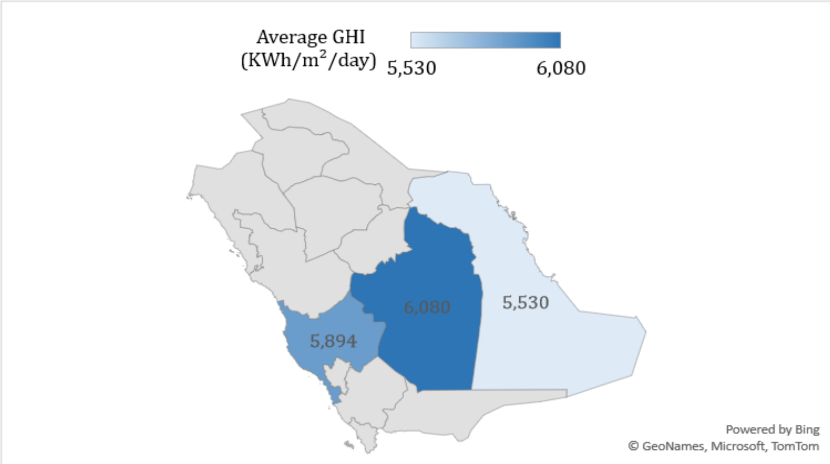


Figure 5. 26 Average (GHI) Across three regions, Source: Author's calculations and statistics based on data from the General Authority for Statistics (GAS, 2020).

Mono-crystalline silicon solar cells are known for their high efficiency due to their single-crystal structure. Each solar module comprises 60 cells connected in series and has dimensions of 1665x1002x35mm, translating to an area of approximately 1.66 m^2 per module based on the manufacturing data (See Table 5.16). The efficiency of these modules is 18.6%, indicating that they convert 18.6% of the received sunlight into electricity. The ratio of available area for PV utilization to the total roof area has been identified to vary between 25% and 40%, demonstrating the effectiveness of rooftops for solar PV installations in buildings (Abu-Hijleh and Jaheen, 2019; Asif et al., 2018).

In this section, different coverage percentages for rooftop PV systems are considered: 20%, 30%, and 40%, which correspond to areas of 39.36 m^2, 59 m^2, and 68 m^2, respectively, and can accommodate ≈24, ≈33, and ≈39 panels, respectively. The solar panels on the rooftop have been positioned at the ideal orientation angles of 20° and 24° facing south for Riyadh, as recommended by Al Garni et al. (2019); Dehwah et al. (2020). Figure 5.27 provides a schematic representation of the PV array layout on the rooftop of the case study building.

Table 5. 16 PV module mechanical data (SUNPRO, 2023).

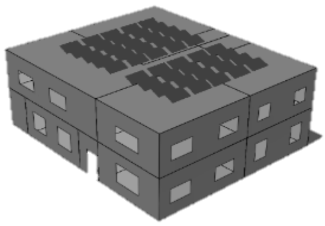
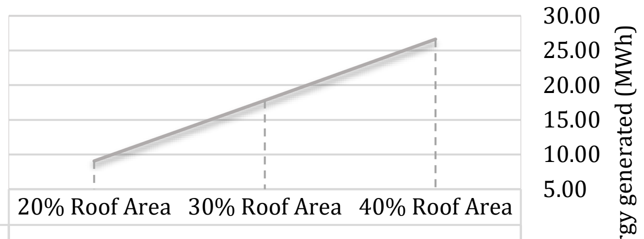
Solar Cells	**Mono-crystalline silicon**
No. of Cells	60 cells in a series
Module Dimensions	1665x1002x35mm
Weight	19 kg
Max power (Pmax)	305 W
Front glass	3.2mm tempered glass
Module Efficiency	18.6%
Operate Temperature Scope	-40/+85°C
Electrical parameters at standard test conditions (STC:AM=1.5, 1000W/ m^2, Cells Temperature 25°C)	 **Figure 5. 27 PV roof array**

Table 5. 17 Total annual energy consumption, energy saving%, and PV energy generation) across three cities for each PV system size.

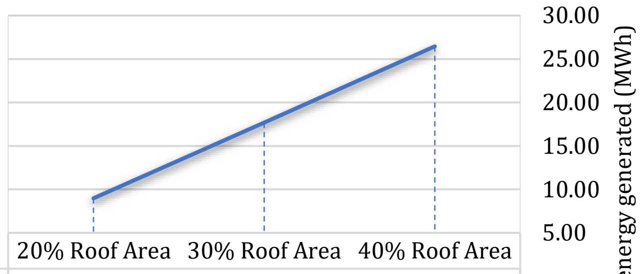
PV system Size	***Total energy consumption (MWh)***			***Energy saving %***			***PV Energy generation (MWh)***		
	Riyadh	*Jeddah*	*Dhahran*	*Riyadh*	*Jeddah*	*Dhahran*	*Riyadh*	*Jeddah*	*Dhahran*
20% *rooftop PV array*	109.3375	140.954312	123.294	8.23%	7.27%	7.51%	9.0614	8.9784	8.7345
30% *rooftop PV array*	100.765	131.6098	114.443	15.42%	13.41%	14.15%	17.8109	17.692	17.1604
40% *rooftop PV array*	91.3577	122.389	105.624	23.32%	19.48%	20.76%	26.6325	26.45355	25.655



	20% Roof Area	30% Roof Area	40% Roof Area
Total annual energy consumption (MWh)	109.338	100.765	91.358
PV Energy generation (MWh)-Riyadh	9.0614	17.8109	26.6325

PV System Size

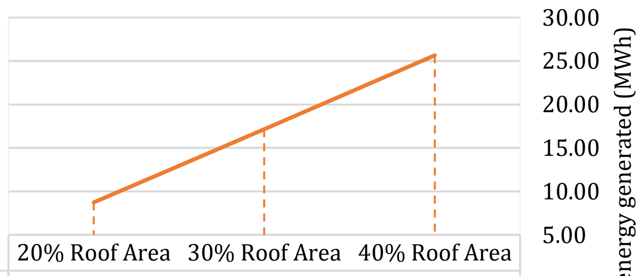
PV Energy generation (MWh)-Riyadh



	20% Roof Area	30% Roof Area	40% Roof Area
Total annual energy consumption (MWh)	140.954	131.610	122.389
PV Energy generation (MWh)-Jeddah	8.9784	17.6920	26.4536

PV System Size

PV Energy generation (MWh)-Jeddah



	20% Roof Area	30% Roof Area	40% Roof Area
Total annual energy consumption (MWh)	140.954	131.610	122.389
PV Energy generation (MWh)-Dhahran	8.7345	17.1604	25.6550

PV System Size

PV Energy generation (MWh)-Dhahran

Figure 5. 28 Annual Energy consumption and generation of different rooftop PV system sizes in Riyadh, Jeddah, and Dhahran.

Table 5.17 outlines the energy generation capacities of photovoltaic (PV) systems installed on rooftops in three cities in Saudi Arabia: Riyadh, Jeddah, and Dhahran. The energy savings shown in the table are due to the integration of (PV) systems. PV systems generate electricity from solar energy, which reduces the demand for energy from other sources, thereby resulting in energy savings. The findings reveal a clear correlation between PV system size and the reduction in total energy consumption. In Riyadh, as the PV system size increases, the total energy consumption decreased from 109.3375 MWh to 91.3577 MWh. These capacities allow for 40% rooftop coverage, which is the highest level of coverage. This reduction corresponds to energy savings percentages increasing from 8.23% to 23.32%. Similarly, in Jeddah, the total energy consumption decreases from 140.954312 MWh to 122.389 MWh, with energy savings percentages increasing from 7.27% to 19.5%. Dhahran exhibits a similar trend, with total energy consumption decreasing from 123.294 MWh to 105.624 MWh and energy savings percentages ranging from 7.51% to 20.76%.

The integration of PV systems also contributes to substantial PV energy generation. In Riyadh, PV energy generation ranges from 9.0614 MWh with the smallest PV system to 26.6325 MWh with the largest system. Jeddah follows a similar pattern, with PV energy generation increasing from 8.9784 MWh to 26.4535 MWh. In Dhahran, PV energy generation ranges from 8.7345 MWh to 25.655 MWh. Through the implementation of 40% rooftop PV array coverage, the cities managed to achieve an average energy reduction of approximately 20% in their total energy consumption (See Figure 5.28).

The performance of the PV system aligns with the findings of other studies in KSA (Dehwah et al., 2018b; Asif et al., 2023; Ahmed et al., 2019; Asif, 2020). These studies have also highlighted the positive impact of PV systems on reducing greenhouse gas emissions and dependence on fossil fuels in Saudi Arabia. Furthermore, they have emphasised the need for further research and investment in PV technology to maximise its potential in the country's energy transition.

In conclusion, the integration of PV systems in residential buildings in Riyadh, Jeddah, and Dhahran demonstrates substantial potential for energy efficiency improvements. By increasing the size of PV systems, significant reductions in energy consumption can be achieved, as well as corresponding increases in energy savings. It is evident that in Riyadh, PV systems generate the most energy across all coverage percentages, followed closely by

Jeddah. Dhahran, while still producing substantial energy, exhibits slightly lower energy generation. The reasons for these variations could be attributed to factors such as solar irradiation conditions.

5.3. Summary

This chapter begins by analysing the baseline model of residential buildings in Saudi Arabia and then individually assessing the impact of various energy efficiency measures (EEMs). Each measure's effectiveness is evaluated through multiple assessments, which is critical for identifying the EEMs that most significantly influence the base-case model's energy performance. This approach provides a comprehensive view of how each measure can independently contribute to the overall energy efficiency of residential buildings. This section is particularly significant for understanding the most beneficial retrofitting options in Saudi Arabia's residential sector. The individual EEMs assessed include enhanced thermal insulation for walls and roofs, the integration of high-efficiency glazing coupled with external shading, HVAC system upgrades, and the implementation of photovoltaic solar panels.

The upcoming chapter will evaluate an improved model that integrates the combined effects of various retrofit energy measures. The analysis will investigate the overall impact of the combined measures on energy consumption and carbon emissions. Furthermore, it will examine the improved model's cost-benefit effectiveness. Emphasizing efficiency and cost-effectiveness is essential for developing energy optimization solutions for housing developments.

Chapter 6

Integration and Optimization of EEM Strategies: Evaluation of Combined Scenarios in the Improved Energy Efficiency Model

6.1. Introduction

In the context of this study, the primary objective is to identify the most energy-efficient outcomes resulting from various retrofitting strategies. This section also evaluates a cost-benefit analysis for the proposed retrofit measures. While financial considerations often influence decisions related to building enhancements, this study emphasizes the lasting benefits of energy conservation. It is important to note that the potential for consistent energy savings over time greatly influences the decision-making process. Although specific retrofitting strategies may involve higher initial material costs, the long-term energy savings from lower energy bills and reduced reliance on energy resources can outweigh these initial investments[1]. As a result, the selected measures for this study were based on their ability to achieve significant overall energy conservation.

Following the detailed evaluation of individual Energy Efficiency Measures (EEMs) for building retrofits outlined in Section 5.3, this chapter explores the combined effects of these measures. It begins with a review of the high-impact EEMs identified earlier, emphasizing their potential when integrated into a unified strategy. Based on theoretical insights and detailed simulations from earlier chapters, these initial assessments set the

[1] The initial investment cost incorporates estimated expenses based on local market rates, which are required to implement the energy efficiency measure across the specified area. This includes the cost of materials and installation, calculated according to the total area covered. Implementation cost = Unit price ($/m2) × EEM area (m2).

stage for a deeper investigation into their impact on energy consumption in Saudi Arabian residential buildings.

This chapter aims to analyse an improved energy efficiency model that incorporates multiple EEMs. The improved model demonstrates how combining various strategies can achieve more significant energy savings. Additionally, this chapter includes a cost analysis of the integrated approach. This analysis is essential as it evaluates the financial feasibility of implementing these combined measures, calculates payback periods, and provides a clear economic perspective on the potential energy-saving measures.

Following the detailed evaluation of individual (EEMs) for building retrofits outlined in Section 5.3 above, this chapter explores the combined effects of these measures. It begins with a review of the high-impact EEMs identified earlier, emphasizing their potential when integrated into a unified strategy. Based on theoretical insights and detailed simulations from earlier chapters, these initial assessments set the stage for a deeper investigation into their impact on energy consumption in Saudi Arabian residential buildings.

This chapter aims to analyse an improved energy efficiency model that incorporates multiple EEMs. The improved model demonstrates how combining various strategies can achieve more significant energy savings. This analysis is essential as it evaluates the financial feasibility of implementing these combined measures, calculates payback periods, and provides a clear economic perspective on the potential energy-saving measures.

6.2. Best Practices in Energy Efficiency Measures (EEMs); Selection of Optimal Energy Efficiency Measures (EEMs) by Category

Given the significant energy consumption of the construction industry globally, it is essential to investigate and implement effective EEMs. Various retrofit strategies have been assessed for their potential to reduce energy consumption. After individual evaluations of their contributions to energy efficiency, the strategies that demonstrated the most substantial reductions in energy consumption were selected. These high-impact EEMs are evaluated against a base case model in Riyadh, Jeddah, and Dhahran.

The selection of combinations of Energy Efficiency Measures (EEMs) was determined based primarily on their high potential for energy savings. This focus on high energy-saving EEMs guarantees that the combined measures not only work harmoniously together but also provide optimal energy savings and economic benefits. Additionally, factors such as cost-effectiveness and regulatory compliance, were considered to enhance the effectiveness and practicality of the integrated measures.

Table 6.1 summarises each measure, detailing the actions implemented, their advantages, potential challenges, and their overall effect on energy conservation. The measures, which include advancements such as improved thermal insulation and solar photovoltaic system installations, are assessed for their energy impact, offering insights into their relative effectiveness. The star ratings assigned to various (EEMs) are based on the quantitative energy savings achieved by each measure. The star ratings for each EEM are scientifically based on the actual energy savings observed. Following the establishment of these categories, it is feasible to provide a metric that can accurately reflect the actual improvement in energy efficiency.

This scale is defined as follows:

- 0-5% energy savings: ★☆☆☆☆
- 6-10% energy savings: ★★☆☆☆
- 11-15% energy savings: ★★★☆☆
- 16-20% energy savings: ★★★★☆
- 21% and above energy savings: ★★★★★

Table 6. 1 Analysis of Selected EEMs for Energy Efficiency Enhancement.

EEMs	Overview	Implementation	Advantages	Potential Challenges	Energy Impact
EEM1 & EEM2	Thermal Insulation Implementation.	Addition of advanced insulative materials	prevent heat transfer, Superior thermal control, reduce heating/cooling costs	Initial investment, adjustments potential spatial	★★★☆☆ (average11-15% savings)
EEM3	High-Efficiency Glazing Upgrade	Installation of high efficiency glazing for windows	Enhanced thermal comfort and energy efficiency	Adapting to existing window frames, structural adjustments	★☆☆☆☆ (3.53-4.7% savings)
EEM4	Shading devices	Installation of shading solutions such as overhangs and louvres	control the amount of sunlight entering the building Reduction in solar heat gain, leading to decreased cooling requirements	Integration with existing building aesthetics and architecture	★☆☆☆☆ (3.53-4.7% savings)
EEM5	HVAC Improvement	upgrading or replacing HVAC equipment for energy-efficient models that meet or exceed industry standards.	Improved energy conservation, indoor temperature control	Initial cost, maintenance.	★★★★★ (Average savings 28.8 %)
EEM6	Air Exchange Adjustment	Reduce infiltration rate by sealing leaks and improving building envelope tightness	Reduced uncontrolled airflow, cooling savings, and enhanced indoor air quality.	Balancing reduction of air changes per hour (ACH) while ensuring adequate ventilation	★★☆☆☆ (6-10.6% savings)
EEM7	Solar Radiation Conversion (PV)	Rooftop photovoltaic panel installation	Green energy production, the potential for energy sell-back.	The significant initial investment, spatial constraints	★★★★★ (19.5-23.3% savings)

Figures 6.1, 6.2, and 6.3. represent single measures with maximum energy savings vs. total energy consumption of the Optimal EEMs[2]. The base-case model (BC), representing energy consumption without efficiency improvements, fails to meet the current building regulations. This discrepancy highlights the necessity for implementing Energy Efficiency Measures (EEMs) to bring these buildings up to current standards and improve their energy performance.

- **EEMs1- EW2** focuses on wall insulation enhancements, that have proven to be significant in reducing energy consumption across various cities in Saudi Arabia. The impact is substantial, with Riyadh observing a 12.9% decrease, Jeddah recording 10.9%, and Dhahran achieving a 12% reduction.
- **EEMs2- R2** is the second phase of roof insulation optimization that enhances the building's energy dynamics. Riyadh experienced a 14.8% decrease, Jeddah 12.7%, and Dhahran 13.8%. Implementing insulation measures (EEM1 and EEM2) resulted in significant energy savings in all three cities. These measures are not only effective in reducing heat transfer and energy consumption, but they are also highly effective.
- **EEM3** and **EEM4 -G6 & S7** concentrate on improving glazing and shading techniques, respectively. Their impacts, while valuable, are relatively moderate, with savings ranging between 3.53% and 5% across the cities. While not as impactful as insulation, glazing improvements still contribute positively to energy efficiency.
- **EEM5** highlights enhancements to the HVAC system by improving the coefficient of performance or EER and increasing the cooling set point. Jeddah

[2] For detailed specifications and codes associated with each EEMs, refer to Table 5.5, Table 5. 7 and Table 5. 9,

Table 5. 11 and Table 5. 16. These include specific Codes of insulation, glazing, shading, HVAC components, and photovoltaic systems related to each EEMs. The most effective energy efficiency retrofit measures, identified by their codes: EEM1-EW2, EEM2-R2, EEM3-G6, EEM4-S7, EEM5-HVAC, EEM6-ACH, and EEM7-PV 40%.

experienced the most significant benefit, achieving a 16.2% reduction through cooling set point adjustments. Riyadh and Dhahran also observed notable energy savings, indicating 11% and 12.9% reductions, respectively. Furthermore, energy savings ranging from 28% to 30% were achieved by upgrading to an efficient HVAC system and increasing the cooling set point in Jeddah, Dhahran, and Riyadh.

- **EEM6** focuses on the building's infiltration rate, specifically Air Changes per Hour (ACH). In Jeddah, a notable 10.6% reduction in energy consumption was observed. Minimizing air leakage is essential for sustaining indoor comfort and reducing energy usage.
- **EEM7** integrates a photovoltaic (PV) roof system, which covers 40% of the accessible roof area. This measure alone led to substantial energy savings of 23.3% in Riyadh, 19.5% in Jeddah, and 20.8% in Dhahran. Integrating solar energy through PV systems is a sustainable solution for reducing reliance on power sources.

Table 6. 2 U-Values for the base-case and improved models against Saudi building code (SBC-602) for climate zone 1.

		U-value W/m²·K		
		Wall	Roof	Window
SBC602	Climate Zone 1	0.342	0.202	2.66
Base Case	Zone 1 Riyadh-Jeddah and Dhahran	2.15	2.123	5.78
Improved Case	Zone 1 Riyadh-Jeddah and Dhahran	0.325	0.205	2.31

Table 6.2 compares the U-values (thermal transmittance) of walls, roofs, and windows in Riyadh, Jeddah, and Dhahran between the base case and improved models, benchmarked against the Saudi Building Code (SBC602) for Climate Zone. These values are significantly higher than the SBC-602 standards, indicating that the base case buildings are highly inefficient. The base case building is old-constructed and non-compliant with current energy efficiency regulations, leading to high energy consumption. By contrast, the improved case in Riyadh shows a dramatic reduction in U-values to 0.325 W/m²·K for walls, 0.205 W/m²·K for roofs, and 2.31 W/m²·K for windows. These values meet or exceed the SBC602 standards, demonstrating a significant enhancement in thermal performance. Overall, while implementing measures such as thermal insulation

and upgrading HVAC systems has benefits, combining all energy-efficient measures significantly impacts energy conservation. These findings emphasize the importance of recognizing the advantages of individual energy-efficient measures and establishing a standard for future energy-saving building techniques.

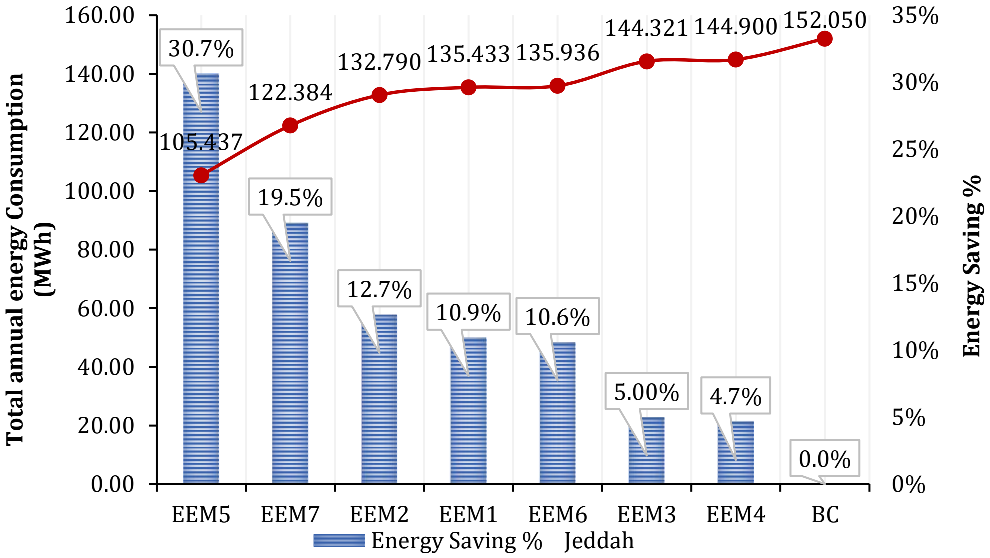


Figure 6. 1 Total annual energy consumption vs. energy savings: combining optimum EEMs -Jeddah

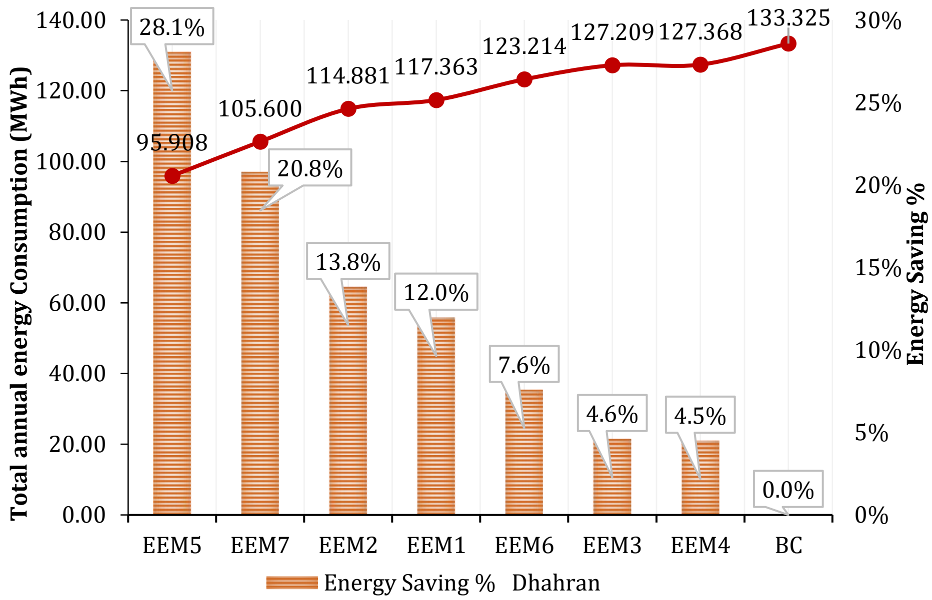


Figure 6. 2 Total annual energy consumption vs. energy savings: combining optimum EEMs - Dhahran.

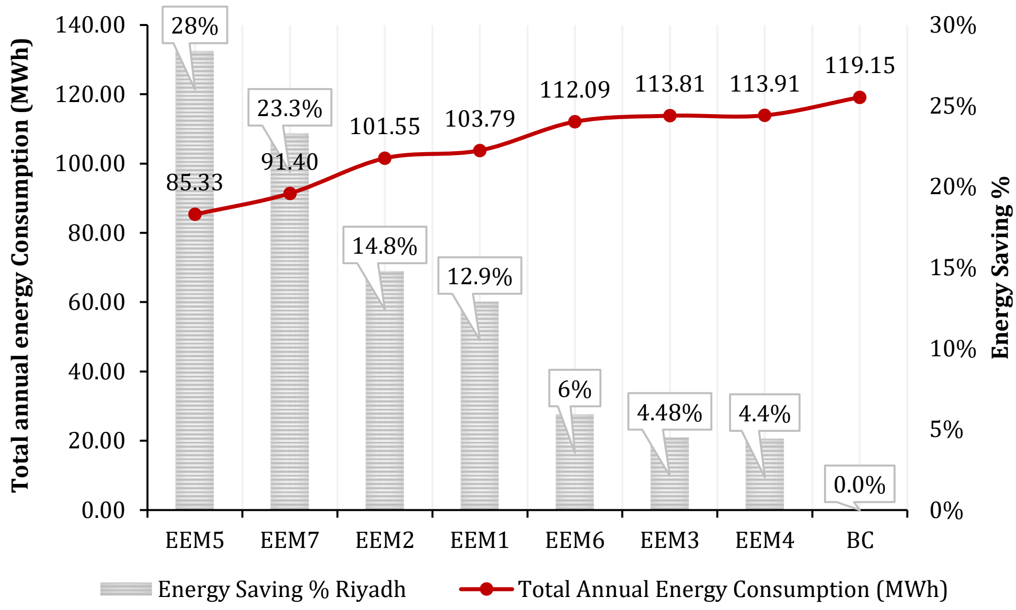


Figure 6. 3 Total annual energy consumption vs. energy savings: combining optimum EEMs - Riyadh.

6.3. Combined Retrofit Model - Energy Efficiency Analysis

This section offers a comprehensive perspective on the optimal Energy Efficiency Measures (EEMs) implemented in the building envelopes of three major Saudi cities: Riyadh, Jeddah, and Dhahran. The research focuses on the practical application of an energy-efficient retrofit method to the base case, which significantly enhances energy efficiency. The results highlight the intersection of energy conservation, environmental responsibility, and economic.

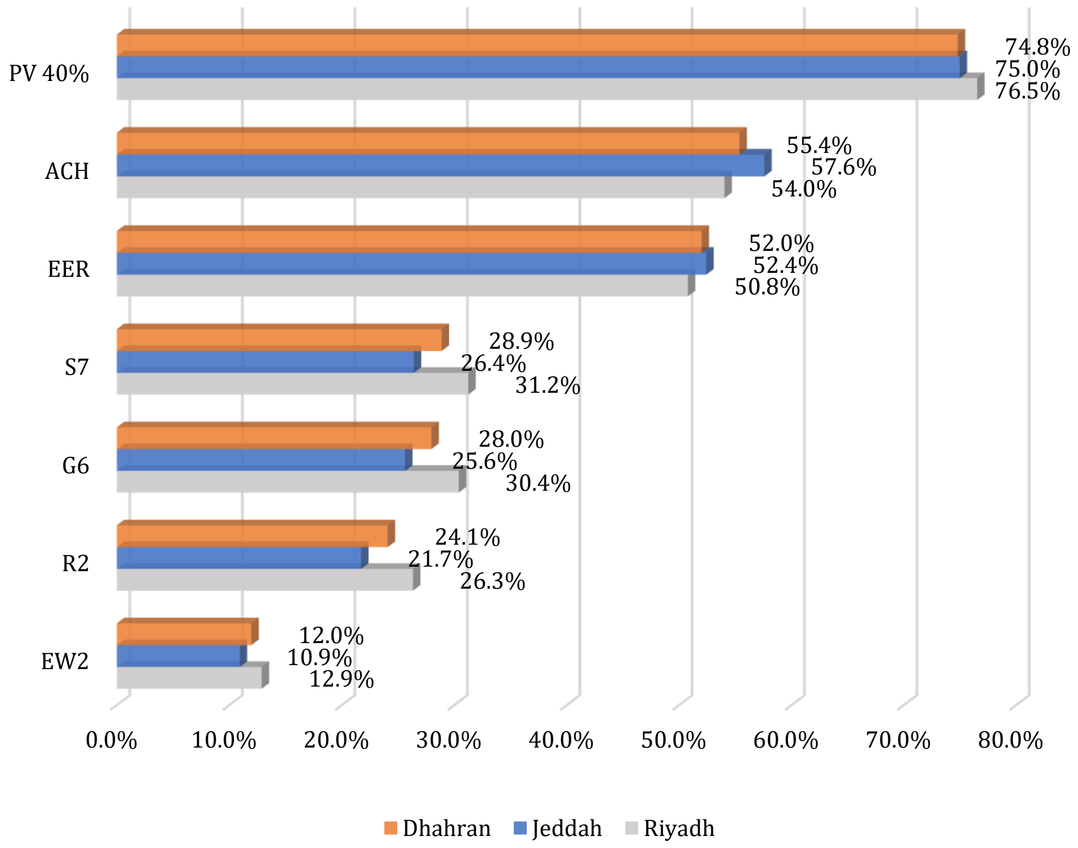


Figure 6. 4 Cumulative Energy Savings improved model for Proposed Energy Efficiency Measures (EEMs) in Dhahran, Jeddah, and Riyadh.

Table 6. 3 Cumulative annual energy consumption and electricity cost savings for the proposed (EEMs) in Riyadh, Jeddah, and Dhahran.

EEMs code		**Total annual energy Consumption (cumulative) (MWh)**			**Annual energy saving (cumulative) %**		
		Riyadh	Jeddah	Dhahran	Riyadh	Jeddah	Dhahran
BC		119.154	152.056	133.3024			
EW2	External wall insulation	103.793	135.433	117.363	12.89%	10.93%	11.96%
R2	Roof Insulation	87.774	119.042	101.210	26.33%	21.71%	24.07%
G6	Double Reflective Glazing	82.933	113.090	96.025	30.39%	25.63%	27.96%
S7	Louver	81.920	111.906	94.810	31.24%	26.40%	28.88%
EER	Efficient AC (EER)/ STP 24°	58.652	72.357	63.992	50.77%	52.41%	51.99%
ACH	ACH .25	54.764	64.509	59.494	54.04%	57.58%	55.37%
PV 40%	Net energy consumption (Solar panel)[3]	27.968	38.056	33.589	76.5%	74.98%	74.8%
Total annual energy savings for the proposed measures % [4]					54.0%	57.6%	55.4%
EUI (MWh/m²/Year)					70.4	90	80.4
Improved Model Annual energy cost USD (SEC)					2682.9	3146.6	2851.4
USD- Annual saving %					64.8%	68.1%	66.3%
Annual Saving CO2 (kg/m²emissions)					76.5%	75.1%	74.6%

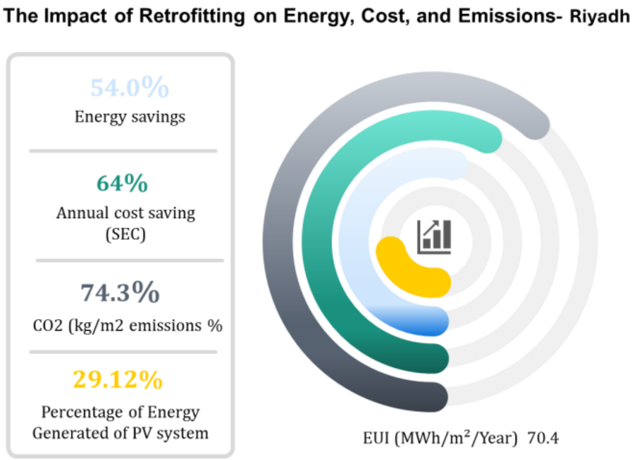
Table 6.3 and Figure 6.4 provide a detailed overview of the cumulative energy consumption and electricity cost savings achieved through the sequential application of the proposed Energy Efficiency Measures (EEMs) in Dhahran, Jeddah, and Riyadh. These measures begin with external wall insulation (EEM1-EW2) and culminate with the integration of photovoltaic (PV) systems covering 40% of the roof area (EEM7-PV 40%). This sequential approach demonstrates significant cumulative effects on energy savings, resulting in potential reductions exceeding 74.8% in Dhahran, 75.0% in Jeddah, and 76.5% in Riyadh. The EEMs are identified by their codes: **EEM1-EW2, EEM2-R2, EEM3-G6, EEM4-S7, EEM5-HVAC, EEM6-ACH, and EEM7-PV 40%.**

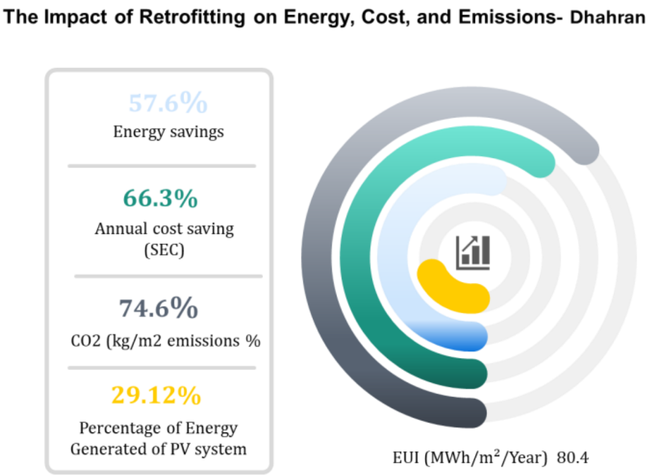
The combination of external wall insulation (EW2) and roof insulation (R2) results in cumulative energy savings of approximately 26% across all cities. Additional measures, such as double reflective glazing (G6) and louvers (S7), further enhance these savings, achieving reductions of up to 31%. Operational improvements like efficient air conditioning systems (EER) produce even more significant cumulative savings, reaching up to 50%.

When all proposed measures without PV integration are implemented, annual energy savings reach 54.0% in Riyadh, 57.6% in Jeddah, and 55.4% in Dhahran. Correspondingly, the energy use intensity (EUI) decreases dramatically from 286 kWh/m^2/year to 70.4 kWh/m^2/year in Riyadh, from 251 kWh/m^2/year to 90 kWh/m^2/year in Dhahran, and from 226 kWh/m^2/year to 80.4 kWh/m^2/year in Jeddah. These reductions exceed international energy-efficiency benchmarks (Alrashed and Asif, 2014). Further benefits are illustrated in the accompanying infographic (see Figure 6.5), which details the comprehensive impact of retrofitting measures including the integration of photovoltaic (PV) systems.

[3] Net energy consumption is calculated by subtracting the energy generated by PV panels from the total energy consumption. The surplus energy produced by the PV panels can be fed back into the grid, potentially generating revenue for the homeowner.

[4] The total energy savings for the proposed measures (excluding PV 40%) reflect the cumulative impact of all energy efficiency measures without considering the additional revenue and savings generated by the photovoltaic (PV) panels. The PV panels contribute to further reducing the net energy consumption, as shown in Table 6. 2.





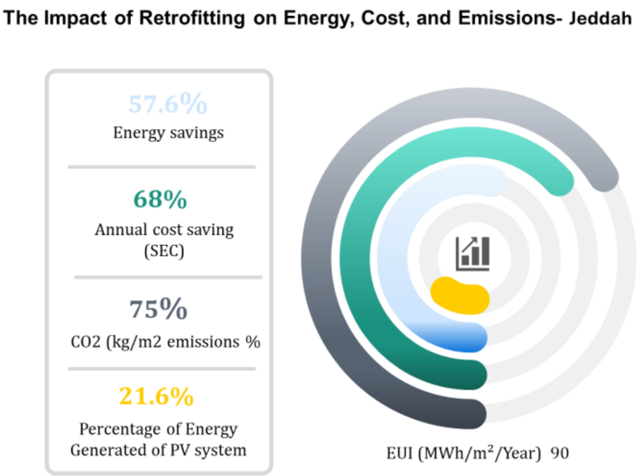


Figure 6. 5 Overview of Energy and Environmental Benefits of the improved model in Riyadh, Jeddah and Dhahran.

Integrating energy efficiency measures with solar PV installations results in compounded energy savings and cost reductions, offering a clear path toward adopting more sustainable energy consumption patterns in buildings. The integration of PV systems contributes approximately 21.1% to total energy savings across the three cities. Annual solar panel-generated electricity production amounts to 26.63 MWh in Riyadh, 26.45 MWh in Jeddah, and 25.66 MWh in Dhahran. PV systems not only enhance the local energy supply but also offer long-term cost savings. Surplus energy generated can be used directly, stored, or fed back into the grid, resulting in immediate reductions in electricity bills, especially in areas with high solar radiation.

The revenue or cost savings from solar energy, given the $0.019 per kWh export rate, are substantial amounting to approximately $487.45 in Dhahran, $502.62 in Jeddah, and $506.02 in Riyadh. This financial aspect emphasizes the economic efficiency and revenue potential of solar energy generation, encouraging confidence in the financial viability of these measures. This alignment with the National Renewable Energy Program (NREP) and Saudi Vision 2030 encourages the adoption of solar panels for both environmental and financial benefits (Nahiduzzaman et al., 2018; Griffiths, 2017a; Al Garni and Awasthi, 2017). It not only motivates more people to install solar panels but also provides a significant return on investment by reducing electricity bills.

The improved models lead to substantial cost savings, with annual energy cost reductions of 64.8% in Riyadh, 68.1% in Jeddah, and 66.3% in Dhahran. These savings are complemented by significant reductions in CO_2 emissions, averaging 75% across all cities and contributing to environmental sustainability goals, as shown in Figures 6.7, 6.9, and 6.11.

Figure 6.12 presents the monthly energy savings for both the baseline and improved models across Riyadh, Jeddah, and Dhahran, highlighting the effectiveness of a holistic retrofitting approach. Figures 6.6, 6.8 and 6.10 detail the monthly energy usage of the baseline and improved models, along with photovoltaic (PV) electricity generation in each city. These figures demonstrate the combined impact of energy efficiency measures and solar PV generation on reducing electricity consumption and energy costs.

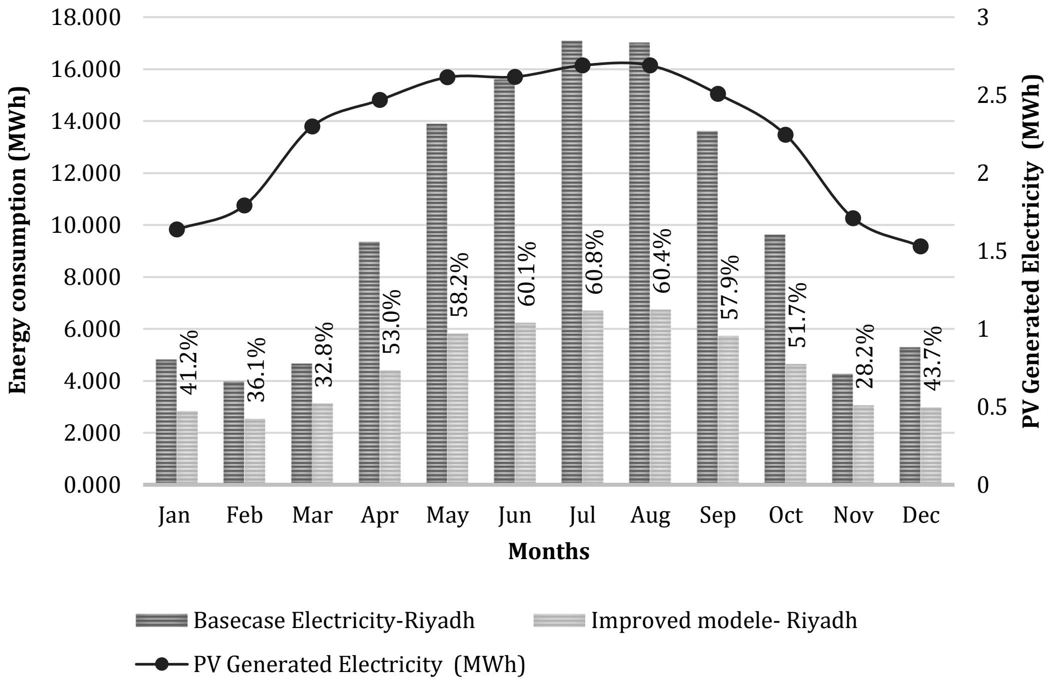


Figure 6. 6 Monthly energy consumption of the base case and improved model in Riyadh.

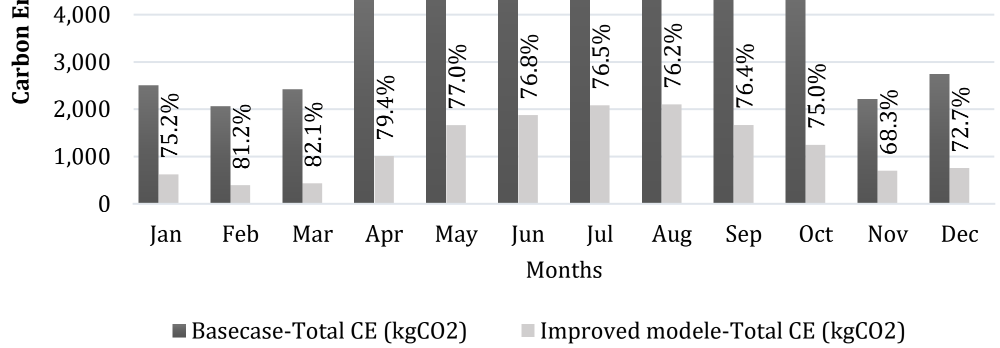


Figure 6. 7 Monthly CO_2 emissions of the base case and improved model in Riyadh.

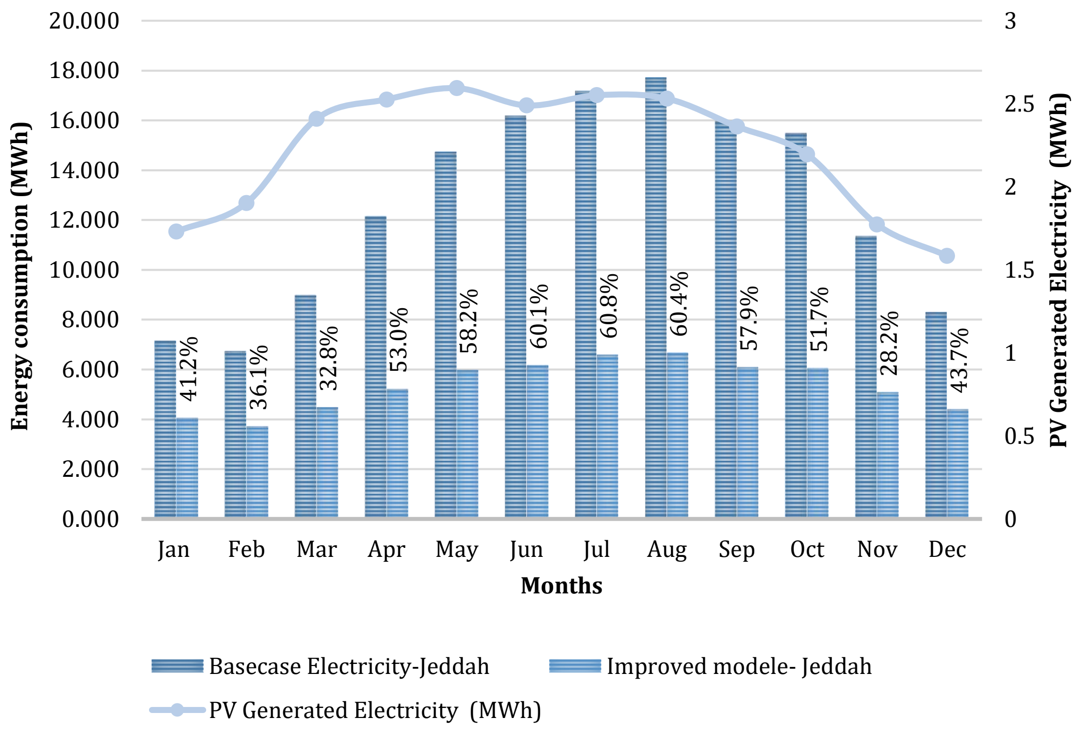


Figure 6. 8 Monthly energy consumption of the base case and improved model in Jeddah.

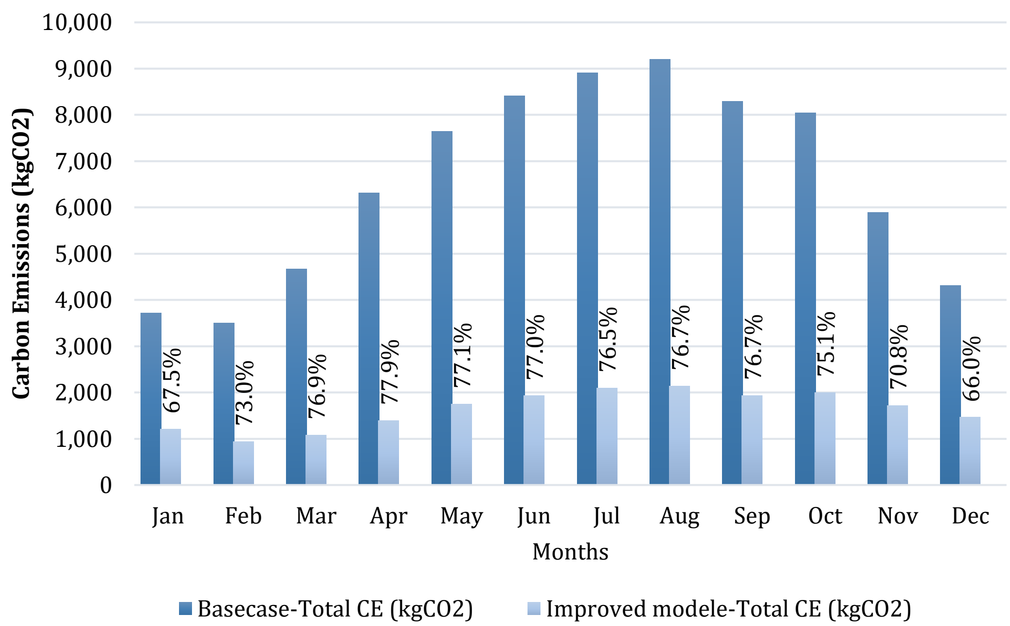


Figure 6. 9 Monthly CO_2 emissions of the base case and improved model in Jeddah.

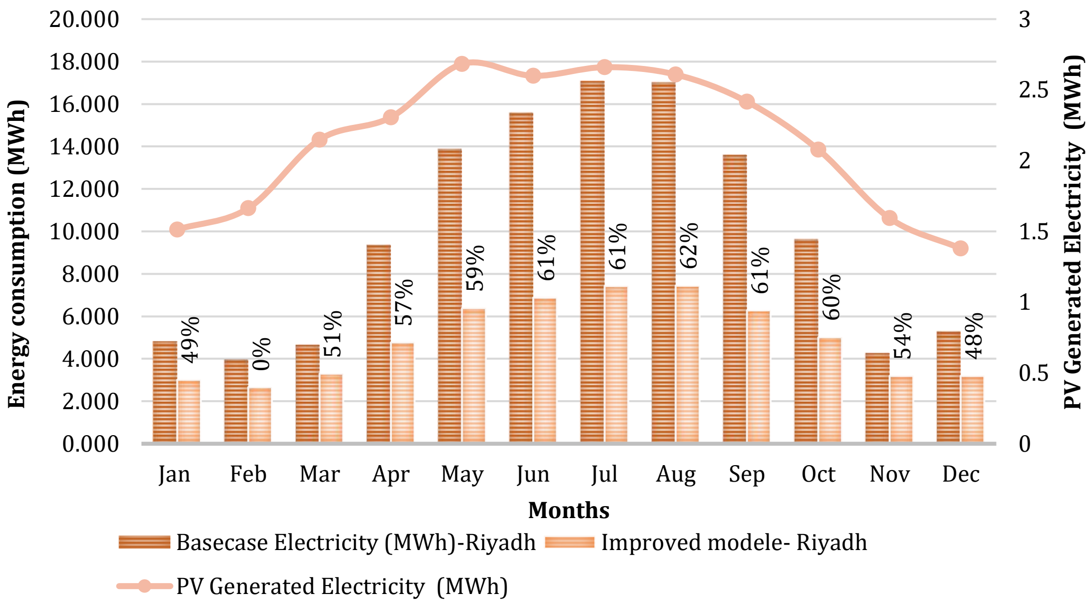


Figure 6. 10 Monthly energy consumption of the base case and improved model in Dhahran.

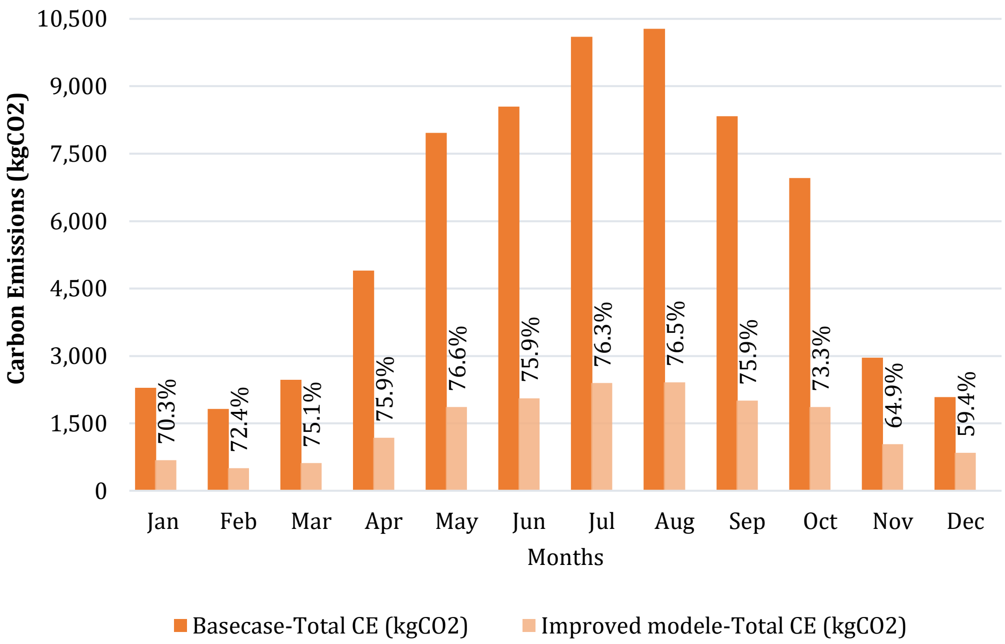


Figure 6. 11 Monthly CO_2 emissions of the base case and improved model in Dhahran.

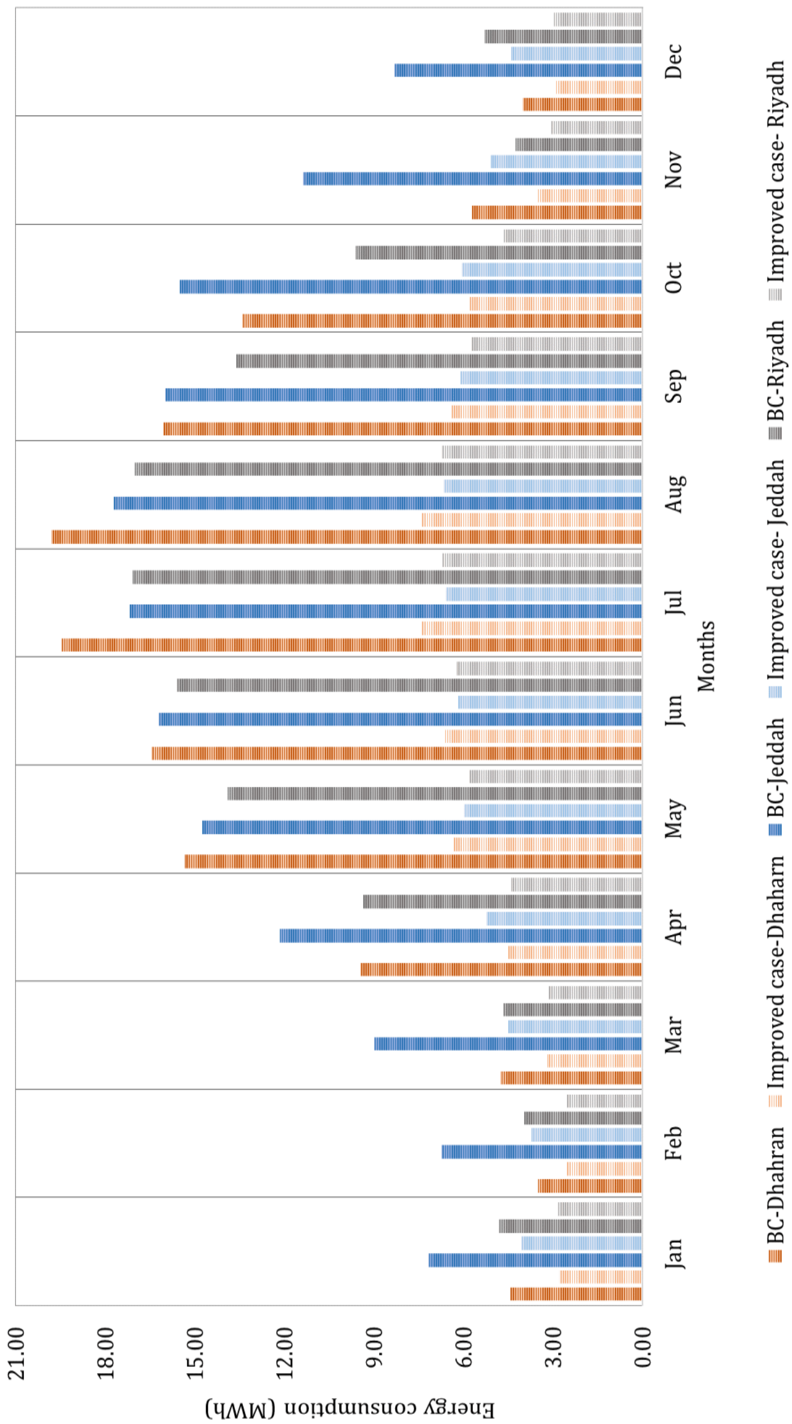


Figure 6. 12 Monthly energy reduction of the base case and improved model in Riyadh, Jeddah, and Dhahran

In conclusion, the comprehensive analysis of energy efficiency measures is tailored to Saudi Arabia's unique climate. The study's findings, demonstrated through detailed simulations and evaluations, show that significant energy savings and reductions in CO_2 emissions can be achieved through targeted retrofitting strategies. Integrating advanced insulation, efficient glazing, optimized HVAC systems, and renewable energy sources not only enhances the energy performance of residential buildings but also contributes to the national sustainability goals outlined in Saudi Vision 2030.

6.4. Cost Benefit Analysis of the Retrofit Model Package

This section presents a cost analysis of the individual Energy Efficiency Measures (EEMs) of a proposed retrofit model implemented in Riyadh, Jeddah, and Dhahran, as stated in Table 6. 4, Table 6. 5 and Table 6. 6 below. The analysis includes cost-savings ($), Net Present Value (NPV), Internal Rate of Return (IRR), Benefit-Cost Ratio (BCR), and simple payback periods (years), providing a holistic view of the financial viability of each measure**.** A simple payback period is a fundamental metric for assessing each retrofitting scenario, highlighting its financial viability and contribution to energy conservation (Caruso et al., 2023; Committee, 2016; Krarti, 2020). Financial metrics were derived using inputs from Section 4.9. Labor costs have been eliminated from this analysis in order to focus on fixed material expenses, resulting in a more simple and consistent financial view. The cost estimates offered are only for materials. Excluding labour costs simplifies the study by eliminating variables such as compensation variations, which ensures consistency in the analysis. This enables a clearer comparison of material costs and time periods. It also helps to separate the influence of material price variations on overall expenses.

Key inputs for financial metrics:

1. **Annual energy consumption reductions**: The estimated annual energy consumption reductions are based on potential improvements for EEMs
2. **Electric cost (SEC)**: Tiered pricing at $0.048 per kWh for usage up to 6000 kWh and $0.08 per kWh for usage above 6000 kWh.
3. **Export rate for surplus solar energy**: $0.019 per kWh, specifically relevant for EEM7 (Solar PV installations).

Evaluating the cost savings for the highest impact parameters within each measure will provide valuable perspective on the potential for retrofitting residential buildings. It allows for a direct comparison of the upfront investment costs of these high-impact measures to their long-term benefits, thus providing a solid basis for decision-making.

1) Applying the most effective energy-saving practices across various building elements:

   - **EEM1-EW2 (External Wall Insulation)**: This involves adding advanced insulative materials to the external walls to prevent heat transfer, thereby reducing heating and cooling costs.
   - **EEM2-R2 (Roof Insulation)**: This measure adds insulation to the roof to further reduce heat gain and improve thermal control within the building.
   - **EEM3-G6 (Double Reflective Glazing)**: Installing high-efficiency glazing for windows to enhance thermal comfort and energy efficiency.
   - **EEM4-S7 (Louver Shading Devices)**: Adding shading solutions such as overhangs and louvres to reduce solar heat gain and decrease cooling requirements.
   - **EEM5 (Efficient HVAC System)**: Upgrading or replacing HVAC equipment to more energy-efficient models to improve energy conservation and indoor temperature control.
   - **EEM6-ACH (Air Exchange Adjustment)**: Reducing the infiltration rate by sealing leaks and improving the building envelope tightness to minimize uncontrolled airflow and cooling savings.
   - **EEM7-PV 40% (Photovoltaic System Covering 40% of Roof Area)**: Installing rooftop photovoltaic panels to generate green energy and potentially sell back excess energy to the grid.

2) After identifying the highest impact parameters within each measure from the simulations, calculate the upfront costs for implementing these measures, including initial costs for materials.

3) Use the energy savings data from the simulation to calculate the annual cost savings resulting from reduced energy consumption.
4) To calculate the payback period, divide the total upfront costs by the annual savings. This is a key metric that clearly explains how long the savings will take to cover the initial investment.
5) Comparing the payback periods of various investment measures helps identify which ones provide the fastest return on investment, valuable for emphasizing specific measures over others.

The baseline building, as detailed in Section 4.6, monthly energy consumption, does not comply with the current building regulations required by the Saudi Building Code (SBC-602). The energy consumption patterns, and associated costs emphasize the building's inefficiency, particularly in thermal insulation requirements, HVAC system efficiency standards, etc. As a result, it emphasizes the importance of implementing EEMs to comply with building regulations, improve the building's energy efficiency, and reduce operating costs.

The baseline buildings across the three cities, Riyadh, Jeddah, and Dhahran, have distinct annual energy uses and costs, reflecting their specific climatic conditions and energy consumption patterns. The baseline building consumption for Riyadh was 119.1452 MWh annually, leading to an estimated yearly energy cost of $7,453. In Jeddah, the annual energy cost for the baseline scenario amounted to $9,860.45, indicating a higher energy demand, possibly due to its coastal climate influencing the building's cooling requirements, while the estimated yearly energy cost for Dhahran's baseline building was $8,599.23. These baseline figures highlight the critical need for energy efficiency measures (EEMs) in each city to mitigate the high energy costs and consumption associated with residential buildings in Saudi Arabia's varying climates. The implementation of such measures would not only reduce energy use and costs but contribute to the country's sustainability and energy efficiency goals. As detailed in Appendix B, the annual energy costs for the baseline buildings in Riyadh, Jeddah, and Dhahran and the proposed (EEMs) were calculated considering the two-tier utility rate, highlighting the significant potential for cost savings through energy efficiency measures.

Cost Details and Payback Periods:

Insulation cot, whether advanced materials like Aerogel blankets or traditional ones such as XPS polystyrene, varies significantly based on the thickness of the material and the total area covered. Aerogel insulation is more expensive per square meter than standard foam insulation panels due to its superior thermal insulation, which can significantly lower cooling energy costs (Omer et al., 2007). In contrast, traditional insulation types like XPS polystyrene are more cost-effective but may not offer the same level of thermal efficiency as more advanced materials like Aerogel, which are costly due to their production methods. Aerogel insulation costs ten times as much as traditional insulation materials, such as extruded polystyrene, but it offers significantly higher thermal performance. As indicated in studies by Cuce et al. (2014); Riffat and Qiu (2013), aerogel insulation costs about £20 per square meter, which is higher than the average cost of traditional insulation materials.

When using a 20 mm Aerogel panel for wall insulation, the payback periods are consistent across different locations, averaging around 13.3 years. In Riyadh, adding external wall insulation with Aerogel panels can save a lot of energy but results in varying payback periods. The 20 mm Aerogel panel (EW1) has a payback period of 14.4 years, while the 30 mm Aerogel panel (EW2) stretches that to 17.73 years because of its higher initial cost. In contrast, the 100 mm XPS Polystyrene (EW5) has a shorter payback period of 7.0 years, making it a more economically attractive option even though it offers slightly lower energy savings. While Aerogel panels are great for saving energy, their higher upfront costs and longer payback periods can make them less appealing for homeowners looking for quicker financial returns. However, Aerogel's thermal conductivity and reduced thickness provide superior insulation with less material. The 20 mm and 30 mm Aerogel panels offer thermal performance comparable to much thicker XPS Polystyrene panels (100 mm), which can be beneficial in terms of space and ease of installation. Also, the financial return on this investment can vary significantly depending on external temperatures, which affect heating and cooling demands. Therefore, it's important to weigh the longer payback periods against the benefits of reduced energy consumption, improved building comfort, upfront costs, and the building's expected lifespan.

In Riyadh, the 100 mm XPS Polystyrene (EW5) provides a payback period of 7.0 years compared to 14.4 years for the 20 mm Aerogel panel (EW1) and 17.73 years for the 30 mm Aerogel panel (EW2). Similar trends are seen in Jeddah and Dhahran, with the 100 mm XPS Polystyrene offering payback periods of 6.01 years and 6 years, respectively.

Despite the longer payback periods, the thinner Aerogel panels can lead to more effective use of space and potentially lower long-term maintenance costs due to their higher durability and thermal efficiency.

Roof insulation measures in Riyadh also show notable energy savings. The 20 mm Aerogel panel (R1) has a payback period of 12.64 years, whereas the 30 mm Aerogel panel (R2) has a longer payback period of 16.24 years. These findings suggest that while Aerogel panels offer substantial energy savings, their high initial costs result in longer payback periods, making XPS Polystyrene a more viable option for quicker financial returns. In Jeddah, the baseline annual energy consumption is higher at 152.0521 MWh, with an annual energy cost of $9,860.45. Similar to Riyadh and Dhahran, the external wall insulation using Aerogel panels shows varying payback periods. The 100 mm XPS Polystyrene (EW5), however, has the shortest payback period of 6 years, highlighting its cost-effectiveness. When considering insulation options, it's worth noting that traditional materials like XPS Polystyrene (EW5, R5) offer a cost-effective choice with a relatively quick payback period of up to 7 years.

The average payback period for traditional insulation in Saudi Arabia ranges from approximately up to 8.8 years, as stated by Al-Tamimi (2021), depending on many factors such as insulation thickness and installation cost. Esmaeil et al. (2019b) indicated that by applying envelope insulation, the anticipated average simple payback period would be 6.8 years, based on the subsidized KSA electricity pricing, whereas between 10 and 15.15 years by applying the SBC-602 in the residential buildings in Qassim region (Almasri et al., 2020). Local climatic conditions and energy use patterns vary between Saudi areas, resulting in variations in the cost-effectiveness and payback times of such energy-saving solutions.

A short payback period and a high internal rate of return (IRR) enhance the case for investing in inefficient HVAC systems, highlighting the significant energy savings and financial benefits over time. These savings align to achieve significant, long-term reductions in energy consumption. On the other hand, implementing thermal insulation (XPS) according to the SBC-602 standards, with its faster payback period of approximately 6 years and lower initial costs, provides energy efficiency enhancements. This aligns well with the payback time findings reported by (Esmaeil et al., 2019b), offering a beneficial balance between initial investment and payback time.

Upgrading air conditioning (AC) systems, as outlined by Krarti and Howarth (2020) for the local Saudi market, yields an average annual energy cost savings of approximately $553 for each unit, with an initial investment of $681 to $821. This investment significantly enhances efficiency, reducing cooling load by up to 33% compared to units with lower Energy Efficiency Ratios (EER). This efficiency upgrade to systems with a Seasonal Energy Efficiency Ratio (SEER) of 14, aligning with the standards mandated by the Saudi Standards, Metrology and Quality Organization (SASO), results in energy cost reductions of 31% in Riyadh, 33% in Jeddah, and 31% in Dhahran, when compared to lower-EER units. The investment in inefficient HVAC systems is further justified by a low payback period and a high Internal Rate of Return (IRR), reflecting the significant energy savings and financial benefits over time.

Similarly, the installation of solar PV on 40% of the roof exhibits notable financial returns, underscoring the economic and environmental benefits. It is noteworthy that while some measures like insulation (EEM1, EW2) show negative NPVs and low IRRs, their addition may be justified by the energy savings they contribute to when combined with other measures, as well as their long-term benefits in reducing carbon emissions and improving building envelope performance.

In determining the financial viability of installing Monocrystalline silicon photovoltaic (PV) systems in residential buildings, the specific grid-connected PV system has a capacity of 12.96 kWp, with each panel rated at 305 W, as specified in Table 5. 16. The estimated installation cost for this system is $10,750. This estimate includes the local panel prices as well as the connection fees required to connect the system to the grid.

To assess the cost-effectiveness of the installation, the cost per kilowatt-peak (kWp) was calculated by dividing the total installation cost by the system's capacity. For residential solar panel installations in Saudi Arabia, the average system capacity ranges from approximately 4 kW to 12.25 kW based on recent studies (Imam et al., 2020; Alblawi et al., 2019). Incorporating energy-efficient measures and solar PV systems in residential buildings in the three cities led to significant energy savings, up to 23% compared to baseline scenarios. The overall combined cost for the PV system, incorporating the initial system investment, maintenance cost over 25 years, and the costs associated with inverter replacement, is estimated at 15,138 USD based on the local market. Despite the higher upfront cost, the substantial long-term savings and environmental benefits make solar PV systems a viable and economically advantageous investment for residential buildings in Saudi Arabia. (See Appendix B EEM7-PV 40% -PV System cost breakdown)

The payback period of approximately 5 to 6 years further highlights the PV system as a long-term investment across the three cities examined. This time frame shows how long it will take for the system's savings to cover the initial investment. In areas like Saudi Arabia, characterized by high solar insolation, the energy-generating capacity can significantly lower household energy expenses, making them a cost-effective choice. Furthermore, the positive Net Present Value (NPV), as clarified in Table 6. 6 represents a positive outcome, indicating that the project's returns exceed its costs when considering the time value of money. Moreover, the Benefit-Cost Ratio (BCR) corroborates the project's economic viability, demonstrating that the investment's benefits decisively outweigh its costs.

Upgrading to double glazing and external window shading represents a key strategy for reducing energy consumption in residential buildings. These measures not only improve thermal comfort for residents but also lead to substantial energy savings over time. The initial cost for upgrading windows to double-glazing units ranges from 120 to 170 USD per square meter, reflecting average market prices. This cost is influenced by the quality of the materials used. Similarly, the cost of external window shading varies, depending on the design, materials, and coverage area required. In the Saudi Arabian market, achieving the specifications for double glazing recommended by (SBC-602) often involves using a double-glazed unit with either a 100% air or argon gas cavity, aiming for a U-value of 2.6 W/m2K. For a glazing area of around $40m^2$covering 13% of the external wall, the cost of double reflective glazing, including a 15% VAT expense, totals approximately $5,587.62.

The payback period for these energy efficiency investments varies across Riyadh, Jeddah, and Dhahran, reflecting the time needed for the energy savings to recover the initial costs. For double reflective glazing (G6), the payback periods are estimated at 11.1 years in Riyadh, 9 years in Jeddah, and 10.9 years in Dhahran. External window shading, on the other hand, offers a shorter payback period, making it a desirable option for quicker energy savings, especially in areas with high temperatures and intense sunlight. In Dhahran, for example, the payback period for shading upgrades is approximately 4.44

years. These measures' (IRR) and (BCR) highlight their potential for effective energy savings and financial returns in a climate characterized by extreme temperatures.

Applying the most effective energy-saving practices across various building elements aim to reduce energy consumption, with estimated payback periods of approximately 8.78 years in Riyadh, 6.4 years in Jeddah, and 6.85 years in Dhahran[5]. This highlights the substantial energy savings and financial benefits of targeted retrofit strategies. Additionally, incorporating the energy generation benefits of Solar PV (EEM7-PV) would modify the payback periods, further enhancing the overall retrofit energy model. The shorter compound payback period for the entire set of EEMs, compared to the payback period for External Wall Insulation (EEM1-EW), is due to the cumulative savings from multiple measures, and diverse return on investment timelines.

[5] Combined payback period calculations include (EEM1-EW2, EEM2-R2 EEM3-G6, EEM4-S7, EEM5-HVAC, EEM6-ACH, EEM7-PV).

Table 6. 4 Financial Analysis of Maximum Energy Savings Retrofit Measures in Riyadh.

Maximum Energy Savings Retrofit Measures			**Electric Cost (SEC): $0.048 per kWh for usage up to 6000 kWh and $0.08 per kWh for usage above 6000 kWh**					
EEMs code		Potential Improvements for EEMs	Annual Energy Consumption (MWh)	Post-Implementation-Annual Energy Cost ($)	Initial Investment cost of Retrofitting ($)	Annual Energy Cost Saving ($/Year)	Annual Energy saving %	Simple Payback (years)
BC			119.1452	$7,453				
EEM1	EW1	External Wall Insulation: Aerogel panel /20mm	104.3133	$6,343.56	$15,932	$1,281.7	12.4%	14.4
	EW2	Aerogel panel /30mm	103.7930	$6,104.72	$23,898	$1,420.5	13%	**17.73**
	EW5	EW5 XPS Polystyrene /100mm	105.1965	$6,414.56	$7,248	$1,210.7	11.7%	7.0
EEM2	R1	Roof Insulation: Aerogel panel /20mm	102.4210	$6,319.84	$14,322	$1,305.4	14.0%	12.64
	R2	Aerogel panel /30mm	101.549	$6,130.42	$21,483	$1,494.8	14.8%	**16.24**
	R5	XPS polystyrene /100mm	102.4791	$6,204.72	$6,363.53	$1,420.5	13.9%	**5.10**
EEM3	**G6**	Replace base case glazing type to Double reflective Glass.	113.823	$6,949.71	$5,587.6	$580.54	4.47%	**11.1**
EEM4	**S7**	Louvers	114.591	$7,146.33	$3,200	$478.99	3.82%	**10.43**
EEM5	**EER**	Efficient HVAC (High EER)	85.327	$5,297.96	$4,60	$2,327.3	28.4%	**2.13**
EEM6	**ACH**	ACH .25	112.088	$6,904.24	$260.76	$721.08	6%	**0.56**
EEM7	**PV**	Install Solar PV on 40% of the roof	91.3991	$5513.11	$15,138	$2,444.8	23.3%	**6.2**
(Proposed Retrofit Model) Integration of High-Efficiency Measures for Optimal Energy Savings							**76.53%**	**8.7**

Table 6. 5 Financial Analysis of Maximum Energy Savings Retrofit Measures in Jeddah.

Maximum Energy Savings Retrofit Measures				**Electric Cost (SEC): $0.048 per kWh for usage up to 6000 kWh and $0.08 per kWh for usage above 6000 kWh**				
EEMs code		Potential Improvements for EEMs	Annual Energy Consumption (MWh)	Post-Implementation-Annual Energy Cost ($)	Initial Investment cost of Retrofitting ($)	Annual Energy Cost Saving ($/Year)	Annual Energy saving %	Simple Payback (years)
		BC	152.0521	$9,860.45				
EEM1	EW1	External Wall Insulation: Aerogel panel /20mm	135.917	$8,561.40	$15,932.40	$1,299.0	10.7%	12.26
	EW2	Aerogel panel /30mm	135.433	$8,278.15	$23,898.60	$1,582.30	10.9%	**15.1**
	EW5	EW5 XPS Polystyrene /100mm	136.9899	$8,654.10	$7,248.0	$1,206.3	9.9%	6.01
EEM2	R1	Roof Insulation: Aerogel panel /20mm	133.5384	$8,451.82	$14,322.	$1,408.6	12.2%	10.17
	R2	Aerogel panel /30mm	132.7895	$8,319.17	$21,483.	$1,541.2	12.7%	**14**
	R5	XPS polystyrene /100mm	133.9899	$8,415.20	$6,363.5	$1,445.2	11.88%	**4.4**
EEM3	**G6**	Replace base case glazing type to Double reflective Glass.	144.3212	$9,241.69	$5,587.6	$618.76	5.08%	**9.03**
EEM4	**S7**	Louvers	145.621	$9,308.21	$3,200	$552.24	4.23%	**5.79**
EEM5	**EER**	Efficient HVAC (High EER)	105.437	$6,571.23	$4,600	$3,289.2	30%	**1.40**
EEM6	**ACH**	ACH .25	135.936	$8,619.12	$260.76	$1,241.3	10.60%	**0.21**
EEM7	**PV**	Install Solar PV on 40% of the roof	122.389	$7551.46	$15,138	$2,811.6	20%	**5.4**
(Proposed Retrofit Model) Integration of High-Efficiency Measures for Optimal Energy Savings							***75%***	***6.4***

Table 6. 6 Financial Analysis of Maximum Energy Savings Retrofit Measures in Dhahran.

Maximum Energy Savings Retrofit Measures			**Electric Cost (SEC): $0.048 per kWh for usage up to 6000 kWh and $0.08 per kWh for usage above 6000 kWh**					
EEMs code		Potential Improvements for EEMs	Annual Energy Consumption (MWh)	Post-Implementation- Annual Energy Cost ($)	Initial Investment cost of Retrofitting ($)	Annual Energy Cost Saving ($/Year)	Annual Energy saving %	Simple Payback (years)
BC			133.3024	$8,599.23				
EEM1	EW1	External Wall Insulation: Aerogel panel /20mm	117.859	$7,416.50	$15,932.40	$1,182.73	11.6%	13.4
	EW2	Aerogel panel /30mm	117.363	$7,208.50	$23,898.60	$1,390.73	12.0%	**17.2**
	EW5	EW5 XPS Polystyrene /100mm	121.913	$7,494.39	$7,248.00	$1,104.84	8.5%	6
EEM2	R1	Roof Insulation: Aerogel panel /20mm	117.58	$7,380.32	$14,322.00	$1,218.91	11.8%	11.27
	R2	Aerogel panel /30mm	114.724	$7,183.29	$21,483.00	$1,415.94	13.9%	**14.64**
	R5	XPS polystyrene /100mm	116.009	$7,272.81	$6,363.53	$1,326.42	13.0%	4.62
EEM3	**G6**	Replace base case glazing type to Double reflective Glass.	127.26	$8,090.74	$5,587.62	$459.24	4.5%	**10.9**
EEM4	**S7**	Louvers	127.89	$7,929.92	$3,200.00	$669.31	4.1%	**4.44**
EEM5	**EER**	Efficient HVAC (High EER)	95.9082	$5,963.58	$4,600.00	$2,635.65	28%	**1.71**
EEM6	**ACH**	ACH .25	123.214	$6,814.54	$260.76	$1,784.69	7.6%	**0.14**
EEM7	**PV**	Install Solar PV on 40% of the roof	105.624	$6,819.47	$15,138	$2,427.97	21%	**6.23**
(Proposed Retrofit Model) Integration of High-Efficiency Measures for Optimal Energy Savings							***74.80%***	***6.9***

Table 6.7 represents the average Internal Rate of Return (IRR) and Benefit-Cost Ratio (BCR) for each measure across Riyadh, Jeddah, and Dhahran. The cash flow and cumulative Net Present Value (NPV) for each measure is calculated using Equation 4.10. (Refer to Appendix B for details). This analysis takes into account a 4% discount rate and a 25-year lifespan.

Table 6. 7 Financial Performance Indicators for Energy Efficiency Measures.

EEM CODES	Average IRR (%)	Average BCR	Strategy Insight
EW1	4.99	1.25	Moderate IRR, BCR &NPV; reliable, consistent returns
EW2	3.8	0.95	Low returns; Negative NPV; low returns, long-term savings
EW5	15.85	2.57	Positive NPV, attractive investment
R2	1.94	1.07	Low NPV, good energy savings
R5	20.88	3.48	High NPV, very attractive
G6	5.52	1.59	Moderate energy savings.
S7	11.13	2	Moderate NPV and energy savings.
HVAC	48.72	8.02	High IRR/BCR reflects substantial cost savings. Upgrading to a high EER HVAC system dramatically improves energy efficiency and reduces operational costs, making it a highly effective investment.
PV 40%	15.29%	2.97	Positive NPV: sustainable energy, significant investment.

The NPV values highlight the importance of assessing the long-term financial impacts of energy-efficient retrofit strategies. Most strategies have positive NPVs. However, it is important to note that EEM1-EW2 has a negative NPV, suggesting a potential financial loss over a 25-year lifespan. It's important to note that EEM1-EW2 offers significant long-term energy savings and operational costs that outweigh the initial expenses. EEM5-HVACH stands out with the highest IRR and BCR among all measures. EEM7- PV 40% contributes significantly to green energy and positive NPV, as well as its long-term benefits and role in achieving sustainability goals. These energy savings contribute to the building's overall energy efficiency.

6.5. Summary

Applying the best practice for each element can reduce the envelope's responsibility for increasing cooling load demand. Furthermore, the financial analysis emphasises the necessity of considering a combination of measures to optimise energy savings and financial returns. In conclusion, the financial evaluation of retrofit measures in Saudi Arabia, emphasising cost estimation, demonstrates their critical role in enhancing energy efficiency and sustainability in the built environment. Adopting targeted retrofit measures offers a path toward achieving substantial energy savings and operational cost reductions by moving away from the baseline scenario of non-insulated buildings.

In conclusion, the comprehensive analysis of energy efficiency measures is tailored to Saudi Arabia's unique climate. The study's findings, demonstrated through detailed simulations and evaluations, show that significant energy savings and reductions in CO_2 emissions can be achieved through targeted retrofitting strategies. Integrating advanced insulation, efficient glazing, optimized HVAC systems, and renewable energy sources not only enhances the energy performance of residential buildings but also contributes to the national sustainability goals outlined in Saudi Vision 2030.

Chapter 7

Conclusions & Recommendations

7.1. Overview of Finding

This study has investigated the impacts of various energy-efficient measures on the energy demand of an archetypical residential building model in Saudi Arabia, aligning with the Kingdom's Vision 2030 and global sustainable development goals. Comprehensive simulations conducted using the Integrated Environmental Simulation Virtual Environment (IES-VE) have demonstrated significant potential for reducing energy consumption and carbon emissions in residential buildings across Riyadh, Jeddah, and Dhahran. The findings reveal that implementing thermal insulation, shading devices, glazing solutions, and rooftop photovoltaic (PV) systems can lead to a reduction in energy consumption by approximately 70% and a decrease in carbon emissions by nearly 58-61.7%.

The study addressed several key research questions, which are discussed below.

1. How does the existing residential building fabric in Saudi Arabia contribute to high energy consumption?

The existing residential building stock in Saudi Arabia, primarily constructed from thermally inefficient materials such as concrete without proper insulation, is a major driver of high energy consumption. Additionally, there is a lack of understanding and adherence to local building standards and specifications within the building industry. The failure to enforce these standards has allowed outdated practices to continue, resulting in buildings that require excessive use of air conditioning to maintain comfort. To accurately evaluate energy performance, a prototypical villa representing the most common type of dwelling and located in the largest climatic zone (Zone 1) based on Saudi code classifications was selected for modelling and energy simulations.

2. Which retrofitting strategies are most effective in improving energy efficiency in Saudi residential buildings?

Among evaluated retrofitting strategies, thermal insulation, HVAC upgrades, and photovoltaic (PV) integration prove most effective, demonstrating significant potential for reducing energy consumption. However, the effectiveness of these measures varies widely depending on the building's existing conditions and the quality of installation. The analysis underlines the necessity of holistic approaches that consider not just the technical aspects but also the socio-economic factors such as initial cost barriers and homeowner preferences that influence the adoption of these technologies.

3. How do the proposed retrofitting strategies align with and support the Saudi Building Code (SBC)?

The retrofitting strategies proposed in this study do comply with the existing Saudi Building Code (SBC). The research highlights that while the SBC provides a basis, it needs to develop to incorporate advancements in energy-efficient materials and renewable energy systems that have been successful in comparable arid climates. This study emphasizes an urgent need for a regulatory framework that integrates continuous updates reflecting the latest technological innovations. The alignment of retrofitting strategies with an enhanced SBC would not only reinforce national energy efficiency efforts but also promote resilience in urban infrastructure against climatic extremes.

4. What economic benefits can be derived from implementing these energy-efficient retrofitting measures?

Implementing these retrofitting measures can lead to significant cost savings, but the benefits are mostly available to those who can afford the initial costs. This creates an unfair advantage where only wealthier households can benefit from energy savings. Although some measures, such as advanced insulation materials, involve higher initial costs, the long-term energy savings and reduced operating expenses outweigh these investments. Payback periods varied among different measures. To make energy efficiency more accessible, policymakers should consider introducing financial aids like subsidies. Also, reviewing and adjusting the expected payback periods could make these measures more appealing and feasible for a wider range of the population. This approach would help make energy efficiency a more common practice, supporting national goals for sustainability.

5. What are the challenges to adopting energy-efficient retrofit solutions in Saudi Arabia's residential buildings?

Key challenges include high upfront costs, low awareness among homeowners, and weak enforcement of building codes. These issues reflect cultural resistance to new practices for adoption. Overcoming these obstacles will require efforts in education, and active community involvement to promote energy efficiency more effectively. Additionally, cultural preferences and aesthetic considerations may affect the acceptance of certain measures, such as shading devices and PV roof system.

6. What are the long-term impacts of adoption of retrofitting strategies on Saudi Arabia's residential energy landscape?

The adoption of these retrofitting strategies can lead to a significant transformation of the residential energy landscape. Long-term impacts include sustained reductions in energy consumption, decreased reliance on fossil fuels, enhanced environmental sustainability, and alignment with national goals outlined in Saudi Vision 2030. This shift contributes to building more resilient and energy-efficient urban environments for current and future generations.

Key findings include:

This study set out to investigate the efficacy of various energy efficiency measures in reducing total annual energy consumption across three major cities: Riyadh, Jeddah, and Dhahran. Various retrofit strategies were analysed, including insulation, glazing upgrades, shading installations, HVAC improvements, and PV roof system integration. Each strategy was assessed for its effectiveness in reducing energy consumption and enhancing building performance. Table 7.1 presents the total annual energy consumption (MWh) and energy savings percentages for each of the seven energy efficiency measures implemented in Riyadh, Jeddah, and Dhahran.

Table 7. 1 Energy conservation percentages for individual measures implemented in Riyadh, Jeddah, and Dhahran.

EEMs	**Energy Saving-Riyadh (%)**	**Energy Saving-Jeddah (%)**	**Energy Saving-Dhahran (%)**	**Implementation Recommendation**
EEM1-EW2	12.90%	10.90%	12.00%	Support local production of advanced insulation to reduce the cost.
EEM2-R2	14.80%	12.70%	13.80%	
EEM3-G6	4.58%	4.48%	3.53%	Implement glass technology to balance energy efficiency with aesthetic preferences.
EEM4-S7	4.40%	4.70%	4.50%	Integrated shading devices to make them more acceptable with architectural features and functional.
EEM5-HVAC	28.40%	30.70%	28.10%	Educate the public on the benefits of increasing cooling set-points and replacing AC units with high-efficiency HVAC systems.
EEM6-ACH	6%	10.60%	8%	Improve building airtightness through better sealing and regular inspections. Common areas where air leaks occur in buildings include windows and doors.
EEM7-PV	23.30%	19.5%	20.80%	Develop government awareness programs to promote solar energy adoption and address maintenance challenges.

By evaluating various retrofit strategies, the research identified effective methods to improve energy efficiency. Upgraded building models were evaluated against baseline models to quantify energy savings and assess buildings performance. Thermal insulation emerged as a consistently effective measure, with energy consumption reductions of up to 14.8%. Advanced insulation materials significantly reduced heat transfer, maintaining comfortable indoor temperatures and lowering cooling demands.

Glazing and shading improvements contributed to moderate energy savings, enhancing thermal comfort and reducing reliance on cooling systems. Upgrading to double reflective glazing and installing shading devices resulted in energy savings of up to 4.7%.

HVAC improvements were particularly impactful, with efficient systems reducing energy consumption by up to 30 %. Upgrading to high-efficiency HVAC units and educating the public on optimal cooling set-points can substantially lower energy use and operating costs. Additionally, improving building airtightness by reducing infiltration rates yielded energy savings between 6% and 10.6%, highlighting the importance of minimizing air leakage through better sealing and regular inspections.

The integration of PV systems covering 40% of the roof area contributed approximately 21.1% to total energy savings across the three cities. Annual solar panel-generated electricity production amounted to 26.63 MWh in Riyadh, 26.45 MWh in Jeddah, and 25.66 MWh in Dhahran. PV systems not only enhanced the local energy supply but also offered long-term cost savings, reducing reliance on fossil fuels and contributing to environmental sustainability goals.

Economically, the improved models led to substantial cost savings. Annual energy cost reductions were observed at 64.8% in Riyadh, 68.1% in Jeddah, and 66.3% in Dhahran. Although the initial investment costs for some measures, such as advanced insulation materials, are higher, the long-term energy savings and reduced operating costs outweigh these expenses. The payback periods varied among different measures, with efficient HVAC systems and PV installations showing shorter payback periods, enhancing their financial viability.

Environmentally, the implementation of energy efficiency measures resulted in significant reductions in CO_2 emissions, averaging 75% across all cities. This substantial decrease contributes to environmental sustainability goals and underscores the environmental benefits of these retrofit measures. The reductions in energy use and emissions not only align with international energy-efficiency benchmarks but also support the national sustainability objectives outlined in Saudi Vision 2030.

Despite these benefits, challenges such as high initial costs for advanced materials, lack of homeowner awareness, and insufficient enforcement of building codes remain obstacles. The long-term implications of adopting these retrofitting strategies are profound. Implementing these measures promotes resilient and energy efficient urban development, setting a benchmark for sustainable practices in hot climates.

This research contributes significantly to the field of energy efficiency in residential buildings, particularly within the context of Saudi Arabia.

- **Comprehensive Analysis of Retrofit Strategies:** This study provides an in-depth evaluation of both passive (e.g., insulation, glazing) and active (e.g., HVAC upgrades, PV integration) energy efficiency measures, offering a holistic approach to improving residential building performance in hot climates. By identifying the best energy-saving strategies through simulation and evaluating their financial viability, the research pinpoints optimal solutions. This study utilizes cost-benefit analysis in residential structures while considering the Saudi Building Code (SBC), providing valuable insights into the financial implications of energy efficiency measures within the regulatory framework.

- **Integration with National Policies:** Aligns retrofit strategies with the Saudi Building Code and Vision 2030 objectives, offering practical solutions that support national sustainability goals.

- **Economic Evaluation:** Enhances understanding of the financial implications of retrofitting through detailed cost-benefit analysis, assisting stakeholders in making informed investment decisions.

- **Environmental Impact:** Quantifies CO_2 emissions reductions, adding valuable data on climate change mitigation and emphasizing the role of building retrofits in environmental sustainability.

- **Guidelines for Stakeholders:** Provides recommendations for homeowners, builders, policymakers, and urban planners, assisting the adoption of energy-efficient practices in the residential sector.

7.2. Limitations

While the study provides valuable insights, certain limitations must be acknowledged:

- Exclusion of Labour Costs: The economic analysis focused solely on material costs, excluding labour expenses. This omission may affect the overall financial feasibility assessment for homeowners and investors, as labour costs can constitute a significant portion of the total investment in retrofit projects.

- Reliance on Simulations: The results are based on simulations using IES-VE software and may not account for all real-world variables such as occupant behaviour, maintenance issues, and varying installation quality. These factors can influence the actual performance of the retrofit measures, and therefore, the simulated results may differ from real-life outcomes.

- Regional Focus: The study focuses on three major cities—Riyadh, Jeddah, and Dhahran. Results may vary in other regions with different climatic conditions and building practices. Consequently, the applicability of the findings to other areas should be considered with caution.

Additionally, the research highlights that a building's age significantly impacts its energy performance. Many Saudi residential buildings, particularly those constructed over the last decade, often lack proper thermal insulation and efficient HVAC systems. This issue is not limited to older homes; despite the implementation of the Saudi Building Code in 2017, newer buildings are not consistently adhering to these regulations. The lack of awareness and insufficient enforcement of modern building standards mean that even recent constructions fall short of optimal energy efficiency. This challenge highlights the need to raise awareness and enforce building codes to enhance the energy efficiency of residential buildings across Saudi Arabia.

In summary, implementing energy efficiency measures significantly reduces energy consumption in Riyadh, Jeddah, and Dhahran. Adapting these measures to local climate conditions and building characteristics is necessary to maximizing their effectiveness in achieving energy savings. As cities grow and urbanization expands, the demand for energy-efficient solutions becomes increasingly urgent. By incorporating energy efficiency measures into development strategies, stakeholders can substantially reduce environmental impacts and build more resilient cities for current and future generations.

7.3. Recommendations

Several key recommendations are proposed to promote sustainable development and enhance energy efficiency in the residential building sector in Saudi Arabia:

1. **Implementation and improvement of the Saudi energy conservation code;** will standardize energy efficiency practices and lead to substantial reductions in energy consumption. Regular updates to building codes, incorporating the latest advancements in energy efficiency and sustainable materials, are necessary to maintain high standards of energy conservation in the building sector

2. **Investment in renewable energy sources:** Encouraging the installation of rooftop photovoltaic (PV) systems and other renewable technologies is crucial for diversifying energy sources and reducing reliance on fossil fuels.

   - Given research's findings, it is recommended that Saudi Arabia introduce government-funded subsidies, such as low interest loans, to reduce the initial cost of PV system installation for homeowners. Commencing workshops on the benefits and maintenance of PV systems would be beneficial.
   - Establishing quality standards for PV panels and installation services ensures reliability. Promoting battery storage systems can enhance energy security by storing excess energy for use during peak demand times or power outages.

3. **Public awareness:** Launching public awareness to inform homeowners and construction stakeholders about energy-efficient buildings' economic and environmental benefits will drive demand for sustainable practices.
4. **Assess the impact of EEMs on urban temperatures;** future research on mitigating urban heat islands through energy efficiency measures:

   - Investigate the effectiveness of energy efficiency measures in reducing the urban heat island effect in major cities, with a focus on how these measures can contribute to cooler urban environments and lower energy consumption in cooling systems.
   - Conduct experimental studies using temperature monitoring to measure the impact of specific EEMS like reflective roofing, green roofs, and enhanced insulation on urban temperatures.

5. **Integration with green urban infrastructure;** to enhance urban sustainability, explore the integration of EEMs with other green urban infrastructure initiatives, such as urban parks and absorptive pavements.
6. **Analysis of EEMs on indoor thermal comfort**; conduct experimental studies to evaluate how various EEMs affect the thermal comfort levels inside buildings.

7. **Occupant Behaviour and Energy Usage Patterns**; Conduct studies on occupant behaviour and its impact on energy usage patterns.

This study has contributed valuable insights into enhancing energy efficiency in residential buildings through strategic retrofit measures and renewable energy integration. The findings highlight the importance of retrofit strategies to address regional climate conditions and building characteristics, ultimately promoting sustainable development and reducing environmental impact. Future research should explore innovative technologies and policies to further advance energy efficiency goals in urban environments.

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Appendix A

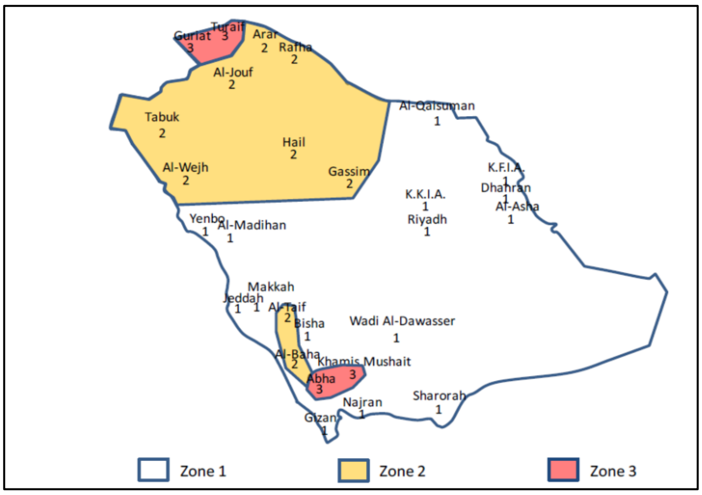
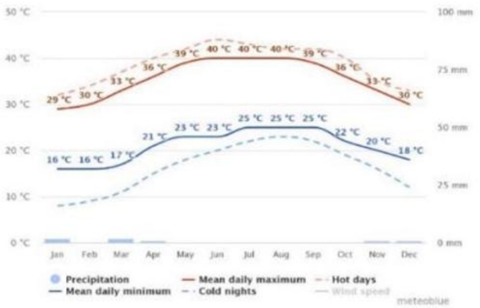
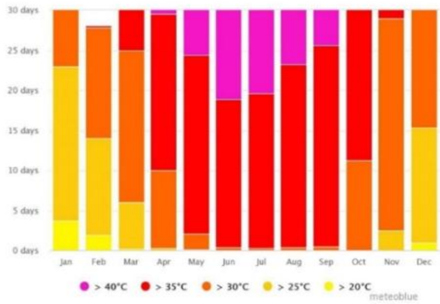
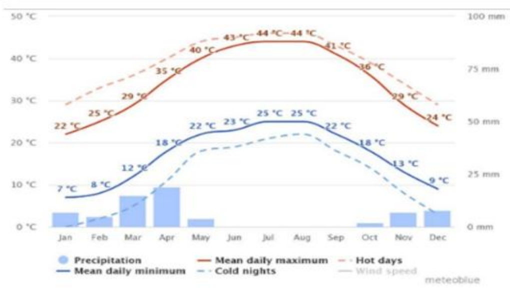
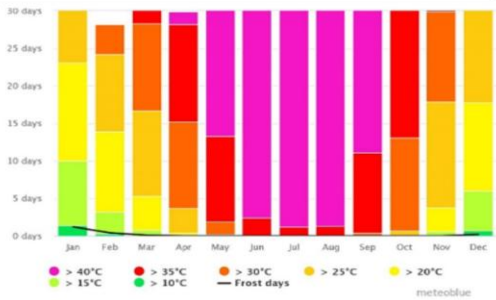


Figure A. 1 SBC climate specifications.

Table A. 1 Climate database for Riyadh, Jeddah, and Dhahran, KSA; Source: (Meteoblue, 2022)

Coordinates	**Jeddah**
Latitude	21°7
Longitude	39°2
Average temperatures and precipitation	**Temperatures distribution**
	

Coordinates	**Dhahran**
Latitude	26°29
Longitude	50°1
Average temperatures and precipitation	**Temperatures distribution**
	

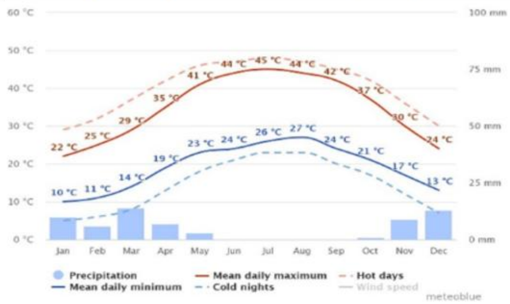
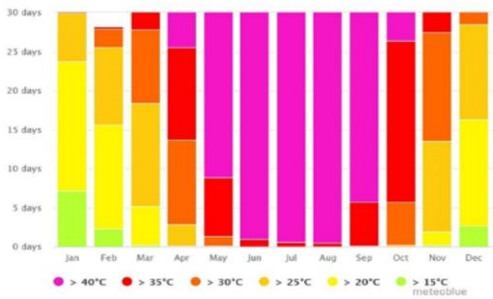
Coordinates	**Riyadh**
Latitude	24°7
Longitude	46°73
Average temperatures and precipitation	**Temperatures distribution**
	

Table A. 2 Housing Units (Occupied with Saudi Households) by Type of Housing Unit. Source: Housing Survey 2019 _General Authority for Statistics.

Administrative Area	**Type of Housing Unit**					
	Traditional House	**Villa**	**A Floor in a Villa**	**A Floor in a Traditional House**	**Apartment**	**Total**
Al-Riyadh	48160	395560	131672	1638	288360	865390
Makkah Al-Mokarramah	183876	117827	21090	10150	576285	909228
Al-Madinah Al-Monawarah	60840	37341	2604	687	151575	253047
Al-Qaseem	25857	97980	31992	19	15100	170948
Eastern Region	57770	176118	30628	10582	253116	528214
Aseer	57312	112326	32512	1140	111972	315262
Tabouk	38055	8379	1222	282	78174	126112
Hail	31825	34675	3564	78	14241	84383
Northern Borders	6552	16500	4698	1939	10842	40531
Jazan	103649	33864	11970	378	32560	182421
Najran	22411	18018	4100	5	28032	72566
Al-Baha	14056	24089	5248	67	29232	72692
Al-Jouf	14628	22560	2788	238	20919	61133
Total	**664991**	**1095237**	**284088**	**27203**	**1610408**	**3681927**

Appendix B

Financial Analysis for Retrofit Measures in Riyadh: The table below summarizes monthly energy consumption alongside the cost breakdown, following the two-tiered utility rate in Saudi Arabia.

Table B. 1 Monthly Energy Consumption and Cost Analysis for -BC.

Month	Total electricity (MWh)	Usage up to 6000 kWh (MWh)	Usage above 6000 (MWh)	Cost up to 6000 kWh ($)	Cost above 6000 kWh ($)	Total Cost ($)
Jan	4,815.40	4,815.40	0	$231.07	$0.00	$231.07
Feb	3,967.80	3,967.80	0	$190.82	$0.00	$190.82
Mar	4,660.90	4,660.90	0	$223.88	$0.00	$223.88
Apr	9,351.40	6,000.00	3,351.40	$288.00	$268.11	$556.11
May	13,892.10	6,000.00	7,892.10	$288.00	$631.37	$919.37
Jun	15,595.90	6,000.00	9,595.90	$288.00	$767.67	$1,055.67
Jul	17,074.20	6,000.00	11,074.20	$288.00	$885.94	$1,173.94
Aug	17,013.40	6,000.00	11,013.40	$288.00	$881.07	$1,169.07
Sep	13,605.10	6,000.00	7,605.10	$288.00	$608.41	$896.41
Oct	9,618.60	6,000.00	3,618.60	$288.00	$289.49	$577.49
Nov	4,260.20	4,260.20	0	$204.97	$0.00	$204.97
Dec	5,290.30	5,290.30	0	$254.17	$0.00	$254.17

Table B. 2 Monthly Energy Consumption and Cost Analysis for EW1.

Month	Total electricity (MWh)	Usage up to 6000 kWh (MWh)	Usage above 6000 (MWh)	Cost up to 6000 kWh ($)	Cost above 6000 kWh ($)	Total Cost ($)
Jan	4,157.70	4,157.70	0	$199.57	$0.00	$199.57
Feb	3,522.30	3,522.30	0	$169.07	$0.00	$169.07
Mar	4,309.40	4,309.40	0	$206.85	$0.00	$206.85
Apr	8,225.10	6,000.00	2,225.10	$288.00	$178.01	$466.01
May	12,076.70	6,000.00	6,076.70	$288.00	$486.14	$774.14
Jun	13,561.90	6,000.00	7,561.90	$288.00	$604.95	$892.95
Jul	14,812.20	6,000.00	8,812.20	$288.00	$704.98	$992.98
Aug	14,710.30	6,000.00	8,710.30	$288.00	$696.82	$984.82
Sep	11,847.40	6,000.00	5,847.40	$288.00	$467.79	$755.79
Oct	8,522.30	6,000.00	2,522.30	$288.00	$201.78	$489.78
Nov	3,981.80	3,981.80	0	$191.11	$0.00	$191.11
Dec	4,586.10	4,586.10	0	$220.49	$0.00	$220.49

Table B. 3 Monthly Energy Consumption and Cost Analysis for EW2.

Month	Total electricity (MWh)	Usage up to 6000 kWh (MWh)	Usage above 6000 (MWh)	Cost up to 6000 kWh ($)	Cost above 6000 kWh ($)	Total Cost ($)
Jan	4,106.60	4,106.60	0	$197.12	$0.00	$197.12
Feb	3,500.50	3,500.50	0	$168.02	$0.00	$168.02
Mar	4,325.20	4,325.20	0	$207.61	$0.00	$207.61
Apr	8,211.40	6,000.00	2,211.40	$288.00	$176.91	$464.91
May	12,016.60	6,000.00	6,016.60	$288.00	$481.33	$769.33
Jun	13,481.70	6,000.00	7,481.70	$288.00	$598.54	$886.54
Jul	14,718.70	6,000.00	8,718.70	$288.00	$697.50	$985.50
Aug	14,614.60	6,000.00	8,614.60	$288.00	$689.17	$977.17
Sep	11,785.20	6,000.00	5,785.20	$288.00	$462.82	$750.82
Oct	8,503.80	6,000.00	2,503.80	$288.00	$200.30	$488.30
Nov	3,998.90	3,998.90	0	$191.95	$0.00	$191.95
Dec	4,530.20	4,530.20	0	$217.45	$0.00	$217.45

Table B. 4 Monthly Energy Consumption and Cost Analysis for -EW5.

Month	Total electricity (MWh)	Usage up to 6000 kWh (MWh)	Usage above 6000 kWh (MWh)	Cost up to 6000 kWh ($)	Cost above 6000 kWh ($)	Total Cost ($)
Jan	4.1337	4.1337	0	$198.29	$0	$198.42
Feb	3.5092	3.5092	0	$168.46	$0	$168.44
Mar	4.3268	4.3268	0	$207.32	$0	$207.69
Apr	8.323	6,000.00	2.323	$288.00	$185.84	$473.84
May	12.2133	6,000.00	6.2133	$288.00	$497.07	$785.07
Jun	13.7167	6,000.00	7.7167	$288.00	$617.34	$905.34
Jul	14.9809	6,000.00	8.9809	$288.00	$718.47	$1,006.47
Aug	14.8699	6,000.00	8.8699	$288.00	$709.59	$997.59
Sep	11.9642	6,000.00	5.9642	$288.00	$477.14	$765.1
Oct	8.5917	6,000.00	2.5917	$288.00	$207.34	$495.3
Nov	3.9938	3.9938	0	$191.46	$0	$191.7
Dec	4.5733	4.5733	0	$219.68	$0	$219.5

Table B. 5 Monthly Energy Consumption and Cost Analysis for – R1

Month	Total electricity (MWh)	Usage up to 6000 kWh (MWh)	Usage above 6000 kWh (MWh)	Cost up to 6000 kWh ($)	Cost above 6000 kWh ($)	Total Cost ($)
Jan	4,179.20	4,179.20	$0.00	$200.38	$0.00	4,179.20
Feb	3,564.80	3,564.80	$0.00	$171.10	$0.00	3,564.80
Mar	4,373.10	4,373.10	$0.00	$209.94	$0.00	4,373.10
Apr	8,167	6,000.00	$2,167.10	$288.00	$173.37	8,167
May	11,934	6,000.00	$5,934.10	$288.00	$474.73	11,934
Jun	13,419	6,000.00	$7,419.30	$288.00	$593.54	13,419
Jul	14,663	6,000.00	$8,662.50	$288.00	$693.00	14,663
Aug	14,612	6,000.00	$8,611.70	$288.00	$688.94	14,612
Sep	11,859	6,000.00	$5,859.30	$288.00	$468.74	11,859
Oct	8,665	6,000	$2,664.50	$288.00	$213.16	8,665
Nov	4,114	4,113.60	$0.00	$197.56	$0.00	4,114
Dec	4,570.90	4,570.90	$0.00	$219.38	$0.00	4,570.90

Table B. 6 Monthly Energy Consumption and Cost Analysis for – R2

Month	Total electricity (MWh)	Usage up to 6000 kWh (MWh)	Usage above 6000 kWh (MWh)	Cost up to 6000 kWh ($)	Cost above 6000 kWh ($)	Total Cost ($)
Jan	4.0392	4.0392	0	$194.02	$0	$193.88
Feb	3.4755	3.4755	0	$166.82	$0	$166.82
Mar	4.3074	4.3074	0	$206.95	$0	$206.76
Apr	7.9843	6	1.9843	$288.00	$158.74	$446.74
May	11.6295	6	5.6295	$288.00	$450.36	$738.36
Jun	13.0675	6	7.0675	$288.00	$565.40	$853.40
Jul	14.2662	6	8.2662	$288.00	$661.30	$949.30
Aug	14.2256	6	8.2256	$288.00	$657.81	$945.81
Sep	11.5765	6	5.5765	$288.00	$446.12	$734.12
Oct	8.504	6	2.504	$288.00	$200.32	$488.32
Nov	4.06	4.06	0	$195.84	$0	$195.84
Dec	4.4134	4.4134	0	$211.07	$0	$211.07

Net Present Value (NPV), Internal Rate of Return (IRR), and Benefit-Cost Ratio (BCR) Analysis for EEMs in Riyadh City. (Discount Rate: 4%, Lifespan: 25 years. EEM1-EW1

IRR 6%

BCR 2.01

Year	Discounted Cash Flow	Cumulative Discounted Cash flow
1	1232.452	-14699.9
2	1185.05	-13514.9
3	1139.471	-12375.4
4	1095.645	-11279.8
5	1053.505	-10226.3
6	1012.986	-9213.29
7	974.0247	-8239.27
8	936.5622	-7302.7
9	900.5405	-6402.16
10	865.9044	-5536.26
11	832.6004	-4703.66
12	800.5773	-3903.08
13	769.7858	-3133.3
14	740.1787	-2393.12
15	711.7103	-1681.41
16	684.3368	-997.07
17	658.0162	-339.054
18	632.7078	293.6539
19	608.3729	902.0268
20	584.974	1487.001
21	562.475	2049.476
22	540.8413	2590.317
23	520.0397	3110.357
24	500.0382	3610.395
25	480.806	4091.201

EEM1-EW2

Year	Discounted Cash Flow	Cumulative Discounted Cash flow
1	1365.952	-22532.6
2	1313.415	-21219.2
3	1262.899	-19956.3
4	1214.326	-18742
5	1167.621	-17574.4
6	1122.713	-16451.7
7	1079.532	-15372.1
8	1038.011	-14334.1
9	998.0877	-13336
10	959.6997	-12376.3
11	922.7882	-11453.6
12	887.2963	-10566.3
13	853.1695	-9713.09
14	820.3553	-8892.73
15	788.8032	-8103.93
16	758.4646	-7345.47
17	729.2929	-6616.17
18	701.2432	-5914.93
19	674.2723	-5240.66
20	648.3387	-4592.32
21	623.4026	-3968.92
22	599.4256	-3369.49
23	576.3708	-2793.12
24	554.2027	-2238.92
25	532.8872	-1706.03

EEM1-EW5

IRR 16.3%

BCR 4.176187

Year	Discounted Cash Flow	Cumulative Discounted Cash flow
1	1159.952	-6088.05
2	1115.338	-4972.71
3	1072.441	-3900.27
4	1031.193	-2869.08
5	991.5318	-1877.54
6	953.3959	-924.148
7	916.7269	-7.42135
8	881.4681	874.0468
9	847.5655	1721.612
10	814.9668	2536.579
11	783.622	3320.201
12	753.4827	4073.684
13	724.5025	4798.186
14	696.6371	5494.823
15	669.8433	6164.667
16	644.0801	6808.747
17	619.3078	7428.055
18	595.4883	8023.543
19	572.5849	8596.128
20	550.5624	9146.69
21	529.3869	9676.077
22	509.0259	10185.1
23	489.448	10674.55
24	470.623	11145.17
25	452.5222	11597.7

EEM2-R1

IRR 3.02%

BCR 2.27

Year	Discounted Cash Flow	Cumulative Discounted Cash flow
1	1255.26	-13066.7
2	1206.98	-11859.8
3	1160.558	-10699.2
4	1115.921	-9583.28
5	1073.001	-8510.28
6	1031.732	-7478.55
7	992.0499	-6486.5
8	953.8941	-5532.6
9	917.2059	-4615.4
10	881.9288	-3733.47
11	848.0084	-2885.46
12	815.3927	-2070.07
13	784.0315	-1286.04
14	753.8764	-532.16
15	724.8812	192.7212
16	697.0011	889.7223
17	670.1934	1559.916
18	644.4167	2204.332
19	619.6314	2823.964
20	595.7995	3419.763
21	572.8841	3992.647
22	550.8501	4543.498
23	529.6636	5073.161
24	509.2919	5582.453
25	489.7037	6072.157

EEM2-R2

IRR 2%

BCR 1.30

Year	Discounted Cash Flow	Cumulative Discounted Cash flow
1	1437.394	-27206.6
2	1382.11	-25824.5
3	1328.952	-24495.5
4	1277.838	-23217.7
5	1228.691	-21989
6	1181.433	-20807.6
7	1135.994	-19671.6
8	1092.301	-18579.3
9	1050.29	-17529
10	1009.894	-16519.1
11	971.052	-15548.1
12	933.7039	-14614.3
13	897.7922	-13716.6
14	863.2617	-12853.3
15	830.0594	-12023.2
16	798.134	-11225.1
17	767.4365	-10457.7
18	737.9197	-9719.74
19	709.5382	-9010.21
20	682.2483	-8327.96
21	656.008	-7671.95
22	630.7769	-7041.17
23	606.5162	-6434.66
24	583.1887	-5851.47
25	560.7584	-5290.71

EEM2-R5

IRR 23%

BCR 5.5

Year	Discounted Cash Flow	Cumulative Discounted Cash flow
1	1365.952	-4997.58
2	1313.415	-3684.16
3	1262.899	-2421.26
4	1214.326	-1206.94
5	1167.621	-39.3157
6	1122.713	1083.397
7	1079.532	2162.929
8	1038.011	3200.94
9	998.0877	4199.028
10	959.6997	5158.727
11	922.7882	6081.516
12	887.2963	6968.812
13	853.1695	7821.981
14	820.3553	8642.337
15	788.8032	9431.14
16	758.4646	10189.6
17	729.2929	10918.9
18	701.2432	11620.14
19	674.2723	12294.41
20	648.3387	12942.75
21	623.4026	13566.15
22	599.4256	14165.58
23	576.3708	14741.95
24	554.2027	15296.15
25	532.8872	15829.04

EEM3-G6

IRR 6.36%

BCR 1.6

Year	Discounted Cash Flow	Cumulative Discounted Cash flow
1	558.2115	-5029.41
2	536.7419	-4492.67
3	516.0979	-3976.57
4	496.248	-3480.32
5	477.1616	-3003.16
6	458.8092	-2544.35
7	441.1627	-2103.19
8	424.1949	-1678.99
9	407.8797	-1271.11
10	392.192	-878.921
11	377.1077	-501.813
12	362.6036	-139.209
13	348.6573	209.448
14	335.2474	544.6954
15	322.3533	867.0486
16	309.9551	1177.004
17	298.0337	1475.037
18	286.5709	1761.608
19	275.5489	2037.157
20	264.9509	2302.108
21	254.7605	2556.869
22	244.962	2801.83
23	235.5404	3037.371
24	226.4811	3263.852
25	217.7703	3481.622

EEM4-S7

IRR 12.6%

BCR 1.77

Year	Discounted Cash Flow	Cumulative Discounted Cash flow
1	460.5673	-2739.43
2	442.8532	-2296.58
3	425.8204	-1870.76
4	409.4427	-1461.32
5	393.6949	-1067.62
6	378.5528	-689.069
7	363.993	-325.076
8	349.9933	24.91747
9	336.532	361.4495
10	323.5885	685.038
11	311.1428	996.1807
12	299.1757	1295.356
13	287.669	1583.025
14	276.6048	1859.63
15	265.9661	2125.596
16	255.7367	2381.333
17	245.9007	2627.234
18	236.4429	2863.677
19	227.349	3091.026
20	218.6048	3309.63
21	210.1969	3519.827
22	202.1124	3721.94
23	194.3389	3916.279
24	186.8643	4103.143
25	179.6772	4282.82

EEM5-EER

IRR 50.6%

BCR 12.64

Year	Discounted Cash Flow	Cumulative Discounted Cash flow
1	2237.837	-2362.16
2	2151.766	-210.398
3	2069.006	1858.608
4	1989.429	3848.037
5	1912.912	5760.949
6	1839.339	7600.287
7	1768.595	9368.882
8	1700.572	11069.45
9	1635.165	12704.62
10	1572.274	14276.89
11	1511.802	15788.7
12	1453.656	17242.35
13	1397.746	18640.1
14	1343.987	19984.08
15	1292.295	21276.38
16	1242.591	22518.97
17	1194.799	23713.77
18	1148.845	24862.61
19	1104.659	25967.27
20	1062.172	27029.45
21	1021.319	28050.77
22	982.0379	29032.8
23	944.2672	29977.07
24	907.9492	30885.02
25	873.0281	31758.05

EEM6-ACH

Year	Discounted Cash Flow	Cumulative Discounted Cash flow
1	616.4231	355.6631
2	592.7145	948.3776
3	569.9178	1518.295
4	547.9979	2066.293
5	526.921	2593.214
6	506.6548	3099.869
7	487.1681	3587.037
8	468.4309	4055.468
9	450.4143	4505.882
10	433.0907	4938.973
11	416.4333	5355.406
12	400.4167	5755.823
13	385.016	6140.839
14	370.2077	6511.047
15	355.969	6867.016
16	342.2779	7209.294
17	329.1133	7538.407
18	316.4551	7854.862
19	304.2838	8159.146
20	292.5805	8451.726
21	281.3274	8733.054
22	270.5072	9003.561
23	260.103	9263.664
24	250.0991	9513.763
25	240.4799	9754.243

EEM7-PV 40%

IRR:16.45%

BCR: 3.09

Year	Discounted Cash Flow	Cumulative Discounted Cash Flow
1	1977.69	-13048.31
2	1969.44	-11078.87
3	1960.85	-9118.02
4	1951.94	-7166.08
5	1942.74	-5223.33
6	1933.26	-3290.07
7	1923.52	-1366.55
8	1913.53	546.98
9	1903.31	2450.28
10	1892.87	4343.15
11	1882.23	6225.38
12	1871.40	8096.78
13	1860.40	9957.18
14	1849.23	11806.41
15	1837.91	13644.33
16	1826.46	15470.79
17	1814.87	17285.66
18	1803.17	19088.82
19	1791.35	20880.17
20	1779.44	22659.61
21	1767.44	24427.05
22	1755.35	26182.40
23	1743.20	27925.60
24	1730.98	29656.58
25	1718.70	31375.28

Pv System Specifications based on the Saudi local market:

System Size: 12.96 kW

Panel Rating: 305 W

Number of Panels Required:

Number of Panels= Total Capacity/Panel Rating=305W12,960W=42.49≈43panels

Assumptions for Cost Estimation:

Total Panel Cost Including VAT: $250 per m^2 for the total area of panels. (assumed)

Panel Cost=43×250=$10,750

Annual Maintenance Cost per kW: Typically, between $30 or 2% of the initial system cost. (Assumed).

Annual Maintenance Cost=12.96 kW×20 USD/kW=388 USD

Inverter Cost: inverters typically cost around $0.20 per watt.

Inverter Cost=12,960×0.20=$2,592

Mounting and Racking Cost: These costs are generally around $0.10 per watt. Mounting and Racking Cost=12,960×0.10=$1,296

Electrical Components and Wiring= $500 (Assumed)

Total Initial Cost=10,750+2,592+1,296+500=$15,138