Faculty of Engineering

An Approach to Enhancing Energy Performance in Residential Buildings in Hot Climate Regions (The Case of Saudi Arabia)

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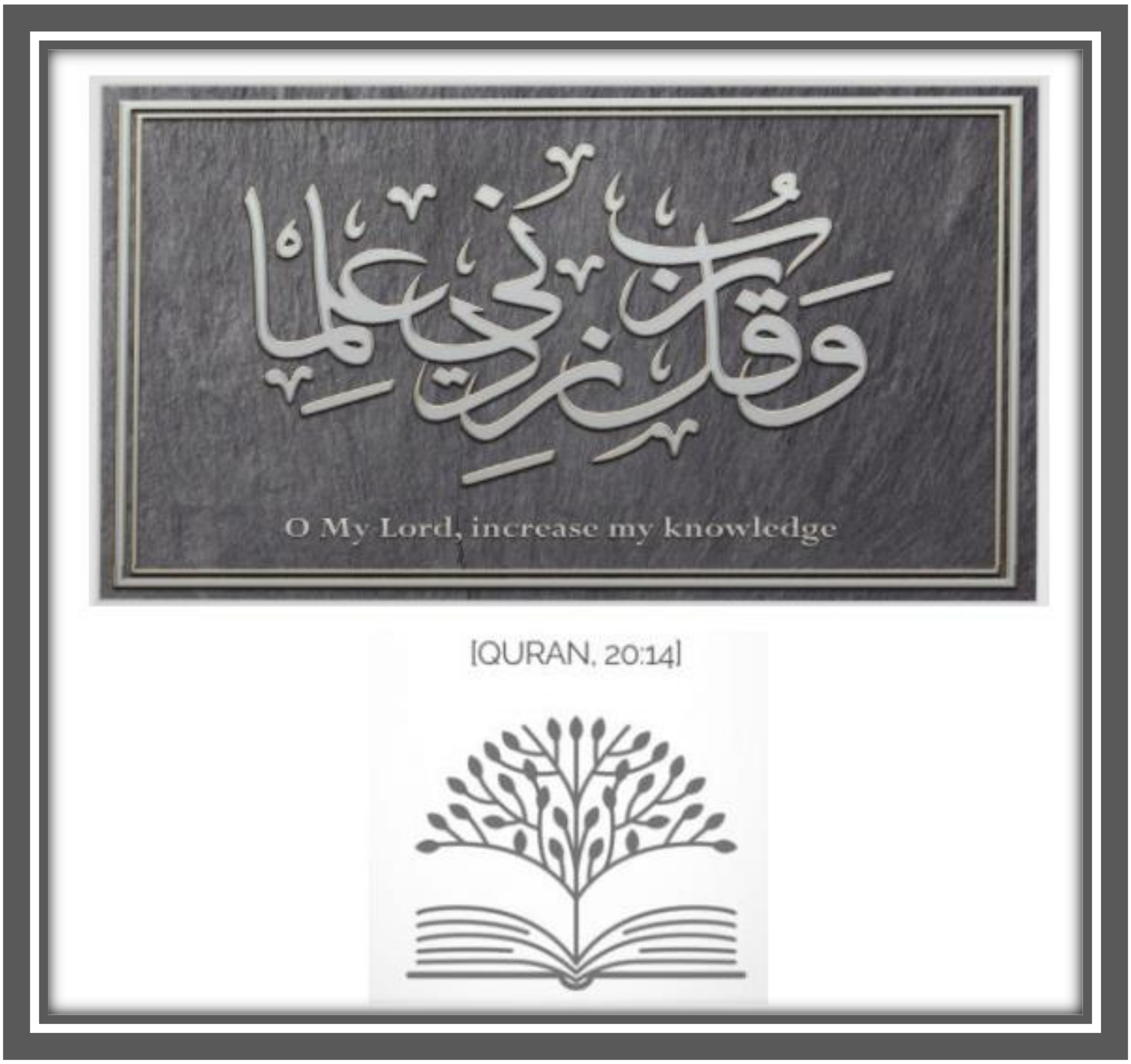
Quotation



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Abstract

Saudi Arabia, like many developing countries, is experiencing rapid urbanisation and infrastructure expansion, especially in the area of residential buildings. As an oil-producing nation with an extremely hot climate, the country is also renowned for high rates of energy consumption and carbon emissions. The construction sector is no exception, accounting for approximately 80% of total national electricity consumption, with residential cooling demand consuming almost 66% of domestic energy use. Although sustainability has now become a major focus for the Saudi government, with sustainable development being a key goal of the country's economic and social development plan, the Saudi Vision 2030, the lack of energy efficiency in Saudi buildings has yet to be given serious consideration. However, with current demand threatening long-term energy security and forecasts indicating that domestic energy consumption will rise at a rate of 5% to 7% annually, it is crucial to improve the energy and environmental performance of the building stock.

In order to support sustainable development within the Saudi residential sector, this study identifies the main causes of high energy consumption in the sector and the key barriers to enhancing building energy performance from a design and operational perspective, including environmental, economic and socio-cultural factors. It goes on to explore a number of possible solutions, assessing their effectiveness via simulation and calculating cost benefits in order to identify the optimal energy efficiency measures. These are then tested against local building regulations and benchmarked against international low-energy standards. The most effective measures are incorporated into a proposed framework for energy-efficient building design in the Saudi context, which takes local environmental, economic and socio-cultural factors into account. The framework covers both new builds and retro-fitting and constitutes one of the main contributions of this research.

The study was performed in four stages, each utilising a specific methodology. Stage one involved an exploratory public survey, distributed electronically, designed to gauge public awareness of the benefits of sustainable building design and to identify design and operation factors causing energy consumption in residential buildings. Next, an existing family villa, representing a typical dwelling type in Saudi Arabia, was selected for modelling purposes and examined to identify design weaknesses. The third stage involved a consultation with experts in the field to assess current building issues and identify viable solutions in the local context. A model was then created using DesignBuilder simulation software, and its energy performance validated using data collected from the case study villa. Additional simulations targeting building design and operating parameters to enhance energy efficiency were also analysed to establish the optimal solutions within the local context. The use of

surveys, a case study, and computer simulations to collect and validate the results is considered appropriate for the purposes of proposing energy strategies for residential buildings in hot climates.

The findings indicate that much of the high energy consumption in the residential sector results from poor building design and construction techniques, inefficient operating practices, a lack of stakeholder engagement, and an absence of coordinated enforcement. However, the results of the simulations show that energy consumption and peak electricity demand could be reduced significantly by implementing the optimal strategies proposed in the framework. A potential reduction of 68% in total electricity consumption and 74% in peak electricity demand was shown to be possible, with an 81% reduction in cooling energy use intensity (EUI) bringing Saudi Arabia within the range of recommended European standards. Analysis of the improvement simulations also indicated that a reduction of 80% in carbon emissions was achieved in comparison with the base case study building. This amounted to almost 23 tonnes of CO_2 avoided annually and was equivalent to nearly five cars not being used per year. The cost-saving analysis employed to determine the economic viability of incorporating the proposed techniques indicated a typical payback period of 7 years, average annual savings of 1,603 USD, and total operational cost savings of up to 51% over a 30-year period. By incorporating the optimal sustainable design features, energy-efficiency measures, and renewable solar energy technologies proposed in the framework, the representative home was transformed into an energy-efficient structure.

This study demonstrates that relatively simple strategies can significantly reduce residential energy demand in hot climate conditions and that the strategies in the proposed framework are effective. These findings have significant implications for building sector professionals, policy-makers and building occupants. A dramatic reduction in energy consumption would save costs, reduce CO_2 emissions, alleviate the need to increase power generation capacity, and enhance the country's profile internationally, resulting in significant environmental, economic, and social benefits. However, this cannot be achieved without support from the government, the housing industry; and the general public, so the study concludes by recommending further measures to support the development of a sustainable building sector in Saudi Arabia in line with the aims expressed in Vision 2030.

Table of content

List of Figures

List of Tables

List of Abbreviation

AC: Air Conditioning

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

BEI: Building Energy Index

BEMs: Building Energy Models

BP: British Petroleum

BPS: Building Performance Simulation

BREEAM: Building Research Establishment Environmental Assessment Method

CDD: Cooling Degree Days

CFL: Compact Fluorescent Lamps

CO_2: Carbon Dioxide

CoP: Coefficient of Performance

DB: DesignBuilder

DBT: Dry Bulb Temperature

DWS: Double Wall System

ECI: Energy Cost Index

ECRA: Electricity and Cogeneration Regulatory Authority

EEMs: Energy Efficiency Measures

EER: Energy Efficiency Ratio

EIA: Energy Information Administration

EIFS: External Insulation and Finish System

EPA: Environmental Protection Agency

EUI: Energy Use Intensity

FEMP: Federal Energy Management Program

GAS: General Authority for Statistics

GCC: Gulf Cooperative Council

GHGs: Greenhouse Gases

HVAC: Heating, Ventilation and Air Conditioning

HDD: Heating Degree Days

HEAC: High Efficiency AC

ICC: International Code Council

IEA: International Energy Agency

IECC: International Energy Conservation Code

IIFS: Internal Insulation and Finish System

IPMVP: International Performance Measurement and Verification Protocol

KACARE: King Abdullah Centre for Atomic and Renewable Energy

KSA: Kingdom of Saudi Arabia

LCA: Life Cycle Assessment

LCB: Low Carbon Buildings

LCC: Life Cycle Cost

LED: Light Emitting Diodes

LEED: Leadership in Energy and Environmental Design

MENA: Middle East and North Africa

MEPS: Minimum Energy Performance Standard

MoH: Ministry of Housing

MoMRA: The Ministry of Municipality and Rural Affairs

NCSBC: National Committee of the Saudi Building Code

NDC: Nationally Determined Contributions

NEEP: National Energy Efficiency Program

NREP: National Renewable Energy Program

PMV: Predicted Mean Vote

PPD: Predicted Percentage of Dissatisfied

PR: Performance ratio

PUR: Polyurethane

PV: Photovoltaics

RH: Relative Humidity

R-Value: Thermal Resistance

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

SGBC: Saudi Green Building Council

SHGC: Solar Heat Gain Coefficient

SPT: Setpoint Temperature

SR: Solar Reflectance (sometimes referred to as R)

SRI: Solar Reflectance Index

STC: Standard Test Conditions

UAE: United Arab Emirates

USSBC: US-Saudi Business Council

U-Value: Thermal Transmittance

Wp: Peak Watt

WWR: Window-to-Wall Ratio

XPS: Extruded Polystyrene

Chapter One: Research Introduction

1.1 Introduction

This study explores the most effective ways to achieve energy efficiency in residential buildings in the context of Saudi Arabia, a developing nation with high energy consumption rates and a rapidly rising population. This chapter introduces the context of the study and sets out the research problem it seeks to address. It goes on to identify the research aim, the objectives established for the study, and the research questions. It offers an overview of the methodology adopted to achieve the research aim and defines the scope of the study, identifying key constraints. The chapter concludes by outlining the contents of each chapter and provides a flow chart to illustrate the thesis structure.

1.2 Research Background

A large amount of energy and natural resources are consumed by the construction of buildings around the world. Specifically, the building sector worldwide accounts for half of global energy consumption, over one third of greenhouse gas (GHG) emissions, 25% of harvested wood, and 16% of fresh water (UNSTAT, 2010; Sahebzadeh et al. 2017; Piotrowska and Borchert, 2017; Paudel et al., 2014). These figures are even higher in some developing countries, notably the Gulf regions, whose economies rely heavily on the exploitation of their fossil fuel resources. CO_2 emissions in the Gulf Cooperation Council (GCC) countries, for example, are approximately three times higher than the EU average (Aldossary et al., 2014a). As concerns about the effects of global warming and environmental damage increase, the developed world has shown a growing interest in the production of more environmentally-friendly structures. However, while low-energy houses and building energy conservation have become priorities for nations seeking to achieve long-term environmentally sustainable economic growth, in developing countries, such as Saudi Arabia, efforts to limit residential energy consumption are only now beginning to be adequately considered (Ghabra, 2017).

Terms including ‘energy-efficient buildings’, ‘eco-houses’, ‘low carbon buildings’, and ‘green buildings’, are used to describe buildings which are intended to reduce the impact of their construction on the environment. These buildings typically utilise high performance insulation, energy-efficient glazing, and low-energy consumption technologies, especially in heating and cooling systems (European Commission, 2009; Krarti and Howarth, 2020). However, it can be difficult to define exactly what constitutes a ‘low-energy dwelling’ because of the wide range of regulations and specifications in different countries (Felimban et al., 2019). The economy, climate, accessibility to technology and materials, as well as the socio-cultural context, all have a significant impact on sustainable building construction and its long-term viability (Singh et al., 2009). Thus, solutions that help to reduce energy consumption in one location might not be as effective in another (Aldossary, 2015).

Within this context, the Kingdom of Saudi Arabia (KSA), one of the founding GCC members, presents an interesting case for study. As a large developing nation with a rapidly increasing population, an extremely hot climate, a dependency on fossil fuels, and a strong religious identity which governs all aspects of life, the country requires energy solutions which are effective in its particular context. However, contemporary building design in the country typically pay little regard to the climate conditions and building codes are largely based on Western models, so do not adequately meet local requirements.

As concerns about the effects of global warming and environmental damage increase, the developed world has shown a growing interest in the production of more environmentally friendly structures whereas efforts to limit residential energy consumption are only now beginning to be adequately considered in developing countries, such as Saudi Arabia and many GCC countries which have only recently introduced regulations and policies to promote energy conservation in buildings. The issue of energy efficiency has not yet been given serious consideration within Saudi building design and construction. As a result, there is an increasingly urgent need to identify ways to enhance building energy-efficiency in the country which satisfy local climatic, economic, and socio-cultural needs.

The majority of studies on building envelopes in the Gulf region have primarily focused on thermal properties rather than the integration of design and planning processes that focus on energy consumption issues. In fact, there were no energy consumption standards for sustainable houses in the GCC countries, or the wider Middle East, at the time, and, regrettably, to the best of the researcher's knowledge, this is still the case. Furthermore, to the best of the researcher's knowledge, no comprehensive studies have considered the updated version of the SBC, examined the impact of energy efficiency improvements to AC stock in the context of Saudi Arabia, or applied cost benefit analysis in residential buildings. This leaves a gap in the knowledge which has not yet been investigated.

Therefore, this study is driven by the shortage of experimental validated studies in the Gulf region, and the urgent need to address the extremely high rates of energy consumption in the Saudi residential sector which are negatively impacting sustainable development in the country.

1.3 Research Problem and Rationale

In recent years, Saudi Arabia has been experiencing an economic boom which has resulted in rapid population growth, increased urbanisation, and massive infrastructure expansion, especially in the residential sector. This has driven demand for energy to unprecedented levels, and primary energy consumption per capita is now over three times the world average (Mujeebu and Alshamrani, 2016;

Saudi Energy Efficiency Center, 2013). As a result, national electricity generation now consumes approximately one-third of the country's total daily oil production, with buildings accounting for around 80% of this (Al Rashodi, 2014; Felimban et al., 2019). This poses a long-term threat to the nation's energy-security (Al Surf, 2014).

At the same time, the Saudi government has launched an ambitious programme, known as Saudi Vision 2030, to move the economy away from oil dependency (Al Harbi and Csala, 2019). One of the key aims of Vision 2030 is to promote sustainability across all sectors, notably in the construction industry; therefore improving the energy-efficiency of residential buildings and promoting the nascent sustainable development sector have become national goals (Balabel and Alwetaishi, 2021). In order to support these objectives, the government recently introduced a set of standards and regulations, known as the Saudi Building Code (SBC) which are intended to reduce energy consumption levels in the industry.

Despite this, the issue of energy efficiency has not yet been given serious consideration within Saudi building design and construction (Ghabra, 2017). Thermal efficiency of buildings is poor, owing to design and construction defects, and lax implementation of regulations and standards means buildings are still routinely erected without adequate thermal insulation. This leaves occupants heavily dependent on air conditioning to maintain thermal comfort in the hot climate conditions. As a result, residential buildings currently consume about half of overall energy consumption within the building sector, much of this due to cooling loads (Felimban et al., 2019; Krarti et al., 2017; Shenashen et al., 2016). Furthermore, low energy costs due to government subsidies make consumers less motivated when it comes to adopting energy conservation strategies (KACARE, 2020; AlHashmi et al., 2021). Socio-cultural practices, including large family sizes, gender segregation, and the status associated with spacious dwellings, also play a role in driving high levels of energy consumption.

In order to support the sustainable development ambitions expressed in Vision 2030, it is crucial to improve the energy and environmental performance of the residential stock. This can be achieved not only by reducing demand for energy, but also by integrating efficient technologies into buildings. As a first step, existing buildings must be evaluated in terms of their actual energy usage; however, very few studies have involved comprehensive analysis of energy conservation measures in residential buildings in KSA. Therefore, this study aims to make a contribution to literature and to Saudi society by identifying the causes of high energy consumption in residential buildings and proposing viable, cost-effective and culturally appropriate, solutions to address them. Further details of the aims and objectives established for the study are provided below.

1.4 Research Aim and Objectives

This study is driven by the need to address the extremely high rates of energy consumption in the Saudi residential sector which are negatively impacting sustainable development in the country. It aims to identify the most effective strategies to enhance the energy performance of residential buildings, taking into consideration the local climatic conditions, and socio-cultural, economic, and environmental factors that impact building design and performance. The term sociocultural relates to social and cultural characteristics, and it refers to the common traditions, beliefs, habits, and patterns. In order to achieve this, a number of objectives have been developed to guide the theoretical and empirical research as follows:

- To review current building characteristics, performance, practices, and regulations within the residential sector
- To assess public perceptions and the level of stakeholder engagement (building industry professionals and their clients) towards the development of energy-efficient buildings
- To identify the factors that contribute to high levels of energy consumption in residential buildings in Saudi Arabia and identify the barriers hindering the development of sustainable buildings
- To identify common and widely applicable building efficiency and operational measures and apply these measures to a representative case study building model
- To validate the model and to evaluate measures' effectiveness via simulation
- To examine the economic, social, and environmental benefits of incorporating these applications into residential building design and establish the optimal strategies and measures for use in the Saudi context that aids in proposing a practical framework for sustainable residential building in the hot climate conditions of Saudi Arabia

1.5 Research Hypothesis and Questions

The overarching hypothesis of this study is that most residential buildings in Saudi Arabia are not constructed sustainably, and there is a wide-spread lack of appreciation of the benefits of sustainable and energy-efficient strategies and measures, both within the construction sector and among the general public. Therefore, this research is underpinned by the following research questions:

1. What are the key factors that lead to energy intensive consumption in Saudi Arabia's residential sector?
2. What are the barriers to widespread energy-efficiency in dwellings in Saudi Arabia?

3. How can the problem of energy intensive residential buildings in the KSA be addressed from a design and operational perspective?
4. What level of environmental and economic benefits can be achieved by improving the energy-efficiency of residential buildings and creating a sustainable building industry in the KSA?

1.6 Research Methodology

A mixed methods approach involving both quantitative and qualitative methods was adopted for the conduct of this research. The research data was collected from both primary and secondary sources. The primary data was obtained via quantitative approaches, involving questionnaires distributed to the public and to a panel of experts in the building and sustainable development sectors, and computer-based modelling and simulations, and via qualitative approaches, involving building observations and a representative building case study in Riyadh, the Saudi capital that reflects the common dwelling type and design in the Saudi context. The secondary data was gathered via a review of literature relating to sustainable construction, both within Saudi Arabia and more broadly. Secondary data was also gathered from government ministries and organisations within the Saudi building sector.

The findings of the literature review, the public questionnaire, and the expert consultation informed the identification of a range of potential energy-efficiency strategies which were then applied to the base case model. Modelling-simulations software was utilised to assess their effectiveness through holistic parametric analysis and establish the optimal strategies to improve overall building performance. A cost-benefit analysis was also performed to ensure the proposed measures were viable and cost-effective within the Saudi context. Finally, an energy-efficient design framework for residential buildings was developed to help construction industry professionals promote and enhance sustainability within the Saudi residential sector. A number of recommendations to support the implementation of the framework were also made. Figure 1-1 presents an outline of the methodology employed for this study, and a detailed account and justification of the choices made is provided in Chapter 4.

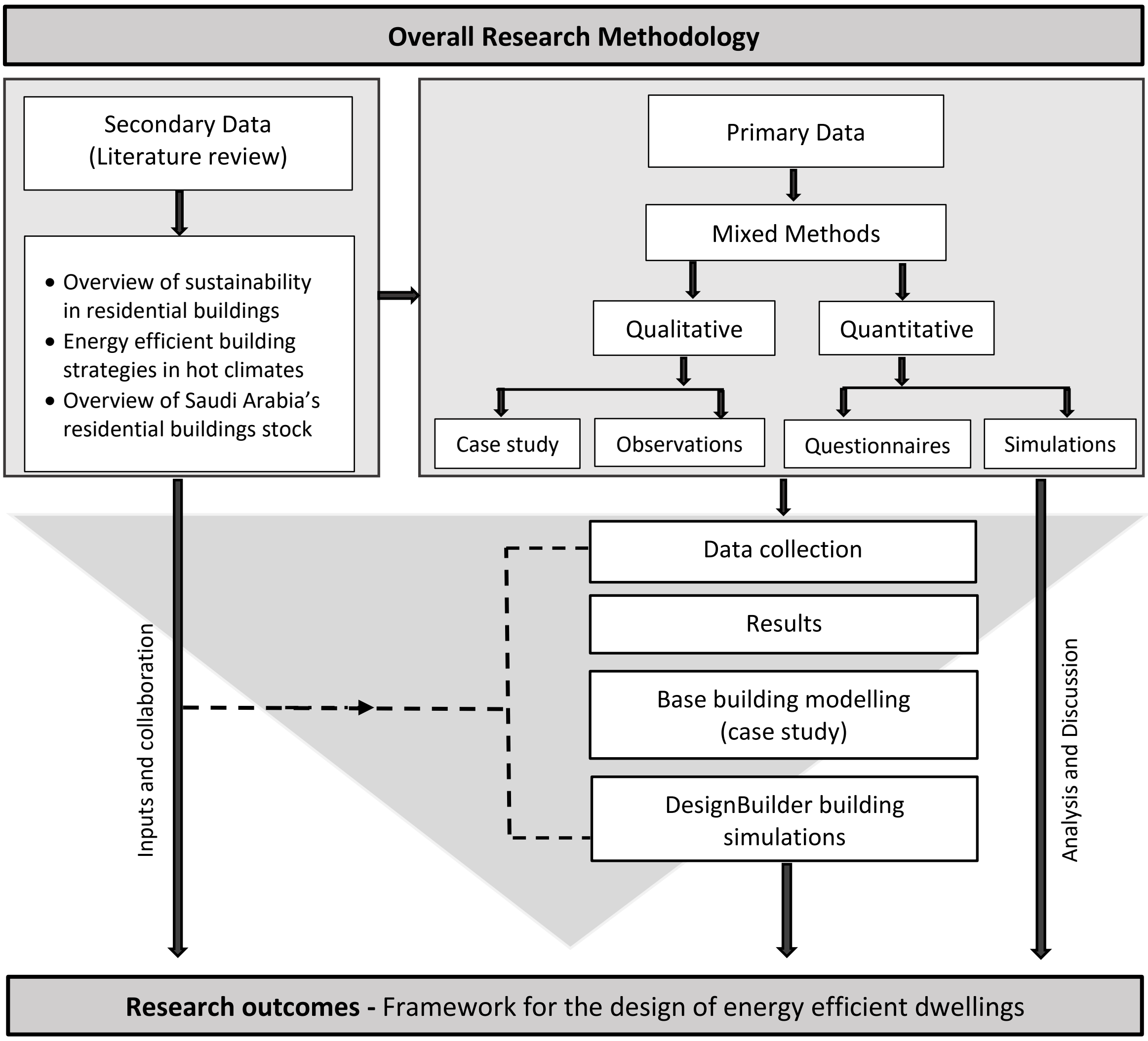


Figure 1-1: Research methodology outline

1.7 Research Scope

Whilst the environmental problems associated with buildings have been well documented, the negative impact of residential buildings on national energy production in Saudi Arabia persists. This study focuses specifically on family villas, as these are one of the two most common housing units in the country (the other being flats). It assesses their performance in terms of energy consumption and thermal comfort, identifying the key factors driving high consumption and the critical barriers to the development of more sustainable housing units. A number of potential solutions are then identified, tested on a base case model, and analysed in order to establish the optimal solutions in light of the climatic, economic and socio-cultural conditions in Saudi Arabia. These findings are then used to inform the development of a practical framework to support architects, engineers, and other building sector stakeholders to enhance the energy efficiency of current and future residential buildings in the country. It was beyond the scope of this study to examine flats too; however, suggestions for future research with regard to this are provided in the concluding chapter.

In order to ensure that the associated objectives were comprehensively addressed, this research was organised into the following phases: a) comprehensive review of pertinent literature, b) distribution of an electronic online-survey to the Saudi public through social media in the form of a link message, c) selection and observation of a representative case study building, which had to have been occupied for at least one year, and collection of key data for modelling purposes, d) consultation with local experts, with a minimum of 10 years' experience in construction and building sustainability, to identify potential design weaknesses and propose effective solutions, e) modelling and validation of the selected base case building, f) parametric analysis using DesignBuilder simulation software to find the optimal building energy-reduction strategies, g) cost-benefit analysis to assess their viability in the Saudi context, and h) development of the practical framework for energy-efficient building design based on the research findings. The proposed methodology of using surveys, observation, and computer-based building simulation to validate the results has been established as appropriate for this type of study.

Given the broad scope of this research and the time restrictions associated with doctoral study, the researcher had to adhere to strict conceptual and time limits. The time available for gathering responses to the public survey was limited to a maximum period of 40 days, and the number of expert participants was limited to 33. The decision was made to focus on the largest climatic zone in Saudi Arabia, Zone 1, which covers more than half the country, and to identify a single representative case study villa in Riyadh, the Saudi capital and the largest city in Zone 1. These constraints are discussed in more detail in subsequent chapters.

1.8 Thesis Structure

A roadmap showing the structure of this study is provided in Figure 1-2.

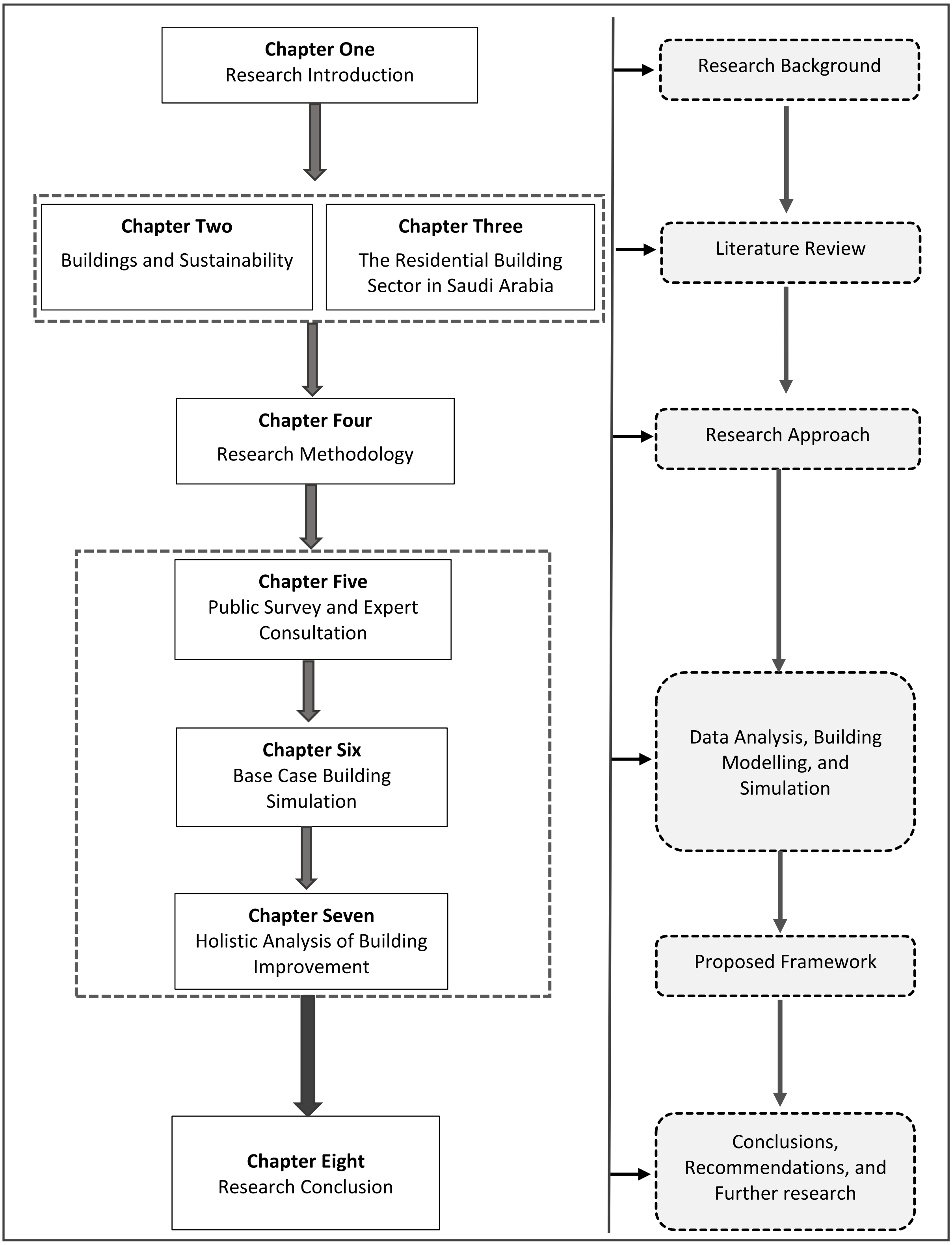


Figure 1-2: Organisation of the thesis

The following paragraphs provide a brief summary of each chapter's purpose and content:

Chapter One introduces the context of the study and sets out the research problem. It identifies the research aim, objectives, and the research questions. It offers an overview of the methodology adopted and defines the scope of the study, identifying key constraints. It concludes by describing the structure of the thesis.

Chapter Two presents the first section of the literature review which assesses existing studies concerning the concept of sustainability and the way it is applied to buildings, especially those conducted in hot climates. It provides insights into buildings' thermal and energy performance, international standards for energy conservation in buildings, the integration of sustainable and renewable measures, and building designs and materials.

Chapter Three provides more information about Saudi Arabia, the site of this study, and offers an overview of the country's residential building stock. It begins with the country's profile in terms of population, climate, and energy trends, and Saudi building regulations are outlined and compared with those in other Gulf states. Saudi residential buildings and their characteristics, energy consumption, and related building-practice issues are reviewed. The chapter concludes by highlighting the country's energy policies and the national initiatives to achieve sustainable development goals.

Chapter Four describes the methodology adopted to meet the aim of this research. The research design, the methodological choices, the methods and techniques selected, and the research tools are discussed and a justification for their selection is provided. A number of common building performance simulation tools are reviewed in order to identify the most suitable tool for this study. The chapter ends with a methodology flowchart to provide a clear visualisation of the research process and the sequence of stages involved.

Chapter Five presents the findings of the public survey and the expert consultation on the topic of energy-efficient buildings. It provides interpretation and analysis of the main findings, focusing on public perceptions of sustainable construction, factors causing high energy consumption in residential buildings, the barriers preventing the development of energy-efficient dwellings, and stakeholder engagement. The chapter concludes by identifying key recommendations and strategies to enhance residential energy-efficiency based on the views of the expert panel.

Chapter Six describes the process of constructing the case study building model using DesignBuilder. It begins by providing the base case building's characteristics, construction details, occupancy profile, and energy consumption costs and patterns (based on actual utility bills). The parameters and settings of the simulation are highlighted. The chapter goes on to analyse the base case building simulation outputs in terms of design data, energy consumption rates, comfort performance, and daylighting. Finally, the validation of the model is presented.

Chapter Seven provides a detailed description of the holistic parametric analysis of the base building improvements to assess their overall impact on building performance. The building's parameters are identified and their impacts were analysed at two levels: improvement on the reference case based on individual parameters and improvement achieved with combined parameters. Optimal design values for 16 energy efficiency measures (EEMs) are evaluated to determine the most effective combination, and a cost-benefit analysis of the highest impact measures is also provided. The final improved model is then compared with previous simulations, local codes, and benchmarked against other low-energy standards. The chapter concludes by presenting the practical framework for energy-efficient residential buildings in the climatic, economic, and socio-cultural context of Saudi Arabia.

Chapter Eight concludes the study by summarising the key research findings in relation to the research aim and questions. It demonstrates how each of the research questions has been answered and provides a number of recommendations to support the development of a sustainable construction sector in Saudi Arabia. It goes on to identify the contributions to knowledge this study makes as well as setting out its limitations. The chapter concludes by considering the potential areas for further research which arise from this study.

Chapter Two: Literature Review - Sustainability and Buildings

2.1 Introduction

Current rates of urbanisation and industrialisation have caused profound changes and raised serious issues at environmental, social, and economic levels. The building sector has experienced considerable development following rapid economic growth, and this has led to greater exploitation of natural resources. These developments involve the extraction of substantial amount of raw materials, the consumption of large quantities of energy, and, perhaps most significantly, the emission of greenhouse gases (GHGs) which contribute to global warming. In order to address these negative environmental outcomes, and their high social and economic impact, the building sector requires a much greater commitment to sustainable development, which, as Zhu et al. (2016) note, is key to social, economic, and environmental stability.

The review of literature presented in this chapter aims to assess existing studies concerning the design of sustainable buildings, especially those conducted in hot climates. This will provide insight into the concept of sustainability, the way it is applied in the building construction industry, and illustrate the need for the development of sustainable buildings which meet local needs. Building performance, in terms of energy consumption and thermal comfort, building envelope design, and building materials, will also be examined in this chapter.

2.2 Sustainable Buildings

Sustainability is defined in myriad ways in existing literature. Tsimplokoukou et al. (2014) define it in terms of the interactions and relationships between environmental, social, and economic parameters. Similarly, Taleb and Sharples (2011) explain sustainability as a mixture of environmental, economic, and social responsibilities. Another definition is given by Petrişor and Petrişor (2014), who describe sustainability as a development which meets today's needs without compromising future needs. The term "sustainable architecture" is a general term that refers to a design method which includes environmentally conscious techniques. It seeks to minimise the negative environmental impact of buildings by enhancing efficiency and exercising moderation in the use of materials, energy, and the development of space. Other terms used to describe sustainable architecture include "climate-responsive architecture," "energy-efficient architecture", "green architecture," "high-performance architecture" and, "low carbon architecture". The goal is to apply these concepts to the entire life cycle of a structure (Olotuah, 2015). In the building sector, sustainability is taken to mean a building is environmentally friendly, economically feasible, and able to provide a healthy and high-quality indoor environment to users. As Wang et al. (2017) observe, it is essential for buildings to enhance their functionality and performance in order to meet current and future human, environmental, and societal needs, and, in this regard, buildings serve both as a challenge and an opportunity for environmental sustainability (Iwaro et al, 2015).

There is agreement in the literature that sustainability is based on three pillars that are categorised as follows: environmental, social, and economic (Clune and Zehnder, 2018; Dhahri and Omri, 2018; Martine and Alves, 2015). Rasouli and Kumarasuriyar (2016) have employed the Venn diagram to represent the relation between these three pillars, highlighting the need for outcomes to be bearable, equitable, and viable (See Figure 2-1). Clune and Zehnder (2018) claim that these three pillars provide a multidisciplinary implementation and solutions based approach which leads to more successful sustainability solutions; however, in their categorisation, they utilise slightly different terms to refer to the pillars, namely: technology and innovation, laws and governance, economics and financial incentives. While building sustainability also includes social aspects, these are often not as thoroughly considered as the environmental and economic factors (Lee and Tiong, 2007). However, as building owners increase the demand for higher quality interior spaces, the need to create comfortable, healthy, and safe indoor environments is now being recognised. For example, a study by Leung et al. (2005) demonstrated that it was worth paying higher costs for indoor comfort if building users believed they would have a more comfortable experience. There is one further less well-known factor of the sustainable building referred to as ‘functional performance’. This aspect is not included in the sustainability rating system or guideline policies, and it is often separated out into a different field called building performance (Preiser and Vischer, 2005; Langston, 2005).

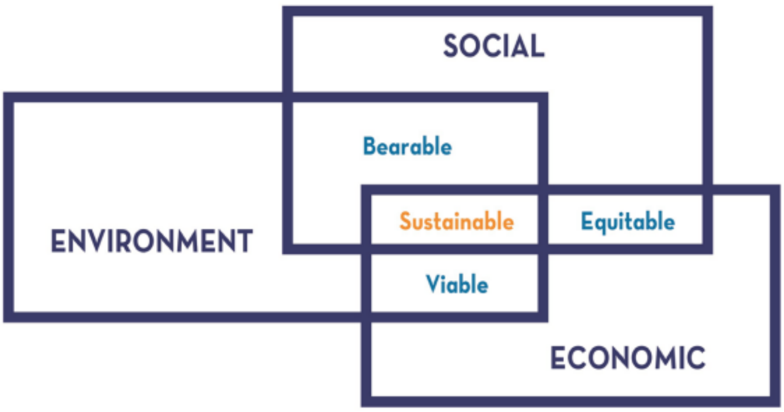


Figure 2-1: The three pillars of sustainability. (Source: Rasouli and Kumarasuriyar, 2016)

According to Olotuah (2015), design is the first step in achieving sustainable architecture, and building practices that strive for integral quality are vital in fostering the development of sustainable buildings. Hasegawa (2002) defines five key objectives for sustainable buildings as follows: resource efficiency, energy efficiency, prevention of pollution, harmonisation with the environment, and the use of integrated and systematic approaches. In a similar fashion, Al Surf (2014) defines a sustainable building as one that has the least impact on the environment, is affordable, and improves the productivity of its occupants. Taleb and Sharples (2011), on the other hand, define sustainable buildings as those that incorporate climate-responsive design. Energy-efficient housing design strategies include the use of the following: passive solar design, proper insulation, natural lighting and ventilation, landscaping, material selection, and the use of solar power.

The development of low carbon buildings (LCBs) is a major step towards achieving sustainable design. These can be defined as "*any type of building that from design, technologies and operation uses less energy than a similar sized or average traditional building*" (Isiadinso et al., 2011). The major inclusion requirements for LCBs govern methods of construction, regulations, management, operations, and the materials themselves. Al Shamsi (2017) suggests that buildings are able to meet low energy objectives through three main channels: reducing energy demand, using renewable energy sources, and improving energy efficiency (See Figure 2-2).

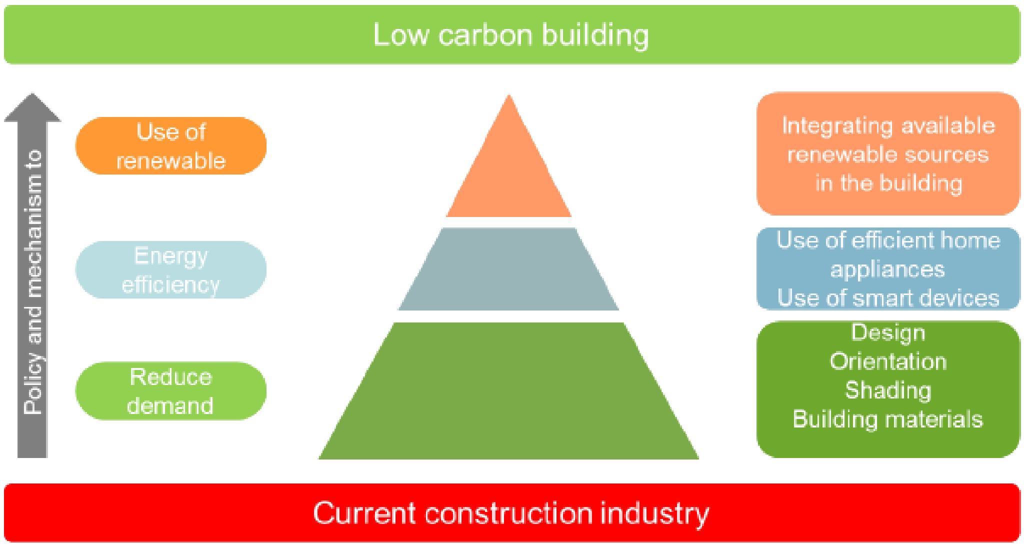


Figure 2-2: Low carbon building hierarchy (Source: Al Shamsi, 2017)

The design of these building practices promotes energy demand reduction through architectural design, the use of energy-efficient appliances, energy recovery systems, and even landscaping. Some LCBs use renewable energy systems to reduce their carbon footprint, with active (e.g. photovoltaic PV panels) or passive (e.g. sunrooms) solar energy among the most commonly used methods (Isiadinso et al., 2011).

It is important to establish whether sustainable buildings have a longer life cycle when compared to traditional buildings. Life Cycle Assessment (LCA) of sustainable buildings plays an essential role in assisting both consumers and professionals to reach more informed decisions regarding design and building operation. It also supports continuous innovation by facilitating improvement in the efficiency and quality of building components. LCA is a significant tool for sustainability since it emphasises whole system analysis (Hue, 2007), taking into consideration the process of construction, the initial building costs, the operational costs, and the long-term benefits to the owners and occupants. In assessing the life cycle of sustainable buildings, the following key features of sustainable construction are taken into account: materials and systems, waste management, energy efficiency, and water conservation (See Figure 2-3).

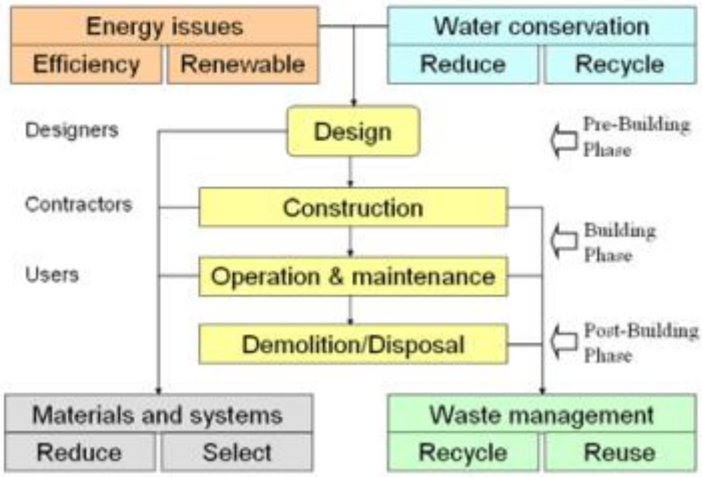


Figure 2-3: Building life cycle and sustainable construction. (Source: Hui, 2007)

The total environmental impact of a building is the result of the environmental loads occurring during the life span of the building. These include initial impact, annually repeating impact, and deconstruction impact. The initial impact occurs during the design and construction of the building. The annually repeating impact is the result of energy use for heating, lighting, ventilation and cooling, and repairs and refurbishments during the usable life of a building. The final stage happens when the building is demolished. As carbon dioxide (CO_2) is emitted during the production of building materials, and at each stage of the life cycle, the whole life carbon emissions of a building are made up of the sum of direct (construction, operation, maintenance, and deconstruction) and indirect (embodied energy of materials) energy. An efficient operational life can be ensured through the use of high-performance envelopes, the careful selection of materials and construction techniques, and good services design (Olotuah, 2015). However, for the purposes of this study, only the energy-saving aspects of a building will be investigated and improved.

2.3 Building Performance

Building performance is a crucial aspect of sustainability. According to Chen et al (2017), the process of green building design should take into consideration building performance in the following areas: material use, indoor environment quality, and energy efficiency. Assessment of building performance should begin early and involves assessing potential sustainability impact relative to the cost efforts made during the various stages of a building project. Chen et al. (2017) further suggest that the use of sensitivity analysis to determine building performance is sound practice. Sensitivity analysis can be used to determine building performance and, specifically, the optimisation of aspects including, but not limited to, building design, impact on the climate, life-cycle assessment, and validation of the energy models utilised.

Additionally, Wang et al. (2017) identify the following key measures of building performance: material consumption, GHGs emissions, water usage, waste, occupant well-being and productivity, and environmental resilience. These build on the findings of Hui (2007), whose measures of building performance included: sustainable site, energy efficiency, renewable energy, water conservation, materials and waste management, and indoor environmental quality. An approach to building performance which foregrounds these parameters will go a long way in fostering the achievement of a sustainable, efficient, resilient, and healthy built environment (Lin et al., 2016). However, a study by Tuohy and Murphy (2015), demonstrated that there are often gaps between intended and actual building performance. They used case studies of domestic and non-domestic buildings and identified faults at the implementation, validation, and operation stages which resulted in significant performance gaps. In term of the overall building performance, the following subsections cover the thermal comfort concept, energy consumption, building standards concerning energy conservation, renewable energy integration, building occupancy and operation, and building design and materials.

2.3.1 Thermal Comfort

Human capacity to acclimatise to different climate conditions, ranging from tropical to high latitudes, has resulted in different concepts of the ‘ideal’ climate. What may be regarded as ideal in one area could be uncomfortable in another, so the concept of thermal comfort differs from region to region. In recent years, studies of the physical, psychological, and physiological reactions of individuals to their environment have been undertaken in order to develop an effective model for defining and predicting the most comfortable temperature. The ability to adapt upon transition from one temperature zone to another, known as acclimatisation, has also been examined. For example, Yamtraipat et al. (2005) found that regular exposure to heat can improve tolerance in that automatic physiological responses reveal reduced strain. The lungs are less active, the skin more so, and circulation lessens. The duration of acclimatisation varies with the location and type of climate, the study showed that people exposed to long-term experiences of a humid and warmer climate over several generations have better tolerance to higher temperatures as compared with people in colder regions (Yamtraipat et al., 2005).

The complex interaction between humans and their environment has led to a number of studies by researchers from different disciplines; physiologists, psychologists, social scientists, environmental engineers, and physicists (see, for example, Brager and Dear, 1998; Cena and de Dear, 2001; Nicol et al., 2012), and each discipline has its own approach to defining thermal comfort. From a physical and psychological approach, it is argued that there is no single temperature at which everyone will feel comfortable; comfort is a psychological state defined by climate, culture, and economics (Nicol et al, 2012). However, it can be argued that the common ground for all definitions is that a range of environmental and personal factors have to be taken into account for people to feel comfortable within their surrounding environment (Gabril, 2014). These factors can be divided into three categories (physiological, psychological, and physical) as shown in Figure 2-4.

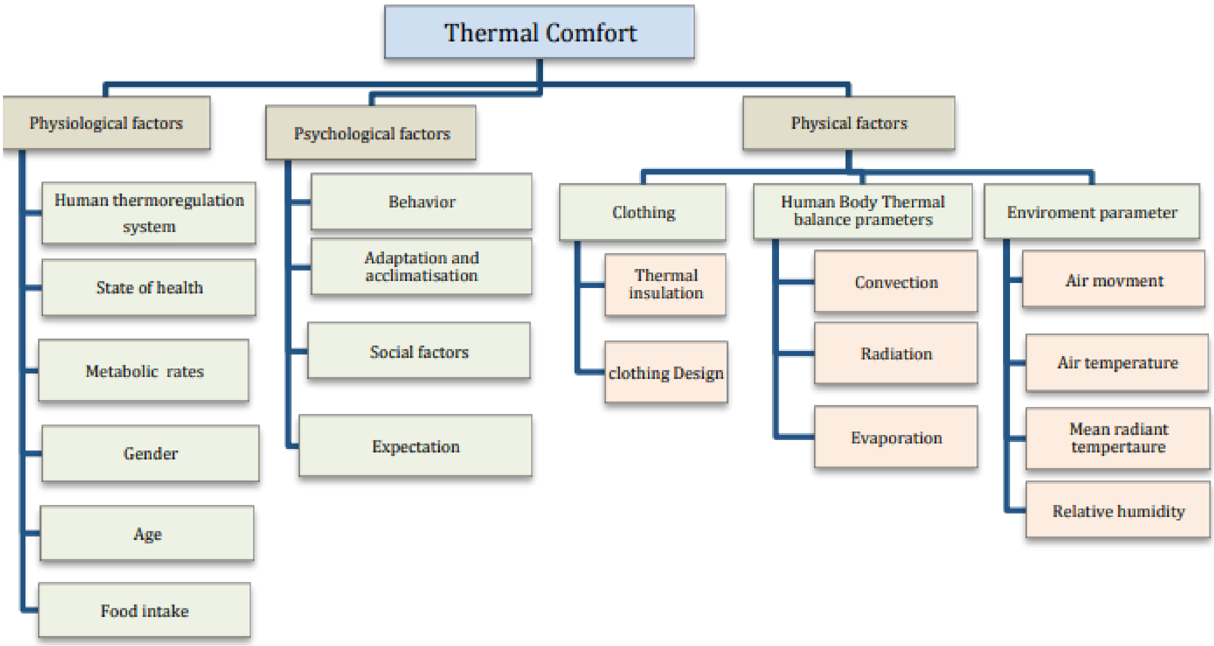


Figure 2-4: Factors that influence human comfort. (Source: Gabril, 2014)

The human thermal comfort zone is subject to complex parametric relationships. Nicol et al. (2012) analysed several completed comfort questionnaires and found the face value for comfort areas ranging from 17°C in England to 30°C in India and Iraq. This variation in comfort level is attributed to the factors detailed in Figure 2-4, which significantly influence comfort sensation, as they deal with people of different environmental backgrounds (Nicol et al, 2012).

Human thermal comfort is strongly affected by the indoor thermal environment of a building, and the majority of a building's energy consumption is dedicated to satisfying this need, especially in hot climates. The issue of thermal comfort has been vital to the development of the Heating, Ventilation and Air Conditioning (HVAC) system in the building industry, but it is still a complicated subject to understand (Gabril, 2014, Abdel-Ghany et al., 2013). The aim of creating thermal comfort has a major impact on the construction of buildings, affecting not only the design but also the choice of materials and the location. According to Alaidroos and Krarti (2015), to achieve physiological thermal comfort in hot regions, buildings must address the extreme summer conditions. Winter space heating loads are low and can be readily met using appropriate planning orientation; however, summer cooling loads present a much greater challenge (Alaidroos and Krarti, 2015). Further discussion on thermal performance of buildings is presented in the following section.

2.3.1.1 Thermal Performance of Buildings

The thermal performance of a building is determined by a number of factors which can be summarised as follows: (1) weather data, such as solar radiation, air temperature, wind speed, and relative humidity; (2) design variables and the geometrical dimensions of a building, such as the building envelope, orientation, shading devices, and its urban context (Ghabra, 2017); (3) the thermophysical properties of the building materials, including density, specific heat, thermal conductivity, and transmissivity; and (4) the internal heat gains due to occupants, lighting, and equipment.

According to Gabril (2014), solar radiation and air movement are the two major local climate criteria that should guide the form and orientation of buildings to achieve 'the optimum shape'. This is the building shape which has minimum heat gain in summer and minimum heat loss in winter. Heat transfer through the building envelope by conduction, radiation and convection is controlled by the thickness and the thermophysical properties of the materials: their conductivity, thermal capacity, and absorptivity (Gabril, 2014). There are a number of thermal measures or indicators which are useful to describe the way in which an envelope will modify internal thermal conditions, including:

- Thermal mass: defined as the ability of materials to store significant amounts of thermal energy and delay heat transfer.
- Thermal resistance - known as R-value: the ability of a material or object to resist heat flow.
- Thermal Transmittance Coefficient - known as U-value. The elements of a building are commonly assemblies of many layers of materials, such as those that make up the building envelope. The higher the U-value, the lower the ability of the building envelope to resist heat transfer. A low U-value (or a high R-value) usually indicates high levels of insulation. U-values are useful as a way of predicting the composite behaviour of an entire building element rather than relying on the properties of individual materials.
- Time Lag: the time delay due to the thermal mass. The thicker and more resistant the material, the longer it will take for heat waves to pass through.
- Thermal conductivity (k-value): the ability of a material to conduct heat; hence, the lower the k-value, the better the material is for insulation.

Generally, the envelope's material affects the heat exchange from the external environment to the internal environment. Passive or active cooling and heating systems may be used, but their effectiveness depends on several factors, including climate, material, and cost. Furthermore, the effect of the envelope depends on the thermophysical properties of materials which alter the rate of heat flow in and out of the building, thereby affecting the indoor thermal conditions and the comfort of occupants (Marzouk et al, 2014). The thermophysical properties of materials can be listed as follow:

- Thermal conductivity: represented by Resistance (R- Value) and Transmittance (U- Value)
- Surface characteristics, such as absorptivity, reflectivity, and emissivity
- Heat capacity
- Transparency to radiation

The transmission value of building envelope materials depends on these properties, which in turn determines the extent to which the envelope responds to the local climatic cyclic pattern (Marzouk et al, 2014). Thermal conductivity is considered to be a significant factor in defining the physical characteristic of materials; hence it plays a major role in thermal strategy design decisions.

Heat flow through the walls depends on the wall's dimension and its material. According to Gabril (2014), relatively thick walls act as a thermal mass that delays temperature fluctuations. Moreover, as Gabril points out, the higher the thermal capacity, the greater the time lag, something which is of particular significance in hot climates as it enables the afternoon heat load to be delayed until the cooler night hours. Indeed, Gabril's (2014) study of building performance in Libya found that traditional vernacular dwellings had a remarkable thermal performance as climate factors such as solar radiation, air temperature, air movement and relative humidity had been modified by the passive cooling and heating strategies in the houses. These are illustrated in Figure 2-5.

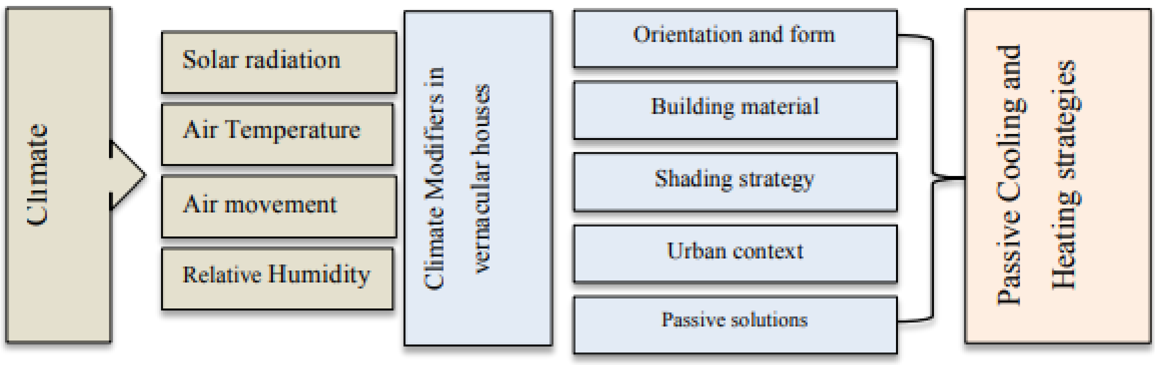


Figure 2-5: Passive heating and cooling strategies (Source: Gabril, 2014)

2.3.2 Building Energy Consumption

A number of research projects have demonstrated that modern buildings tend to consume a considerable amount of energy. Liu et al (2013) affirmed that buildings are significant utilisers of energy and for this reason they heavily impact the environment and resources. Indeed, Piotrowska and Borchert (2017) postulated that the building sector consumes nearly half of the energy consumed worldwide. Similarly, Sahebzadeh et al. (2017) asserted that modern buildings typically consume an estimated 30-40% of the total energy utilised around the world. Given the steady rise in the global population and increased urbanisation, studies suggest that this proportion may increase in the future. For example, Chen et al (2018) indicated that the building sector in densely populated Hong Kong accounts for close to 60% of the total energy used.

Ghabra et al. (2017) investigated energy consumption in the context of Saudi Arabia and found that the majority of energy utilisation in the country is directed towards electricity generation and water purification. 53% of all electricity generated is used in the residential sector to provide air conditioning for interior cooling as a consequence of the hot climate in the country (Ghabra et al, 2017). Given that residential buildings in Saudi Arabia cause more than half of all energy consumption, they are the main contributors to the rise of carbon dioxide emissions from fossil-based fuels. This is in line with Wang et al (2017), Friess and Rakhshan (2017), and Bataineh and Alrabee (2018) who found that buildings are responsible for an estimated one-third of global carbon emissions and account for 40% of primary energy consumption. It is also in accord with the assertion of Pomponi and Moncaster (2016) that, of all industries, the building sector places the most pressure on the natural environment and it is expected that this will increase in the future. In other words, the building sector is perceived to be the largest single cause of GHG emissions (Häkkinen et al., 2015), which contribute directly to problems such as global warming and climate change (Sahebzadeh et al., 2017).

Given the high levels of energy consumption caused by the need for cooling and heating in buildings, and the environmental damage this causes, there is an urgent need to raise awareness of the use of sustainable practices within the building sector. This is particularly true for hot climate regions, where large amounts of energy are utilised in an effort to make buildings more comfortable for occupants, as evidenced by Aboulnaga and Moustafa (2016) in their investigation of sustainability in residential and higher education buildings in Egypt.

2.3.2.1 Review of related international standards on energy conservation in buildings

Energy use and conservation in residential buildings has been a topic of increasing prominence in many developed countries (Aldossary, 2015). This has led to the creation of a number of energy consumption definition systems (in kWh/m^2) that have been developed on the basis of local needs and environments (Al Surf, 2014). International codes and standards concerning the minimum and maximum acceptable levels of energy consumption help building designers achieve the efficiency required by designing structures that provides optimal energy use and minimises carbon emissions (Fossati et al., 2016). The regulations vary according to the type of building and the climate zone in which it is located, with elements which are either mandatory or compulsory (Fossati et al., 2016). The energy conservation codes for the construction industry focus on increasing the overall sustainability of building structures through a standard methodology for designing and building which has the least amount of impact on the environment. They also cover new construction and existing buildings that undergo renovation. According to the International Energy Agency (IEA), the 2008 building energy codes were also referred to as “energy standards for buildings”, “thermal building regulations”, “energy conservation building codes” or “energy efficiency building codes”. Governments use different policies to help minimise the amount of energy that buildings consume, but the codes typically include mandatory minimum requirements for energy performance in the design as a way to regulate the amount of energy used in a building. Table 2-1 presents the most well-known international standards and codes for energy conservation.

Table 2-1: International standards for energy conservation in buildings (Source: Al Shamsi, 2017 - Tabulated by author)

Standard/Code	Established by	Origin	Year	Application
The International Energy Conservation Code (IECC)	International Code Council (ICC)	*USA*	*2000*	sets the minimum requirements for the design and construction of energy-efficient buildings.
ASHRAE 90.1 (Energy Standard for Buildings Except for Low-Rise Residential Buildings)	ASHRAE	*USA*	*1975 then in 1999*	sets minimum requirements for low energy buildings except for low-rise residential buildings. It has served as a benchmark for commercial building energy codes in the United States and as a key basis for codes and standards around the world for more than 35 years. The standard was renamed ASHRAE 90.1 in 2001. Since then, several editions and updates have been made to the original version, in 2004, 2007, 2010, and 2013.
ENERGY STAR	US Environmental Protection Agency and Department of Energy	*USA*	*1992*	used for energy-efficient products. Products using the Energy Star mark label include kitchen appliances, buildings, and other products which use up to 30% less energy than standard appliances.
ASHRAE Standard 189.1	ASHRAE	*USA*	*2009*	provides comprehensive building sustainability guidance for the design and operation of high-performance green buildings.
2018 International Green Construction Code (IgCC)	International Code Centre (ICC) and ASHRAE	*USA*	*2018*	provides minimum regulations for building systems and site considerations using performance-related provisions.
Building Code of Australia BCA 2006	National Construction Code (NCC)	*Australia*	*2003*	provides a uniform set of technical provisions for the design and construction of buildings and other structures and the thermal performance of the house and its domestic services.
The Indian Energy Conservation Building Code (BEE 2006)	International Institute for Energy Conservation (IIEC)	*India*	*2006*	provide minimum requirements for the energy-efficient design and construction of buildings. The code is mandatory for commercial buildings or building complexes that have a connected load of more than 500 kW. It is also applicable to buildings with a conditioned floor area greater than 1,000 m^2 and can be recommended for all other buildings.
Building Regulations (Part L) for UK and Ireland	Ministry of Housing, Building Act	*UK*	*1984*	L1 is specific to dwellings whereas L2 refers to all other buildings. It provides for the conservation of fuel and power in buildings and explains the required values of insulation of the building elements, the permitted sizes of windows, doors and other openings, and the air permeability. It sets out the heating efficiency of boilers and the insulation and controls for heating appliances and systems, together with hot water storage and lighting efficiency.

2.3.2.2 Renewable Energy Integration

Buildings can have a significant impact natural resources and the local environment. One important aspect of sustainable architecture is the use of renewable energy, such as wind or solar energy, in a building's operation. However, this depends greatly on the local climate as well as the availability of renewable resources. Kandpal and Broman (2014) argued that unless renewable energy methods and technologies are created and shared on a large scale, it will be difficult to achieve the amount of energy required for economic growth and improvements in the quality of life. As a result, a growing number of countries have dedicated efforts to promoting sustainable development and ensuring the available energy supply is enough to meet current demands (Arent et al., 2011; Manzano-Agugliaro et al., 2013; Chicco and Mancarella, 2009). Wind and solar energy sources are on the top of the list of renewable sources and widely being harvested. However, the main focus was only directed toward solar panels in this study due to its abundancy and insignificant impact on aesthetic aspect.

Efficient construction methods have been shown to improve the performance of a building through a number of vernacular architectural techniques (Zhai and Previtali, 2010). One particular technique, referred to as passive solar methods, can be traced back for many centuries, and such methods were an important part of common life until modern mechanical heating and cooling means were created (Chandel and Aggarwal, 2008). Research by Garcia et al. (2002) shows how different types of passive solar techniques are important in helping to reduce energy consumption. For example, efficient performance is achievable with the careful use of roof monitors, skylights, or clerestory windows, however, a successful design should be influenced by factors such as heat gain and loss, local climate, and human comfort (Rakoto-Joseph et al., 2009). In addition, Delisle and Kummert (2014), suggested that solar applications, including the integration of photovoltaics, will rapidly become standard in the construction industry. Photovoltaic (PV) techniques can already be found in energy generation units on a smaller scale, the technology is versatile, and it could be especially useful for countries that experience warmer climates and have an abundance of solar heat, such as Saudi Arabia. Building-integrated photovoltaics has captured the interest of a number of countries that are seeking methods to reach zero-energy buildings. To obtain this goal, buildings are now being designed to include three key concepts: efficiency, energy saving, and implementation of technologies to produce energy from a renewable source (Aldossary, 2015).

Furthermore, generating energy through PV technology and wind power is currently considered to be a cost-effective technique to generate power which could be integrated in both cities and suburban areas (Moharil and Kulkarni, 2009). A study by Stockton (2004) explored the economic feasibility of a utility-scale wind farm in Hawaii suggested that similar facilities could generate energy up to 34% more cheaply than traditional power plants burning fossil fuels. However, a number of researchers have found that solar energy is more acceptable due to the external factors associated with wind farms, such as the noise and visual aesthetics (Groothuis et al. 2008; Righter, 2002; Swofford and Slattery, 2010). In addition, solar panels can also be used to provide shadowing for the building roof, thereby reducing solar heat gain, as well as to generate power for use in the building.

The solar module or solar panel is the most important part of a PV system and is made up of a number of individual PV cells connected together, in parallel or in series, and residential solar panels available today can produce between 250-400 watts per panel per hour. The power produced by solar modules under standard test conditions (STC) is referred to as Peak Watt (Wp) rating (Krüger and Kravchik, 2021); however, a number of factors can affect the value of diffuse radiation, such as the clarity of the atmosphere, cloud cover variations, daily amounts of solar radiation, temperature, and dust accumulation, which mean that the actual average amount of electrical energy gained from the PV solar cells can be much less than its proposed Wp rating (Alshahrani, 2018; Yadav and Chandel, 2013). Solar radiation is an important parameter which affects solar PV performance through determining electric energy output. Moreover, the tilt angle (angle between the plane of the PV panel's surface and the horizontal) and the azimuth angle (direction of the PV panel's surface according to the direction of the sun) affect the amount of solar radiation the PV panel receives (Zhao et al., 2010). The solar azimuth angle is considered positive before noon, when the sun is in the east, and negative in the afternoon when the sun in the west (Al Garni et al., 2019). Sun-tracking systems can be used to keep the solar panels in an optimum position during daylight hours. However, while the use of solar trackers has been linked to increasing the performance of solar PV systems, there are a number of issues which must be addressed prior to their adoption, including cost, related consumption of energy, maintenance, reliability, and performance. From a practical perspective, therefore, solar trackers are not likely to be employed in PV generating plants because of the high costs of maintenance and mechanical components (Alshahrani, 2018).

With a reference to Saudi Arabia, there is strong potential for solar energy due to the abundant solar radiation available nationally, an estimated average solar radiation of 2470 kWh/m^2 from an average of 3245 sunshine hours per year (Pazheri, 2014; Zell et al., 2015; Rehman et al., 2007). In addition, according to the Electricity and Cogeneration Regulatory Authority (ECRA) report, energy demand on a given day in KSA reaches its peak between 12:00 noon and 5:00 pm, periods when solar energy is in abundant supply (ECRA, 2019). PV technology has already provided positive results as a simple yet effective source of energy in the KSA (Rehman et al., 2007), and recent reports on the usage of PV technology in the Kingdom include the integration of PV into the envelope of buildings (such as on roofs of public buildings) alongside other energy-efficient structures and materials (Mujeebu and Alshamrani, 2016; Mujeebu et al., 2015; Appelbaum, 2012). The Ministry of Municipality and Rural

Affairs in Saudi Arabia (MoMRA, 2017) states that the average size of residential sites in KSA is approximately 625 m^2 and residents are permitted to use up to 60% of the land area. Therefore, renewable energy systems, such as PV, could potentially be installed in the unused spaces. If these spaces were considered unsuitable (e.g. for aesthetic reasons), the roofs of residential units could be used instead (Aldossary et al., 2015; Taleb and Sharples, 2011). On average, roof areas often ranges from 100 m^2 to up to 375 m^2 and, as houses in Saudi Arabia are typically built with flat roof tops raised by 1.5 m at the edge, PV panels could be installed on the roofs without worrying about aesthetic appearance (Alshahrani, 2018).

The coordinates of Saudi Arabia show that the country is part of the northern hemisphere, and the sun maintains a high altitude as it traverses its daily path due to its proximity to the equator (Phillip and Lau, 2013). Generally, the orientation of PV panels is towards the south for locations in the northern hemisphere and towards the north for those in the southern hemisphere. A study by Al Garni and Awasthi (2017) reported that adjusting the orientation each month increases energy yield by 4% compared to the annual optimum but requires considerable labour costs. Therefore, they recommended a practical alternative which is to find the optimal orientation angles (tilt and azimuth angles) to maximise energy yield for solar panels according to the site location. Al Garni et al. (2019) performed a comprehensive study of the annual optimum orientation for solar panel installation in 18 cities in Saudi Arabia with regard to energy yield, revenues, and suitability index. They found that the annual optimum tilt angles for most of the cities were very close to their respective latitudes. This is in line with the basic Thumb Rule which states that the ideal tilt of the solar plant is relatively close to the latitude of the location (Al Garni and Awasthi, 2017). For Riyadh city, for example, Al Garni et al. (2019) recommended, with a high suitability index, an optimal orientation with a tilt angle of 24° south and an azimuth angle of -20° to give the optimum annual energy yield. The azimuth of -20° indicates that the panel will generate more on the west, a result of high solar radiation available in the afternoon due to clearer skies (Al Garni et al., 2019).

2.3.2.3 Occupant Behaviour Impact

Studies have looked into the impacts of occupant behaviour on energy consumption; however, it has been difficult to develop a baseline to determine how much influence is normal due to societal variations (Esmaeil et al., 2019). Furthermore, the impacts could not be studied separately from certain parameters, including the building's characteristics, technological application, and climate conditions. Studies from the Netherlands have indicated that occupant behaviour may have up to 4.2% influence on energy use (Santin et al., 2009); however, the building features take a much greater share of the energy used as nearly 42% is reserved for heating water and living space. Meanwhile, studies such as Zhao et al. (2017) investigated the relationship between building efficiency measures and occupant behaviours in the United States (US) and suggested that energy efficiency could be enhanced by over 50% if occupants adapted their habits compared to 42% stemming from technologically based advances. The article also concluded that, potentially, both technical advances and behavioural plasticity could impact energy conservation efforts.

A related study by Yousefi et al. (2017) observed occupant lifestyles and other aspects affecting the domestic consumption of energy in Iran. The findings indicated that lifestyles in hot climate zones could change the thermal patterns of a building by up to 9%, and the authors argued that, in hot climate areas, users' behaviour should be considered carefully when creating energy consumption simulations to prevent significant errors in the process (Yousefi et al., 2017). An earlier study from Kuwait also highlighted the importance of occupants' lifestyle in the results of energy consumption assessments (Al-Mumin et al., 2003). The authors showed that, by changing lighting schedules according to occupancy times and setting thermostats to 24°C rather than 22°C, energy consumption could be reduced by up to 39%. One of most common and most critical occupant attitudes affecting energy performance is the air conditioner setting point, and several studies have confirmed this. For example, studies by Kharseh et al. (2015) and Al-Mumin et al. (2003) reported that energy savings of 12.4% and 14%, in Kuwait and Qatar respectively, could be achieved by raising the thermostat temperature by just 2 °C.

2.3.3 Climate-Responsive Building Design

Climate and environmental conditions are very important in building design because buildings are intended to improve and regulate the natural atmosphere to achieve human comfort. Comfort, in this context, is defined as the sensation of the complete physical and mental well-being of a person within a built environment (Givoni, 1976). Climate is the prevailing meteorological condition in a given region, and understanding it is a prerequisite for energy sufficient or sustainable architecture. According to Madhumathi and Sundarraja (2014),

> "*it provides vital information to optimize natural energies to create comfortable living conditions. Since climatic data is often very technical, its implication in building design is often limited. There are climate classifications to provide a general outlook of climatic condition of a place. However, a building designer needs more precise information regarding climate, so a rigorous climate analysis is necessary*".

However, despite the significant role climate plays in determining building performance, contemporary buildings do not typically follow the climate-responsive design strategies used in traditional buildings (Opadhayay, 2006). Indeed, a study in the context of Iranian building performance showed that traditional buildings were better than contemporary buildings in terms of climatic design and thermal comfort (Ghobadian, 2003).

Studies such as these suggest that traditional techniques are often ignored or misunderstood. However, use of the Mahoney Table, named after architect Carl Mahoney in 1968, supports the incorporation of traditional building techniques into contemporary designs and developments to achieve the benefits of both. The Mahoney Table is a set of reference tables used in architecture as a guide to climate-appropriate design. They propose a climate analysis sequence that starts with basic and widely available monthly climatic data for temperature, humidity, and rainfall (Eusebius, 2011). They also provide results of thermal comfort analysis using primarily humidity and temperature to make recommendations for predesign guidelines. As Eusebius notes, the tables can be a useful tool for sustainable development since their predictions and recommendations aim to reduce energy consumption and promote the efficient use of materials.

The design of pleasant buildings that ensure the physiological comfort of users is achieved through an understanding of the climate and the human responsive systems. Without proper comprehension of the local climate, it becomes a challenge to achieve optimal building design or efficient building operation (Madhumathi and Sundarraja, 2014). However, research indicates that, in many developing countries, the design of buildings does not usually take the prevailing climate into account. In addition, important factors such as the surroundings and site characteristics, building materials selection, architectural design, and orientation are often not given serious consideration (Al Surf et al., 2015). This leads to buildings with poor indoor climates, which has a negative impact on overall comfort, efficiency, and health (Al Shamsi, 2017). A study carried out by Madhumathi and Sundarraja (2014) identified options for integrating climatic considerations as an integral part of planning and building design in Tiruchirappalli region, India, and found that not all meteorological data are of value for building energy analysis. In most cases, building designers are interested in the climatic elements which affect indoor comfort, heat transfer through building fabric, and ventilation. As a result, the authors identified the following climatic elements as crucial for building thermal design:

- Site information (such as latitude and longitude)
- Temperature data (such as the dry-bulb temperature (DBT))
- Humidity or moisture data (such as wet-bulb temperature (WBT), dew-point temperature (DPT), and relative humidity (RH))
- Solar radiation data
- Wind data (such as wind speed and wind direction)

The study was aimed at identifying the comfort conditions for the Tiruchirappalli region, and climatic data for all months and conditions of various passive design solutions were plotted in a psychrometric chart provided by ASHRAE 2005 using Climate consultant software and Ecotect software. The comfort charts clearly indicate that buildings in the Tiruchirappalli required cooling for ten months (not in February and March), as the lines crossed the comfort range. The psychrometric chart shows the annual temperature and humidity relative to the comfort zone and design strategies (See Figure 2-6). The authors found that the comfort zone was between 21°C and 28.5°C, with an upper bound for relative humidity at 80% (Madhumathi and Sundarraja, 2014).

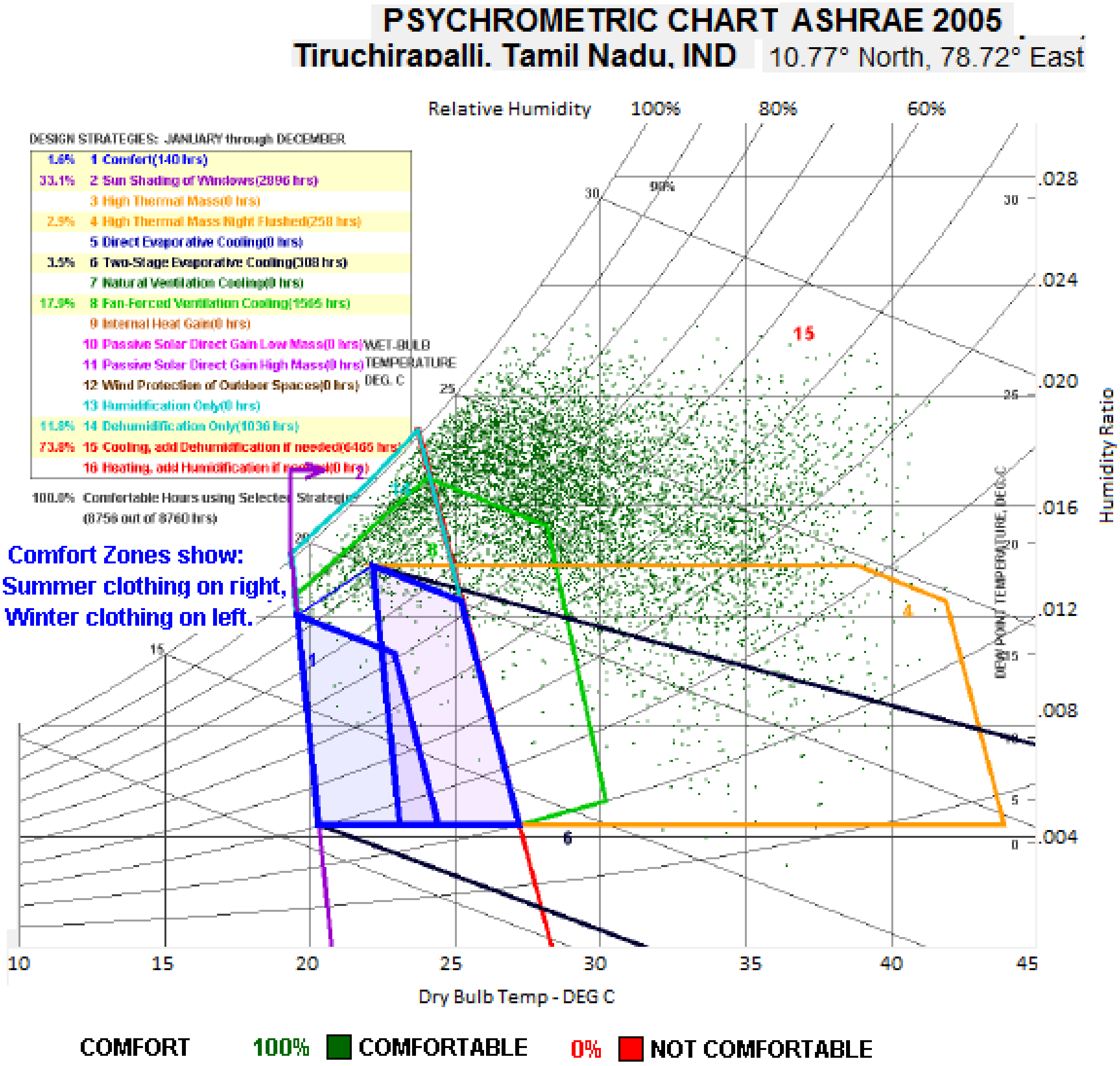


Figure 2-6: Psychrometric chart showing annual temperature and humidity relative to the comfort zone and design strategies (Source: Madhumathi and Sundarraja, 2014)

Madhumathi and Sundarraja (2014) added that the combination of humidity and temperature would assist in the identification of thermal stress conditions such as hot, comfortable, or cold, for mean temperatures above, within, and below the limit for thermal stress comfort.

A number of studies have investigated the climate parameters that impact building design in hot climates. Olotuah (2015) examined the climate-responsive architecture of housing in Nigeria and suggested that, in warm-humid conditions, two main requirements are necessary for the physiological comfort of users: thermal insulation and cross ventilation. Within the Saudi context, a study conducted by Ghabra et al. (2017) explored the hypothesis that most of the approaches used to foster the energy efficiency of buildings in Saudi Arabia are insufficient despite the focus on engineering parameters meant to do this. The study utilised 27 sets of dynamic thermal simulations and compared them in order to identify the best and worst combination of glazing type, glazing ratio, and wall type. This comparison was also significant since it revealed the most influential parameters found to have an impact on the cooling energy loads in a building. The authors concluded that the use of a prescriptive approach to the specifications for building envelopes (engineering parameters) failed to achieve the necessary levels of energy efficiency. Instead, a thoughtful consideration of the design parameters, for example shading, has the potential to have a greater effect on cooling energy loads.

Although buildings consume a considerable amount of energy, it is possible for this energy to be controlled through the application of natural ventilation and daylighting. This is demonstrated by the study of Susilawati and Al-Surf (2011), which showed how daylight can be applied as a form of sustainable integration. Specifically, this is achieved by combining daylight with electrical lighting, using only daylight during the day and electrical lighting during the night. The study also considered passive solar design and identified it as one of the most effective strategies in the reduction of non-renewable energy use. The key concept in passive solar design is to enable daylight, airflow, and heat into a building only where they are useful (Susilawati and Al-Surf, 2011). This makes it possible to control the entrance of sunlight and air into buildings and to store and distribute heat and cool air in such a manner that they are available whenever they are needed.

Green strategies aim to use sustainable features to accommodate extreme climate parameters because they try to work with the actual conditions and use them as an advantage. A sustainable building in this regard is one which is able to take advantage of the surrounding environment (Bonkaney et al., 2017) and incorporates elements which respond to it. The internal courtyard is an example of a climatically responsive urban form (Gabril, 2014). The properties of courtyard spaces depend on their proportions: their height is usually greater than their width and length, and this assists with shading and acts as a sun protector. In other words, internal courtyards are closed areas that act as sinks, where cooler nocturnal air is trapped and directed into the rooms on the lower levels while warm air is pulled out of the rooms at a higher level (Gabril, 2014) (See Figure 2-7). The role of this design element, which is still effective today, reflects the importance of traditional techniques to address climate challenges in buildings.

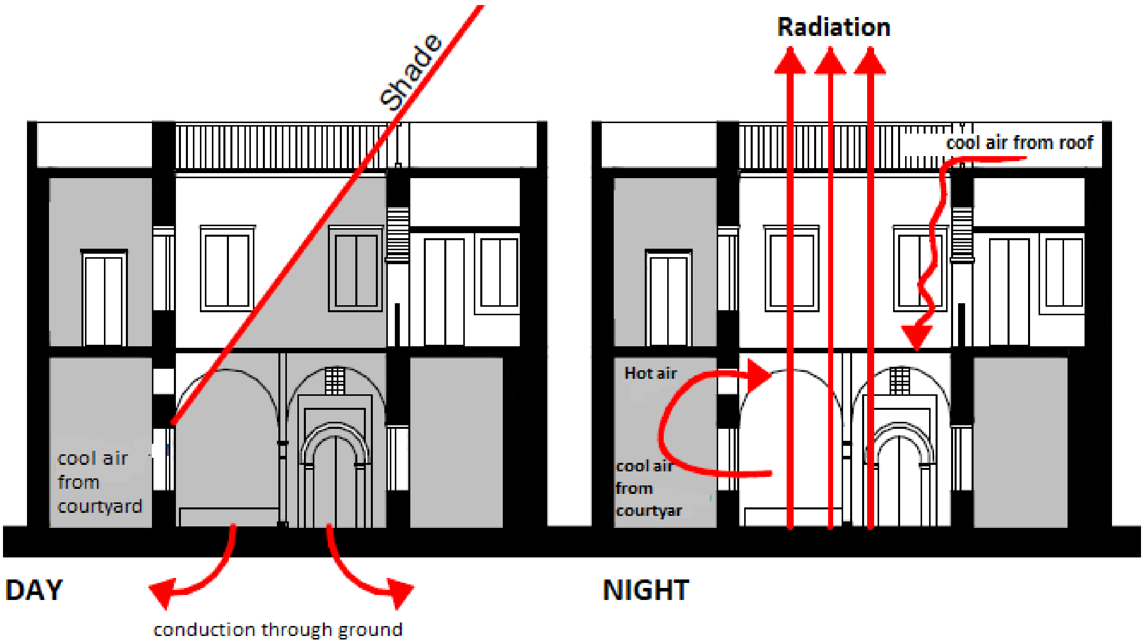


Figure 2-7: The role of the courtyard in the thermal performance of a building (Source: Gabril, 2014)

2.3.4 Building Envelope Design

The building envelope, in simple terms, refers to the element which separates the exterior and the interior of a building. Its main components include windows, doors, roof, floor, and walls. The envelope plays an important role in protecting the interior from the external environment, acting "*as a modifier of direct effects of climate variables such as the outdoor temperature, humidity, wind, solar radiation and rain*" (Wong 2003). As such, it provides solar and thermal control, moisture control, indoor air quality control, fire resistance, and acoustic control (See Figure 2-8). The envelope is perhaps the most important factor in determining a building's energy consumption due to the large surface area it covers (Aydın and Mihlayanlar, 2020), and it is a crucial consideration when designing energy-efficient and climate-responsive buildings. Its importance stems from its ability to fulfil the basic needs of defining the exterior and interior, separating yet allowing exchange and permeability, and determining the interrelationship between the given external conditions and the required internal conditions, all while serving as the 'calling card' of the building and its designer (Ghabra, 2017).

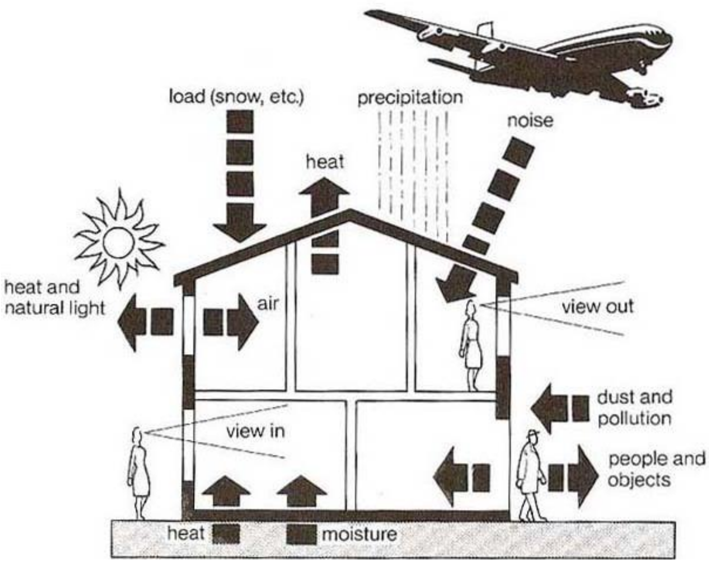


Figure 2-8: The main functions of the building envelope (Source: Ghabra, 2017)

The envelope forms the building's biggest element in terms of size; as such, it can be concluded that the sustainability level of any building is greatly influenced by the materials used in the envelope's construction (Lee and Tiong, 2007). Iwaro and Mwasha (2014) argue that the design of the envelope plays a key part in achieving building sustainability as it regulates all other factors, including element performance, transmission processes, thermal processes, and material properties. The relationship between the building envelope and these factors is illustrated in Figure 2-9.

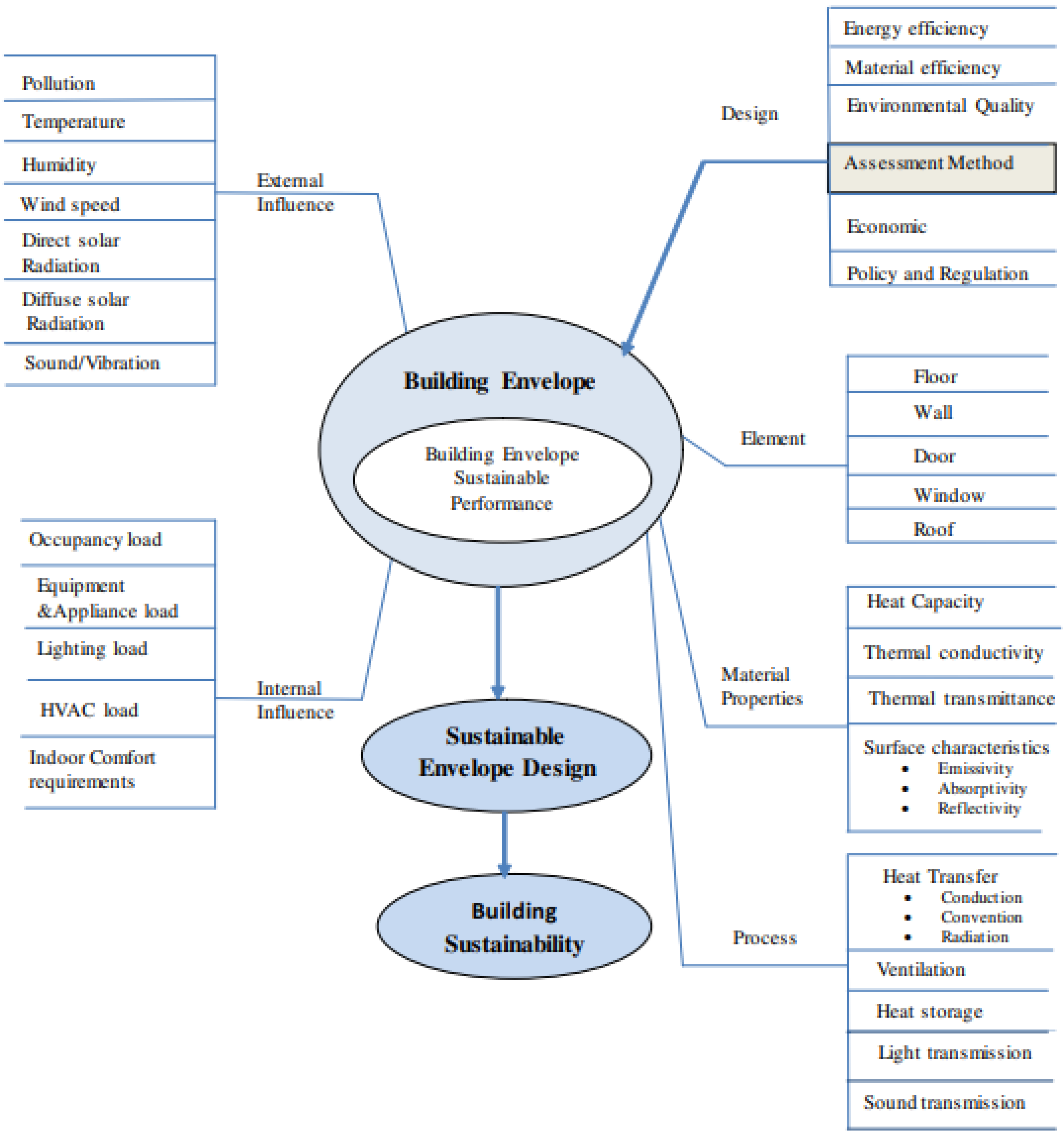


Figure 2-9: The relationships between the building envelope and building sustainability (Source: Iwaro and Mwasha, 2014)

According to Ghabra (2017), three main factors determine a building's energy use: (1) climate, (2) programme (function and occupancy), and (3) form (envelope, building shape, and construction). A building's form and envelope influence its heating and cooling requirements in order to maintain comfort. The envelope alone can be responsible for as much as 30% of the total energy consumption in a building, especially for cooling loads (Ghabra, 2017), so the energy balance of a building depends greatly on the properties of the envelope material. Granadeiro et al. (2013) also identified the envelope as the most significant component affecting the energy performance of a building and proceeded to formulate an indicator for building envelope design based on the use of heating and cooling degree days, (referred to as HDD and CDD), a measurement to quantify the demand for energy needed to heat or cool a building, total solar radiation in the heating and cooling seasons, envelope parameters, such as U-value, solar heat gain coefficient (SHGC), shading coefficient, and window area, and finally, set-point temperature for the interior.

A recent study by AlButhie (2018) stated that any envelope design work should be shaped by the "Four P's" of successful envelope design:

- Performance (function and sustainability)
- Price (affordability)
- Prefabrication (ease of construction)
- Post-occupancy (durability and maintenance)

An important indicator of a well-designed envelope is the U-value, the rate of transfer of heat through a structure (which can be a single material or a composite). In other words, it is a measure of heat loss or gain through the building components (Friess and Rakhshan, 2017). In order to calculate the heat flow through the building envelope, the U-value must be calculated. A lower U-value for a component indicates that the construction has better thermal performance. One of the main techniques for reducing the U-value of the building envelope is to apply insulation in the walls and roof (Al-Homoud and Krarti, 2021). Setting the right value for the U-value input data depends on the thermophysical properties of the material and the thickness of the construction (Ghabra, 2017). Usually, these data can be found in the building regulations of the country concerned. It is worth mentioning that there is no universal U-value for building envelope elements as regulations vary from country to country, mainly due to climatic variations (Meir et al., 2012).

A study by Evola et al. (2017) reported that solar radiation that comes through a glazed envelope of a building can have serious effects on both thermal and visual comfort within indoor spaces. According to Ramesh et al. (2012), a building envelope or fabric with low thermal conductivity and adequate heat capacity can significantly reduce the amount of heat gained or lost in the building, thereby reducing its energy requirements. The reduction of solar heat gain through a building's construction materials can be achieved by methods such as cavities, thermal insulation, radiation barriers, and use of reflective colours (Aldossary et al, 2014). However, the building envelope does not always achieve its goal, often due to a lack of environmentally responsive design or extreme weather conditions which cannot be addressed through passive means and so require the use of mechanical systems to reach desirable comfort levels (Mahdy, 2014). The energy required for lighting, ventilation, performing domestic activities, and operating cooling and heating systems in a building is referred to as the operational energy. A high level of heat gain or loss increases the need to operate cooling or heating systems, thereby increasing operational energy demand and causing greater energy consumption in the building.

Designing a building envelope is not a single but rather a holistic cross-disciplinary design process that depends firstly on the outdoor environment and climatic conditions for each location, secondly on the building design, such as form and material characteristics, and thirdly on the functional recommendations. In a study by Cheung et al. (2005), a number of passive thermal envelope design strategies including colour, insulation, glazing, and shading devices, were used together. As a result, the total annual cooling energy required for a building was reduced by 31.4%, again demonstrating that the envelope design can significantly affect the energy consumption of a building. The majority of studies on building envelopes in the Gulf region have primarily focused on thermal properties rather than the integration of design and planning processes that focus on energy consumption issues. This leaves a gap in the knowledge which has not yet been investigated (Ghabra, 2017).

2.3.4.1 External walls

When designing low energy homes, it is extremely important to consider an efficient housing envelope, and external walls are one of the main components. According to Esmaeil et al. (2019), more than half of a dwelling's enveloping areas are walls, and these, along with roofs, must be designed and operated as passive systems over the lifetime of the building. The most effective way of reducing energy demand in hot-arid climates is by applying thermal insulation to the solid components of the envelope, especially the walls (Ozel, 2011). Figure 2-10 illustrates the impact on the indoor temperature when wall insulation is used.

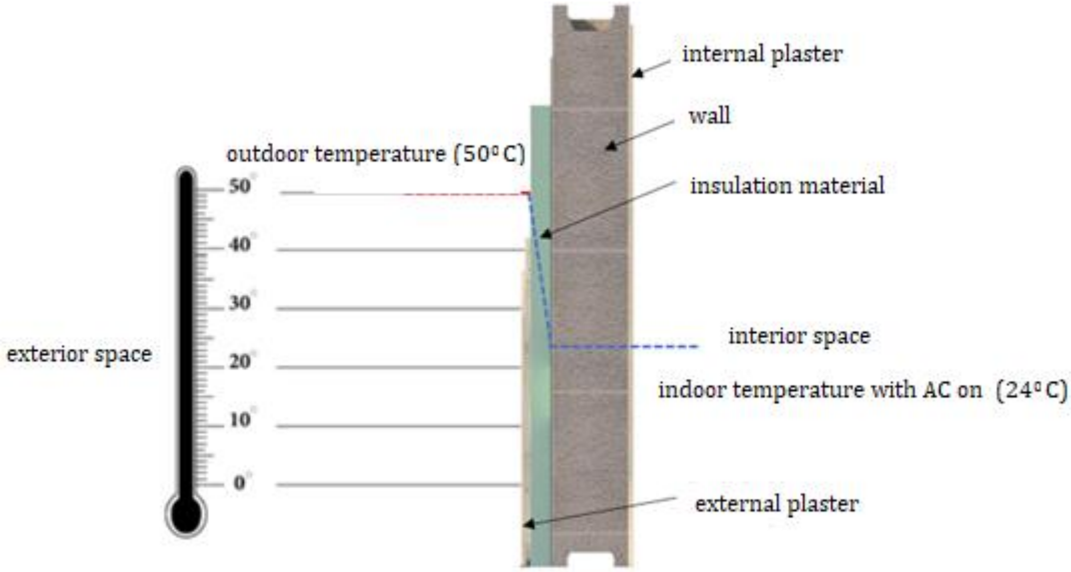


Figure 2-10: Illustration of the impact of wall insulation (Source: SBC602, 2018)

Using proper thermal insulation in the building envelope not only contributes to reducing the required HVAC load, thereby reducing annual energy consumption, but also extends the periods of thermal comfort (Al-Homoud, 2004). Research indicates that the optimum thickness of the insulation depends on its location within the wall (Al-Sanea and Zedan, 2011), and several studies have investigated the most effective thermal insulation thickness (Al-Tamimi, 2021; Li and Chow, 2005; Bojic et al., 2002) and the configuration and thickness of exterior wall designs. According to a study in Bahrain (Radhi, 2009), thermal insulation used in external walls can provide up to 25% energy consumption reduction, while Utama and Gheewala (2009) found that a double wall system is more efficient than a single one in terms of energy performance, reducing demand by about 40%. The study assessed the energy life cycle of an apartment in Jakarta, using clay bricks as the constant material while changing the external wall configuration. In addition, Bolatturk (2006) explored the relationship between energy savings and the thickness of insulation in Turkey and found that increasing the thickness from 2 cm to 17 cm led to an estimated increase in energy saving from 22% to 79%. Clearly, building thicker external walls is a more expensive proposition; however, over the life cycle of the building, the observed reduction of operational costs is expected to provide a greater economic and environmental benefit (Sisman et al., 2007). Thicker external walls also provide passive cooling support such as thermal mass (Feist, 2009), and a study by Najim (2014) found that adding air-cavities to external walls also provides better performance when compared to other methods.

According to AlFaraidy and Azzam (2019), three wall structures are widely known for the architectural installation of thermal insulation. These are the Double Wall System (DWS), the External Insulation and Finish System (EIFS), and the Insulation and Finish System (IIFS). DWS requires the construction of an external wall beside an internal wall, with thermal insulation material inserted into the wall cavity. EIFS requires insulation to be installed on the external wall surface using mechanical cladding methods. Cladding materials used include marble, ceramics, stone, granite, and fibre cement boards (SASO, 2011), and it is essential for EIFS installations to follow international standards relating to density, moisture movement, surface roughness, impact resistance, bending strength, and resistance to fungus (ASTM, 2016). Construction methods should also comply with safety and fire resistance standards which specify that both interior and exterior wall systems can tolerate two hours of fire without failing (BS, 1997). In the case of IIFS, thermal insulation is required to be installed on the interior side of walls. The major difference between EIFS and IIFS is that IIFS uses thermal bridges in roof slabs and columns and can be less effective than external insulation (AlFaraidy and Azzam, 2019). As a result, AlFaraidy and Azzam (2019) concluded that EIFS is a more appropriate technique for architectural installation of thermal insulation which meets the requirements provided by the energy efficiency standards for continuous insulation of a building envelope and eliminating thermal bridges.

2.3.4.2 Roof

Roofs have been found to affect both the form and landscape of a city, and the energy performance of buildings (Aparicio-Gonzalez et al., 2020). It is important to note that the type of roof on a building is often also conditional on the geographical location; for example, in European countries characterised by temperate climates, architects use a sloping design to promote drainage and prevent ponding during heavy rain conditions (Li et al., 2021). By contrast, flat roofs are hugely popular in the building industry in the Middle East region. Numerous studies have been conducted with a focus on roofs (Hamdan et al., 2012), and several have compared various passive cooling strategies (Amer, 2006; Nahar et al., 2003; Meng and Hu, 2005; Kharrufa and Adil, 2008), including painting roofs with reflective or white ceramic paint, installing thermal insulation above and underneath roofs, or installing shallow water ponds. Alternatively, the green roofs method has been found to be a good passive cooling method that decreases the amount of solar radiation absorbed by the structure it covers (Khabaz, 2018). Adding vegetation to a roof provides a number of benefits when compared to more traditional designs, such as reducing solar radiation absorption and a providing a consequential waterproofing layer which heats up during the day and cools at night (Cascone, 2019). Again, the initial cost for such an application is considerably higher. However, over the life cycle of the building, the saving in energy consumption makes it a viable economical choice, and it is gaining in popularity (Cascone, 2019).

Adding solar panels to a roof also impacts building energy consumption through electricity energy production and the effect of shading on the thermal performance of the roof (Wang et al., 2017). Wang et al. (2017) conducted a study which developed a comprehensive energy efficiency model to analyse the integrated contribution of shading and photovoltaics (PV) performance on a flat roof in China. Compared with a conventional roof, heat gain and cooling load were greatly attenuated; the peak value of heat gain was reduced by 67.1% and the peak cooling load by 72.2% (Wang et al., 2017). Furthermore, a study by Alvarado and Martinez (2008) investigated the use of a polyurethane layer to minimise heat transfer. The experimental results based on lab-scale prototypes showed that a well-designed roof insulation system could reduce the typical thermal load by over 70%.

With reference to Saudi Arabia, the external temperature can reach up to 50°C (Rashid et al., 2020), and the main construction material in roofs is reinforced concrete, which is classified as a construction material with high thermal conductivity coefficient. As a result, the demand for air conditioning may reach up to 70% of the total electricity consumption in buildings (Khabaz, 2018). Accordingly, there is a need to review the construction and design requirements related to roof building in Saudi Arabia in terms of thermal conductivity and to determine the necessary adjustments and specifications to improve their efficiency (Khabaz, 2016). The thermal performance of building roof elements was investigated by Al-Sanea (2002) in a study which compared the thermal characteristics of six typical roof structures used in buildings in the Kingdom. The simulation results were compared with an uninsulated roof that used heavyweight concrete foam as a levelling layer. The comparison showed a 32% reduction in the daily average heat transfer load when using 5 cm of standard polystyrene insulation and a 27% reduction for extruded polystyrene. Polyurethane insulation with a thickness of 5 cm gave a 22% reduction in the daily average heat transfer load (Al-Sanea, 2002).

2.3.4.3 Windows

As a study by Lee et al. (2013) demonstrated, windows are accountable for between 20-40% of energy loss from buildings. A number of aspects related to window design have to be considered to maximise energy efficiency, including, but not limited to, window-to-wall ratio (WWR), glazing types and layers, and shading devices. When considering windows and their thermal and optical specifications, solar gain is the most influential factor in relation to thermal comfort (Wright et al., 2009). Research by Ghabra (2017) shows how higher SHGC affects comfort, along with the secondary impact gained through solar radiation absorption through glazed windows. The size of windows also has a significant impact on the indoor air temperature: when the window area increases, occupant user discomfort has been shown to rise (Ghabra, 2017). Because of this, it is vital to improve the solar performance of glazing through optical properties, such as shading, reflection, and absorption, and window regulations that are related to glazing systems have a greater influence.

With a particular reference to hot climates, studies emphasise the effects of building envelope features such as glazing on cooling loads and thermal comfort; however, they also find that building regulations may not adequately address the situation (Al-Homoud, 2004; Aboulnaga et al.; 2016). Alwetaishi (2019) found that glazing systems are one of the most fragile systems, as they acquire direct solar gain due to the transparent materials used, and stressed that architects and engineers should give glazing greater attention. This is supported by Marino et al. (2017) who noted that appropriate window design is critical to energy efficiency in light of their function in heat exchange processes and solar energy acquisition. In this regard, new reactive 'smart windows' are now being developed which become darker or lighter as the sunlight increases or decreases in order to maintain the thermal comfort of residents (Heydari, 2013).

Researchers have made a number of recommendations to enhance the energy efficiency of windows. For instance, Alwetaishi (2019) found that a smaller WWR (10%) was optimal in hot and dry climates as opposed to 20% in temperate climates. Meanwhile, Alghoul et al. (2017) found that a high WWR ratio would reduce heating loads but increase cooling load in hot and humid climates. Aldoassary et al. (2015) explored the use of double glazing for external windows in modern buildings, and found that insulation performance was impacted by several factors, notably type of glass and the addition of thermal breakers in the frames. There have been a number of attempts to find ways to increase the efficiency of double-glazed windows, such as the use of low-e (emissivity) coating, using gas to fill gaps between panes, using thermal breakers made of polyurethane, sealed-air, evacuation, and phase change materials (Song et al., 2007; Chow and Li, 2013). When considering the physical properties of a window, a number of variables must also be included. For example, the SHGC, U-factor, visual transmittance, and emissivity, along with the orientation of the building and local climate data must all be accounted for in the calculation of heating and cooling loads in residential building designs (Banihashemi et al., 2015; Menzies and Wherrett, 2005).

The study by Banihashemi et al. (2015) observed the energy performance of double-glazed windows under different climate conditions in a four-storey building that represented a conventional type of residential apartment block in Iran. The climate conditions included in the simulations were cold, hot-arid, temperate, and hot-humid. The results of the study suggested that double-glazed windows were more advantageous in load savings under each of the climate conditions; however, the energy saving under hot-humid conditions was the most notable (Banihashemi et al., 2015). Forughian and Aiini (2017) performed a similar study using eight different window types orientated in four geographical directions to observe the optimal direction for each window type. They found that double-glazed windows could save up to 13% of the overall households' energy consumption. Furthermore, Iqbal and Al-Homoud (2007) studied the impacts of alternative energy conservation methods on the energy needs of a six-storey office building in Saudi Arabia using the simulation program, DOE-4. The simulation found that glazed systems played a major part in energy uses patterns and decreased the internal heat due to large areas of glazing in the building. The study recommended the use of low-emittance glazing to improve energy efficiency, advice endorsed by Assem and Al-Mumin (2010).

Furthermore, a building envelope can also decrease a building's energy consumption levels by incorporating shading devices, such as overhang shading, around windows. Cheung et al. (2005) found that using a 500 mm overhang shading could contribute to up to 100 kWh of savings per year, and suggested that the longer the projection length of a shading device used in the building, the greater the saving in annual cooling and peak loads required.

2.3.4.4 Insulation Impact

Thermal insulation materials play an important role in the challenge of energy-efficient buildings due to their ability to reduce energy demand and carbon emissions, and research has shown that proper insulation of the building envelope can significantly reduce energy demand (Braulio-Gonzalo and Bovea, 2017; Boermans and Petersdorff, 2007; Al-Tamimi, 2021; Alaidroos and Krarti, 2015). Esmaeil et al. (2019) found that reductions in envelope heat losses between 65% and 80% (average 73%) could be obtained by insulating dwelling envelopes, and Cheung et al. (2005) showed that placing 100 mm thick insulation on the inside of a wall could reduce annual required cooling energy by 19.4 % in a hot-humid climate. The most commonly used insulation materials in the construction industry are presented in Table 2-2.

Table 2-2: Common insulation materials and their characteristics and applications. (Source: Braulio-Gonzalo and Bovea, 2017)

Insulation Material (Conventional materials)	**Density** *(kg/m³)*	**λ** *(W/m.K)*	**Specific Heat** *(kJ/kg.K)*	**Most Common Applications**					
				Roof		**Façade (Outer Walls)**			**Floor**
				Sloping	*Flat*	*ETICS (external)*	*Ventilated (DWS)*	*Internal insulated*	
Glass wool (GW)	40	0.04	0.9-1.0	●	●		●	●	●
Mineral wool (MW)	45	0.035	0.8-1.0	●	●		●	●	●
Expanded Polystyrene (EPS)	25	0.034	1.25	●	●	●	●	●	●
Extruded Polystyrene (XPS)	30	0.035	1.45-1.7	●	●	●	●	●	●
Polyurethane (PUR)	45	0.032	1.3-1.45	●	●		●	●	●
Foam glass (FG)	110	0.04	1		●			●	●
Cork (C)	170	0.04	1.5-1.7	●	●	●		●	●

It is widely accepted that increasing thermal insulation thickness leads to a reduction in energy consumption for cooling and heating spaces. However, as Cheung et al. (2005) demonstrated, the reduction in energy decreases for every increment in the thickness beyond a certain point, so it is important to know when to stop adding extra insulation layers. The economic approach to finding the optimum thermal insulation thickness is to use a life-cycle cost assessment (Boermans and Petersdorff, 2007). This approach is widely used in building construction as an energy-efficiency technique to determine the optimum insulation thickness where the total cost (i.e. energy cost and the initial cost of the insulation material) is at the minimum (Iranfar and Muhy Al-din, 2020; Al-Sallal, 2003; Comaklı, and Yüksel, 2003, Al-Tamimi, 2021).

Research by Adamczyk and Dylewski (2017) explored the importance of thermal insulation investment in buildings in three areas: economic, environmental, and social, with a particular focus on thermal insulation of external vertical walls. Analyses of various combinations were performed, including the condition of the building before thermal insulation, type of construction material, the heat source used, type of thermal insulation, and the climate zone in which the building was located. The results indicated that thermal insulation investment was beneficial for all examined variants, for some of the ecological and social reasons addressed in the study and for almost all the economic reasons (Adamczyk and Dylewski, 2017).

Within the Saudi context, a study by Alrashed and Asif (2014) in the Eastern Province of the KSA indicated that the energy consumed for air conditioning could be reduced by 43% by insulation retrofitting of uninsulated dwellings, leading to a reduction of about 29% in total energy consumption. In addition, Alaidroos and Krarti (2015) recommended placing the insulation on the outside for applications requiring continuous air-conditioning operation throughout the year, as is the case in Saudi Arabia. Higher energy savings can also be obtained when insulation is applied to both walls and roofs compared to insulation applied to only one of these building envelope components (Al-Tamimi, 2021). This is supported by Ghabra et al. (2017) who found that the lack of insulation in the external walls of tall buildings allowed conductive heat gain through opaque walls, thereby contributing to higher indoor air temperatures.

2.3.4.5 Reflective Surfaces Techniques

Building envelopes that integrate reflective coatings can block solar radiation and have a high thermal inertia, helping to lower the indoor temperature and save cooling energy costs, especially in hot climates (Ling et al, 2021; Cheng et al 2005). Solar reflectance (SR), sometimes called albedo, measures the ability of a material to reflect incident solar radiation without absorbing it. The SR (sometimes referred to as R) value is expressed as a number between 0 and 1 or as a percentage. A value of 0 indicates that the material absorbs all solar energy while a value of 1 indicates total reflectance (Asdrubali and Desideri, 2019). To be classified as a cool surface, a material must have a minimum SR value of 0.65 (Casini, 2016). Another indicator used is the solar reflectance index (SRI) which takes into account solar reflectance and thermal emittance to predict the thermal behaviour of a surface subjected to solar radiation (Muscio, 2018). The SRI range is between zero (as hot as a black surface) and 100 (as cool as a white surface), implying that the lower the SRI, the hotter a material is likely to become. SRI is used for compliance with LEED (Muscio, 2018).

Reflective glazing is typically applied to external walls and roofs. Zhang et al. (2017) found that coating external walls with high reflectivity materials was an effective way to reduce heat gains from solar radiation and save cooling energy consumption. Their experiment results showed that for the building box with retro-reflective coating materials (R= 0.59), the average indoor air temperature was about 2.4°C lower than the reference case without coating materials, resulting mainly from decreased absorption of solar radiation (Zhang et al., 2017). Furthermore, Rawat and Singh (2021) performed a very recent study that compared the thermal performance of roofs with different types of surface coatings in different climatic zones (i.e. temperate, tropical, composite, hot, and warm-humid). The average albedo used in their study for temperate, tropical, hot-dry, and composite climatic zones were 0.77, 0.74, 0.70 and 0.57 respectively. They found that the average energy saving effects of the roof coating ranged from 15% to 35.7% in different climatic zones and that the use of cool roof technology could reduce average roof surface temperatures by between 1.4˚C to 4.7°C (Rawat and Singh, 2021).

Cheung et al (2005) also found that a lighter coloured building envelope will lower the solar absorption and that a 30% reduction in absorption could achieve 12.6% savings in annual required cooling energy. This is in accordance with Suehrcke et al. (2008) who found that, for north Australia, a light coloured roof had about 30% lower total heat gain than a dark coloured one. However, Suehrcke et al. (2008) claimed that the effect of the roof solar reflectance on the thermal performance of a building is often ignored. Finally, reflective coating is not limited only to the building’s walls or roof; it can also be applied to the glazing. Indeed, Song et al. (2007) found that replacing glazing with a single layer with a reflective coating, gave savings of up to 4.6% in annual cooling energy and 5.4% in peak cooling load.

2.3.5 Building Materials

Selecting the most appropriate materials and construction methods is essential to the low energy building process. Attention has primarily focused on whether materials have a high thermal mass (Sinha et al, 2013), and building material has typically been analysed and selected based on thermal performance and local availability (Alaidroos and Krarti, 2015). More recently, however, investigating building materials and their related embedded energy has become an essential part of sustainable building development. Khan et al. (2017) conducted a study on the effect of sustainable materials on building energy demand in Italy in light of the local climatic conditions. They found that using sustainable materials for the walls, floor, roof, and windows, led to a 38% reduction in the total energy demand of the building compared to the base-case.

Another study by Egenti et al. (2014) in Nigeria explored the use of stabilised earth bricks for walling as a low carbon alternative to cement. Stabilised brick houses are locally available, appropriate for the variety of climates in Nigeria, and are ideally suited for passive solar heating and cooling: they are warm in cold seasons and cool in hot seasons, with little or no need for auxiliary or mechanical energy (Egenti et al., 2014). In terms of rendering, material and colour have a significant impact on its thermal performance. Lime plaster might be the most common wall coating, and it is considered as a vital element in masonry because it protects the stone and its absorbency allows the evacuation of the inner humidity of the walls (Gabril, 2014). Gabril (2014) explored the properties of white lime wash and found it to be an excellent solar reflector which reflects light into the darker recesses of the house and emits long wave radiation to the night sky. This reduces the absorptivity of the wall surfaces, minimising the quantity of solar radiation entering the building and thus reducing both maximum and minimum temperatures.

In Saudi Arabia, almost all types of buildings are constructed from reinforced concrete, and this plays a considerable part in determining building shapes (Marzouk et al, 2014). This material has been revolutionary as far as building structures are concerned; however, it does not enjoy the same standards of performance when it comes to its thermal properties. Reinforced concrete construction exhibits poor thermal behaviour under hot climates, which make it a weak barrier to heat flow (Ibid., 2014). Al-Sanea et al. (2013) explored the impact of thermal mass on the energy performance of masonry materials in Saudi Arabia’s hot climate. The study investigated clay bricks, concrete blocks, sand-lime bricks, and prefabricated walls, and found that clay bricks provided the best energy performance in terms of capital investment and running costs for a typical residential building in KSA.

It also revealed that the clay bricks consumed 16% less energy compared to the concrete block, 23% compared to the sand-lime bricks, and 25% compared to the prefabricated walls. Furthermore, Almulhim et al. (2020) asserted that further research should be done to investigate the best locally available material that can enhance sustainability.

2.3.5.1 Embodied Energy of Building Materials

Until recently, it was thought that the embodied energy content of a building was small compared to the energy used in operating the building over its lifetime (Hammond and Jones, 2008). Therefore, most effort was put into reducing operating energy by improving the energy efficiency of the building envelope. However, research has shown that this is not always the case (Milne, 2013). Embodied energy can be the equivalent of many years of operational energy. Operational energy consumption depends on the actions of the occupants, but embodied energy is dependent upon many more factors. According to Milne (2013), embodied energy is the energy consumed by all of the processes associated with the production of a building, from the mining and processing of natural resources to manufacturing, transport and product delivery. Research by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) has found that the average house contains about 1,000 GJ of energy embodied in the materials used in its construction (Sattary and Thorpe, 2012). This is equivalent to about 15 years of normal operational energy use. For a house that lasts 100 years, this is over 10% of the energy used in its lifetime (Milne, 2013). The calculation of embodied energy is often performed within the LCA framework (Crawford and Hall, 2020). However, embodied energy does not include the operation and disposal of the building material, which would be considered in a life-cycle approach; instead, it is part of the 'upstream' or 'front-end' component of the life-cycle impact of a home (Milne, 2013).

A recent study in Saudi Arabia employed the LCA of materials used in a three-bedroom house and revealed that some materials were used in more than one form (Asif et al, 2017). Concrete, for example, was used as concrete masonry units as well as ready mix reinforced concrete. Similarly, bitumen was used as a membrane as well as a spray paint. The material audit revealed that concrete was the single largest material in the house, both in terms of mass and embodied energy (See Table 2-3). Overall, concrete accounted for over 43% of the total embodied energy, followed by steel at just over 19%. In terms of embodied energy per unit mass, however, concrete and plaster had the least values while polystyrene had the highest (See Figure 2-11).

Table 2-3: Embodied energy of the materials involved in the house construction (Source: Asif et al, 2017)

Material/Component	Weight (kg)	Embodied Energy (MJ)	Embodied Energy per Unit Mass (MJ/kg)
Concrete	1,012,340	1,692,805	1.7
Plaster	126,900	221,039	1.7
Steel rebars	32,173	747,732	23.2
Cement	28,800	60,971	2.1
Ceramics	18,347	240,081	13.1
Bitumen	6,678	276,677	41.4
Wood	3,928	45,135	11.5
Polyvinyl chloride (PVC) - plumbing	3,308	267,668	80.9
Polystyrene EPS	1,885	199,495	105.8
Galvanised iron sheets	1,728	6,818	3.9
Glass	900	11,804	13.1
Fibre board	854	33,185	38.9
Paint	751	56,022	74.6
Aluminium	361	29,164	80.8
Polyethylene	96	9,054	94.3
Gypsum	46	4,233	92.0

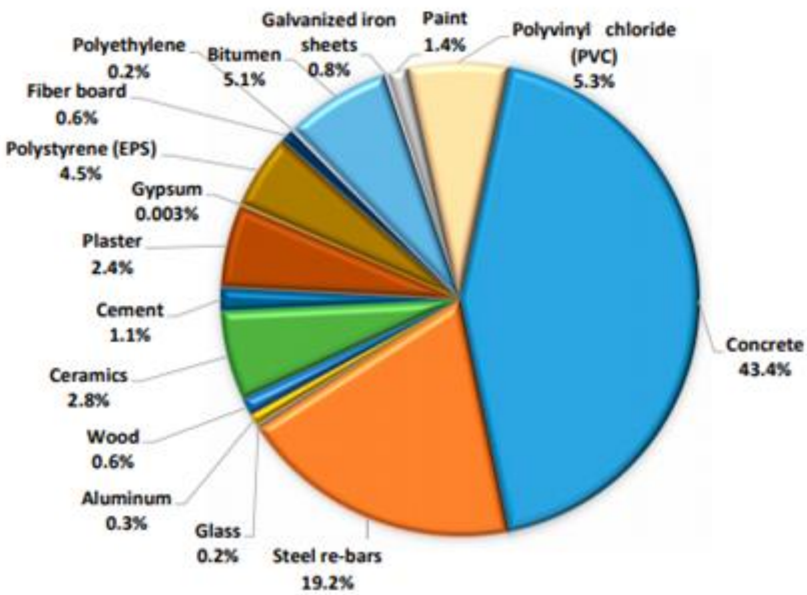


Figure 2-11: The distribution of the embodied energy by type of material (Source: Asif et al, 2017)

Crawford and Hall (2020) stressed that it is important to remember that choosing materials with low embodied energy may result in higher operational energy use. Conversely, materials with higher embodied energy may result in lower operational energy use. As buildings become more efficient in terms of their operation, embodied energy forms a greater proportion of the total energy use (Crawford, 2019). This can be even more pronounced where additional materials (for example, insulation, double glazing, or thermal mass) are used to achieve operational energy savings.

2.4 Building Simulation Tools

Internationally, a broad range of scientifically validated Building Performance Simulation (BPS) tools are accessible. In previous years, several BPS instruments were created to help architects carry out early energy analysis and construct more sustainable and energy-efficient buildings, as the value of decisions taken early in the design process and their effect on energy efficiency and cost was more widely recognised. The recent revolution of technology has made more complex tasks possible through the use of specialist software programs. Modelling of buildings and related energy consumptions has become a much easier task with the availability of a wide range of simulation software tools, such as DesignBuilder, EnergyPlus, Revit, TRNSYS, and IES-VE. These programmes can analyse and predict building energy consumption patterns in accordance with specific databases (Shameri et al, 2013). Computer simulation software tools have made major strides in recent years, and this trend is likely to continue as they make the evaluation of all the design, operation, life cycle, and maintenance processes of a building possible, from concept to design (Alshahrani, 2018). In addition, these tools can be used to assess the energy performance of a new or existing building. Furthermore, BPS can integrate human activity and thermal and visual comfort simulations into the computer modelling and simulation processes (Fasi and Budaiwi, 2015; Dabaieh et al., 2015). Table 2-4 highlights studies which used BPS tools to investigate the energy consumption in buildings in some hot climate regions.

Table 2-4: Studies which used energy simulation software in hot countries (Source: Aldossary, 2015)

Software Used	Study Description	Location	Findings	Reference
IES-VE	Simulated energy consumption in a high rise building to validate the reduction when adopting shading devices	Malaysia	Egg-crate shading compared to other types led to a significant decrease in discomfort hours	*Al-Tamimi and Fadzil, 2011*
DesignBuilder	Analysed energy consumption of one apartment and then multiplied the results by the number of apartments in the building	Saudi Arabia	Potential 32.4% energy reduction can be achieved by improving the external wall and roof insulation	*Taleb and Sharples, 2011*
TRNSYS	Modelled case studies of domestic buildings and simulated energy consumption	Kuwait	Results informed researchers about the need to enhance the national energy conservation code	*Al-ajmi and Hanby, 2008*

Previous literature (Macdonald et al., 1999; Coakley et al., 2012; Alshahrani, 2018) has identified some of the key advantages of the application of computer based simulation and modelling, which include:

- BPS is less costly and time-consuming than experimental approaches
- BPS can control the design specifications throughout the simulation of conceptual design

- Simulation results can be validated using experimental analysis
- BPS can be easily used in scenarios where it is expensive or difficult to evaluate the interaction of various building performance parameters
- BPS can analyse the consequences and effects of improvements and retrofitting in existing buildings
- BPS can do calculation of energy needed to operate the building under external inputs and other specifications
- BPS provides the ability to predict building performance at any stage of the design over a given period through the simulation of building dynamic behaviour
- BPS has the capability of modelling complex systems and building environments

However, despite these benefits and the continuous development of simulation tools, some disadvantages have also been identified (Macdonald et al., 1999; Coakley et al., 2012). The main drawbacks of BPS are as follow:

- Not all modelling data and construction parameters of the building can be known or completely predicted at the initial simulation stage. This introduces uncertainties and/or risk factors in the model.
- The number of input variables to generate a model that would be ideal for simulation can be very high. Therefore, a thorough calibration technique is necessary in order to achieve conclusive results.

There is no clear methodology to compare BPS tools and no common language to describe what they can do (Crawley et al., 2008). For example, the word 'criteria' can refer to capabilities, requirements, functionality, specifications, features, factors etc (Attia, 2010). However, after reviewing current trends in building simulation, a study by Attia (2010) outlined five major criteria for BPS tools selection and evaluation based on analysing users' needs, tool capabilities, and requirement specifications (See Figure 2-12). Attia argued that any future BPS tools should comply with these criteria, and, above all, they should educate as well as inform the user.

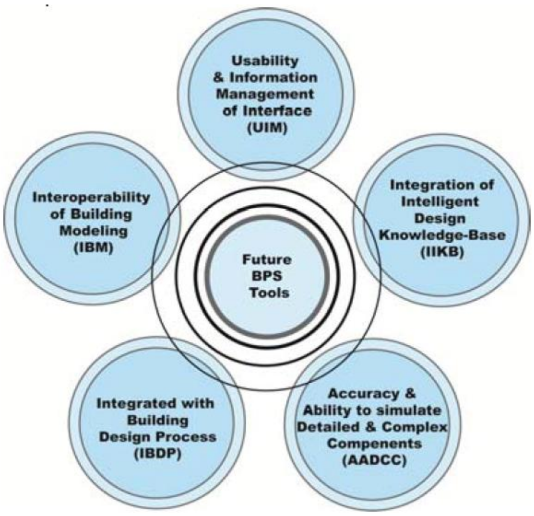


Figure 2-12: The five selection criteria for future BPS tools (Source: Attia, 2010)

Attia also surveyed two groups of users, architects and engineers, in order to rank the main selection criteria and expected functions of BPS tools and compare and evaluate ten existing products. The findings are shown in Table 2-5.

Table 2-5: Comparative study of 10 widely used BPS tools (Source: Attia, 2010, Tabulated by the author)

Criteria	**Design Builder**	**IES-VE**	**ECOTECT**	**eQUEST**	**Green Building Studio**	**HEED**	**Energy 10**	**Energy + SketchUp**	**DOE-2**	**Energy +**
Graphical representation of output results	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓
Flexible use and navigation	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Graphical representation of results in 3D spatial analysis	✗	✓	✓	✗	✗	✗	✗	✓	✗	✗
Easy follow-up structure	✓	✓	✗	✓	✓	✓	✓	✗	✓	✓
Graphical representation of input data	✓	✓	✓	✓	✓	✗	✗	✓	✗	✗
Easy learnability and short learning curve period	✓	✗	✓	✓	✓	✓	✓	✓	✗	✗
Creation of comparative reports for multiple alternatives	✓	✓	✗	✓	✓	✓	✓	✗	✗	✗
Quality control of simulation input	✗	✓	✓	✓	✗	✓	✗	✓	✓	✓
Flexible data storage and user customisable features	✓	✓	✓	✓	✓	✓	✓	✓	✗	✗
Simple input options, input review and modification	✓	✓	✓	✓	✓	✓	✓	✗	✗	✗
Allows assumptions and default values to facilitate data entry	✓	✓	✓	✓	✓	✓	✓	✓	✗	✗
Provide weather data and extensive libraries of building components & systems	✓	✓	✓	✓	✓	✗	✓	✓	✗	✓
Support online user help & training courses	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓
Provide quick energy analysis that supports the decision making	✓	✓	✓	✓	✓	✓	✓	✗	✗	✓
Confidence in creating real sustainable design	✓	✓	✗	✓	✗	✗	✗	✓	✓	✓
Accurate and reality-like results	✓	✓	✗	✓	✗	✗	✗	✓	✓	✓
Validated performance measures	✓	✓	✗	✓	✗	✗	✗	✓	✓	✓
Calibration of uncertainty	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
High model resolution	✓	✗	✗	✓	✗	✗	✗	✓	✓	✓
Allows simulation of complex design strategies and elements	✓	✓	✗	✗	✗	✗	✗	✗	✓	✓
Allows simulation of renewable energy systems	✓	✗	✗	✗	✓	✗	✓	✗	✓	✓
Allows evaluation of emissions associated with building energy use	✓	✓	✓	✓	✓	✓	✗	✓	✗	✗
Support various types of HVAC systems	✓	✓	✗	✓	✓	✗	✓	✗	✓	✓
Allows simulation of unlimited building area	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓
Allows energy cost analysis and LCC analysis	✓	✓	✗	✓	✓	✓	✓	✗	✓	✓
Allows simulation of different types of buildings	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Although it can be difficult to compare and evaluate tools in absolute and valid ways, because tools keeps improving and each has its advantages and limitations, comparison allows us to identify tendencies. The results of Attia's study were used to rank the ten BPS tools according to the architects and engineers who participated in the survey. The results are shown in Figure 2-13. DesignBuilder is the only tool that appears in the top three for both architects and engineers.

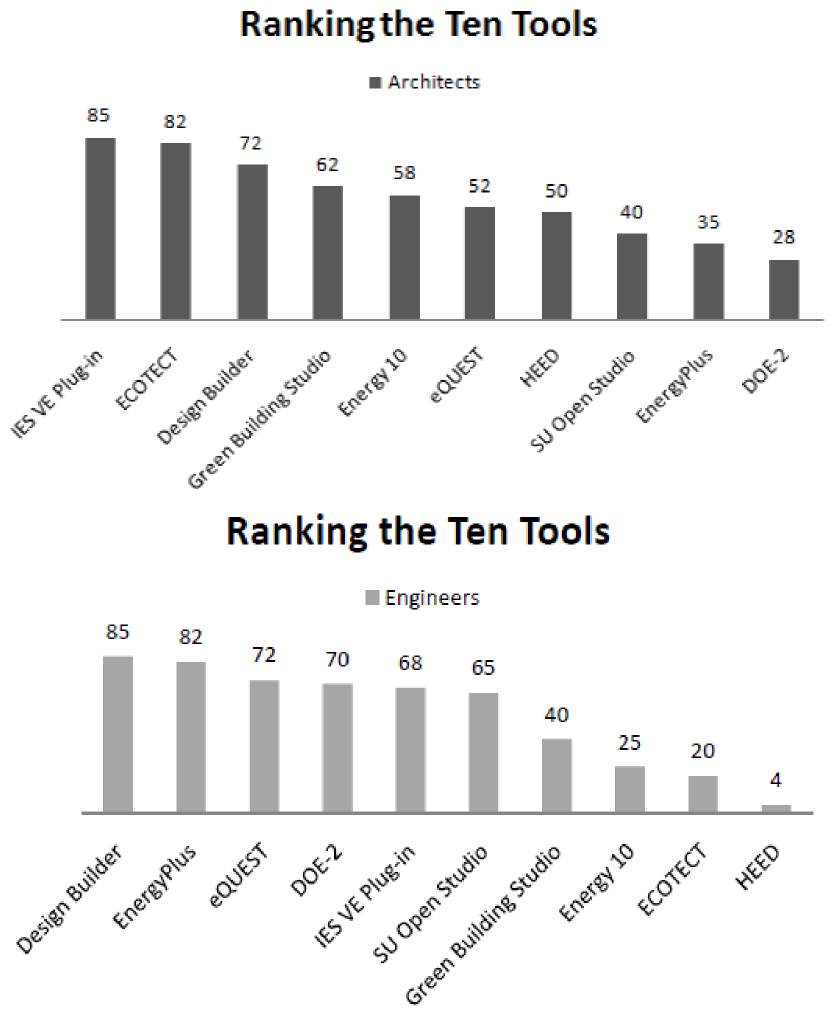


Figure 2-13: Ranking the ten tools according to architects and engineers (source: Attia, 2010)

2.5 Summary

This review of literature has been insightful in demonstrating the need for the development of an approach to design a sustainable building for hot climates. According to the above review of literature, energy consumption by modern buildings is quite high and thus the building sector contributes to the highest amount of energy consumption in the world. It is for this reason that this sector is said to be equally the largest reason for GHGs emissions. Therefore, buildings lead to a considerable amount of pressure on the natural environment that will be clearly detrimental to the future of the world. However, with the application of sustainability, it is possible to combat this issue as noted in the review by fostering the definition of a sustainable building. The emphasis, in this case, is on showing sustainable buildings to be energy and resource efficient, thus being able to adapt to long-term functionality. The previous literatures in this chapter have provided effective building-related techniques in order to enhance buildings performance in terms of energy and thermal comfort. The building envelope was recognised as the major player in building sustainability. Interest was further shown to climate parameters, construction materials, and occupants behaviour and their relations with features of sustainability.

The next chapter provides a specific review of the residential buildings stock in Saudi Arabia and highlights current building practices and related issues experienced which specifically concern the case study country.

Chapter Three: The Residential Building Sector in Saudi Arabia

3.1 Introduction

Having the current buildings trends being generally reviewed in the previous chapter, this chapter mainly aims to provide an overview on the case study country, its climate, and Saudi residential buildings stock. Four sections will be covered in this chapter. These are country profile, building regulations, residential buildings in Saudi Arabia, and energy policies and initiatives. The first section provides geographic and demographic background about the country, followed by an assessment of the national power trends. The local building regulations and some of the GCC regions' building codes will also be covered. Thirdly, important details about the existing residential stock, its overall performance, and practice issues will be presented. The final section will discuss the national energy polices and initiatives taken by the government to achieve its sustainable development goals.

3.2 Country Profile

Saudi Arabia is the largest country in the Middle East, with a total area of nearly 2.3 million km² – roughly half the size of the European Union. It is located between 32° and 17° north latitude, and 56° and 28° east longitude (Alshahrani, 2018) and includes land elevations of up to 3,000 metres above sea level (General Commission for Survey, 2012). Riyadh is the capital city. According to data from the General Authority for Statistics (GAS), the country's population has grown significantly over the last two decades, from 19,895,232 in 2000 to 35,013,414 in 2020 – an average annual growth rate of 2.2%. Furthermore, about two-thirds of the population in Saudi Arabia is under the age of 30 (GAS, 2021).

The climate of Saudi Arabia, and of the other Gulf Cooperative Council (GCC) members, can be categorised as 'arid desert hot' according to Koeppen-Geiger Climate Classification. These countries sit in a hyper-arid environment within the world's desert belt, characterised by an aridity index of less than 0.3, that is the ratio of average annual precipitation to potential evapotranspiration [P/PET] (Meir et al., 2012). As a result, the Kingdom experiences very high temperatures during the day and low temperatures at night, with heat rising quickly after sunrise and remaining high until dusk. The strong surface heating can be attributed to intense solar radiation and abundant sunshine which pushes air temperatures up to 50°C (Rashid et al., 2020). There are primarily two seasons in Saudi Arabia: winter and summer, with peak winter conditions in December and January and peak summer conditions in July and August. Daytime temperatures reach 45°C or higher between May and September. This is the case across the Kingdom, except in Al Baha, Taif, and Asir regions, where slightly cooler temperatures prevail due to their mountainous location.

Due to the large size of the Kingdom and the wide range of sea levels, parts of the country have distinct climatic characteristics. These are particularly significant in relation to building energy modelling at the national level. A study was conducted by Alrashed and Asif (2015) to select an appropriate climatic classification for the country which went beyond generic typologies. This study considered the main climatic factors in the design of building energy systems, namely, air temperature, relative humidity, wind speed and solar radiation, and classified the Kingdom into five inhabited climatic zones and the 'Empty Quarter', a vast uninhabited region in the south of the country (Alrashed and Asif, 2015). These zones are shown in Figure 3-1.

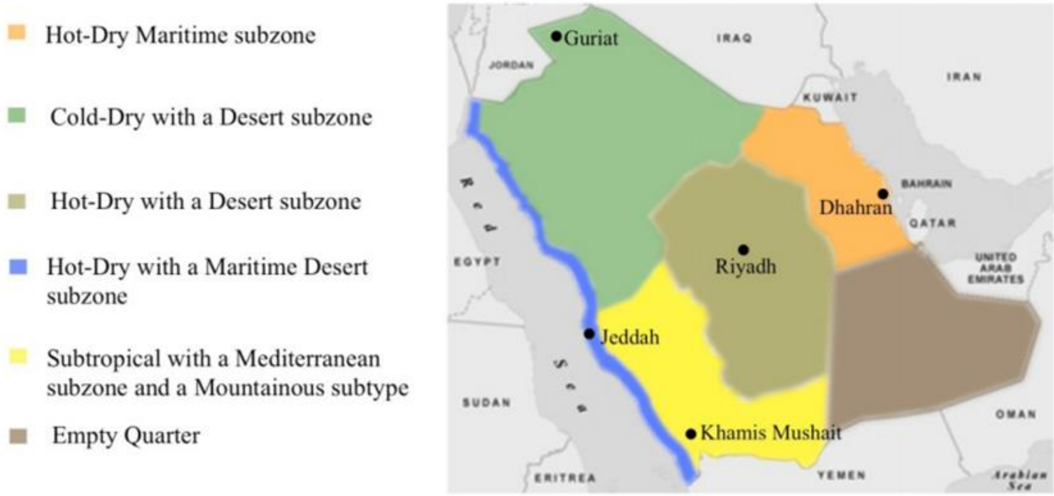


Figure 3-1: Climate zones in Saudi Arabia (Source: Alrashed and Asif, 2015)

3.2.1 City Profile for Riyadh

The capital city, Riyadh, was selected as the main site for this study. It lies in the centre of the country, covering an area of 3,115 km², and is situated about 600 m above sea level sloping eastward. According to the Riyadh Household Survey 2016, the city has a population of a 6,500,700, about 19% of the total population of KSA. Generally, Riyadh has a young population, with people below 24 years of age constituting 46% of the total, with just 4.19% aged 60 or above (Riyadh Development Authority, 2018). Over the last few decades, Riyadh has experienced vast expansion due to rapid population growth, high internal and international migration, and increasing economic and educational opportunities. Riyadh is now the largest city in KSA, with an annual growth rate of 4%, almost double the national average estimated at 2.2%, and this has led to a dramatic increase in demand for housing.

The average annual relative humidity in Riyadh is 27% and average monthly relative humidity ranges from 15% in July to 47% in December (Phillip and Lau, 2013). The city generally experiences dry weather from May to October, with rain falling intermittently in April, and high ambient temperatures between April and October. Peak summer conditions are excessively hot, with ambient temperatures exceeding 44°C (Ghosh et al., 2021). Figure 3-2 shows the monthly average temperature and precipitation profile for the city, highlighting the period when internal cooling in buildings is required to maintain user comfort.

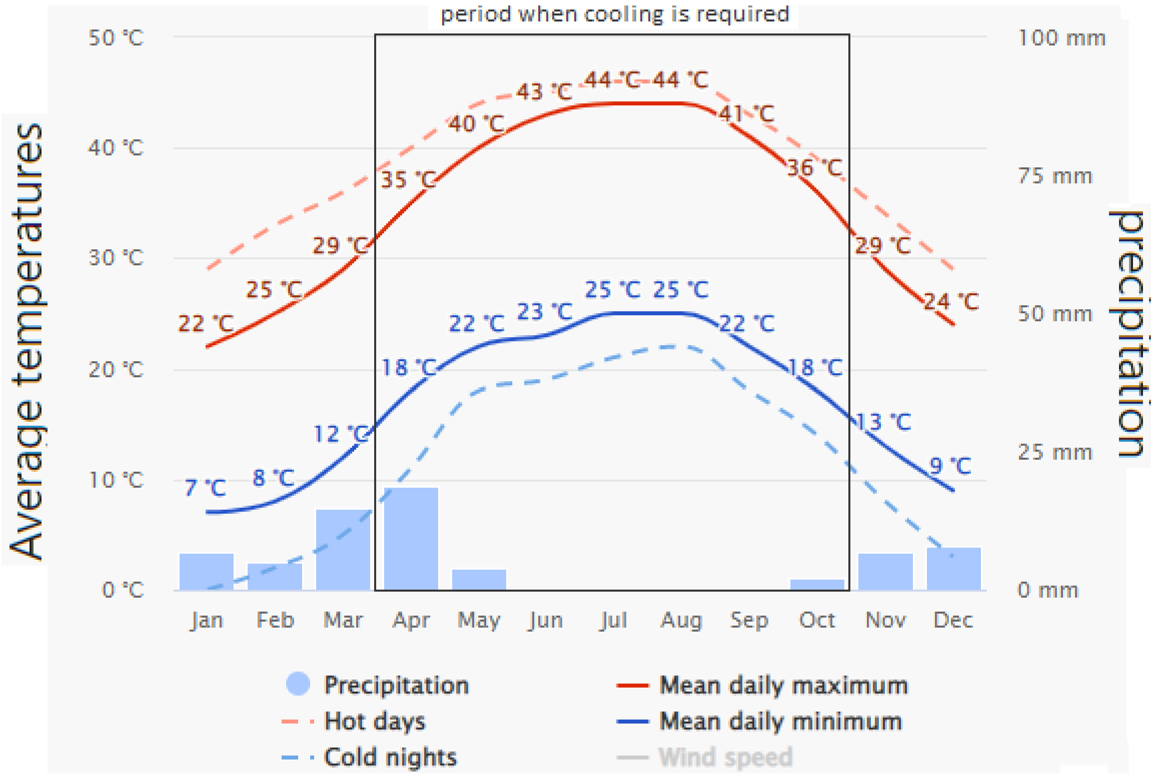


Figure 3-2: Monthly average temperature profiles for Riyadh showing period when cooling is required (Source: Meteoblue-Website, 2021)

The sun maintains a high altitude as it traverses its daily path due to the city's proximity to the equator (Latitude 24.7°N) (Phillip and Lau, 2013). As buildings typically have flat roofs which are exposed to direct sunlight for most of the day, the sun is a major source of heat gain for these structures. The average daily sunshine hours for Riyadh are presented in Table 3-1.

Table 3-1: Average daily sunshine in Riyadh (Alshahrani, 2018)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average Daily Sunshine Hours	7	8	7	8	9	11	11	10	9	10	9	7

Wind speeds vary throughout the year but are normally around 4 m/s on average with a prevailing northerly wind direction. Sand and dust storms also affect the city, most commonly from February to June, filling the air with particles of sand or dust and significantly reducing visibility (Notaro et al., 2013). Table 3-2 shows the average monthly wind velocity, number of days of dust/sandstorms (i.e. days with visibility less than 1.6 km), and mean number of days of blowing dust for Riyadh over the course of a normal year.

Table 3-2: Wind characteristics for Riyadh throughout the year (Alshahrani, 2018)

Month	Average wind speed (*m/s*)	Dust/sandstorms (*no. of days*)	Blowing dust (*mean no. of days*)
Jan	3.9	0	9
Feb	4.2	1	7
Mar	4.3	0	6
Apr	4.1	1	13
May	3.9	5	15
Jun	4.3	0	5
Jul	4.4	0	9
Aug	3.9	1	5
Sep	3.5	0	5
Oct	3.4	1	3
Nov	3.6	0	0
Dec	3.7	1	7
Average	**3.9**	**0.8**	**7**

3.3 National Power Profile

Like many GCC members, Saudi Arabia generates electricity from crude oil and other fossil fuels, such as petroleum products and natural gas; however, it burns far more crude oil for power generation than any other country (EIA, 2019). According to the Electricity and Cogeneration Regulatory Authority (ECRA), Saudi Arabia's electricity generation reached 384 terawatt-hour (TWh) in 2018, an 11% increase on 2017. This constituted 55% of total GCC region's electricity generation and 2% of total global electricity generation, making Saudi Arabia the eleventh largest generator of electricity (BP, 2019). Its peak electrical load in 2018 was around 61 gigawatts (GW), with a total electricity generation capacity of nearly 85 GW (ECRA, 2019). With rapidly rising domestic demand, Saudi Arabia is also considered a major energy consumer. In the last two decades, energy consumption in the Kingdom has increased sharply, specifically, peak load which reached around 24GW in 2001 and is expected to reach 60GW by 2023 (Fasiuddin and Budaiwi, 2011). The electricity market in the Kingdom has also risen by roughly 7% per year during this period (Alshahrani, 2018), and an annual growth rate of at least 5% is expected to continue. In 2018, total electricity consumption was around 290 TWh (SAMA, 2019). In addition, between 2004 and 2016, summer peak demand for electricity increased by 121% (ECRA, 2014; Nachet and Aoun, 2015). According to the King Abdullah Centre for Atomic and Renewable Energy (KACARE), this growth is driven by a number of factors, including population growth, rapid expansion of the industrial sector fuelled by the development of petrochemical cities, high demand for AC during the summer months, and a tariff which is among the lowest in the world (KACARE, 2020; IEA, 2018). In fact, as the country transitions from winter to summer, it was found that each 1°C increase in temperature would necessitate an additional 1.18 GW of electricity generation (Howarth et al., 2020). A study conducted by Al Harbi and Csala (2019) examined the long-term future of the KSA power sector with regard to the goals set out in the Kingdom's Vision 2030. They applied forecasting techniques to estimate future growth based on historical data and reliable sources such as SEC and ECRA. They found that peak load reached 61.7 GW in 2018, decreasing by 0.7% compared to 2017; however, it was forecast to increase to 66.4 GW in 2021, 74.21 GW in 2025, 83.8 GW in 2030, and 103.2 GW by 2040 (see Figure 3-3).

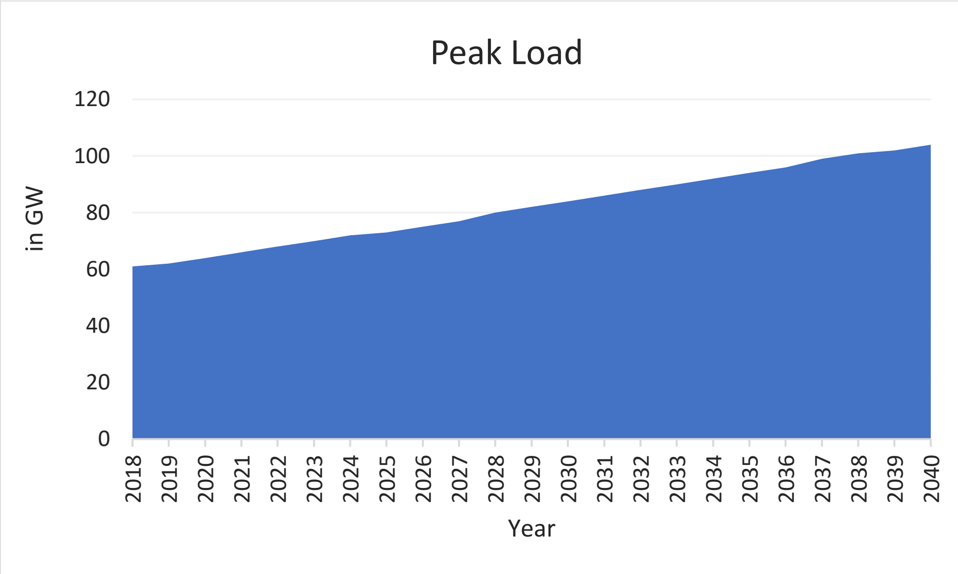


Figure 3-3: Future trends of peak load in KSA (Al Harbi and Csala, 2019)

The study also predicted that electricity consumption would rise by an annual rate of 7.6% between 2015 and 2030, with even faster growth from 2026 to 2040 (See Figure 3-4).

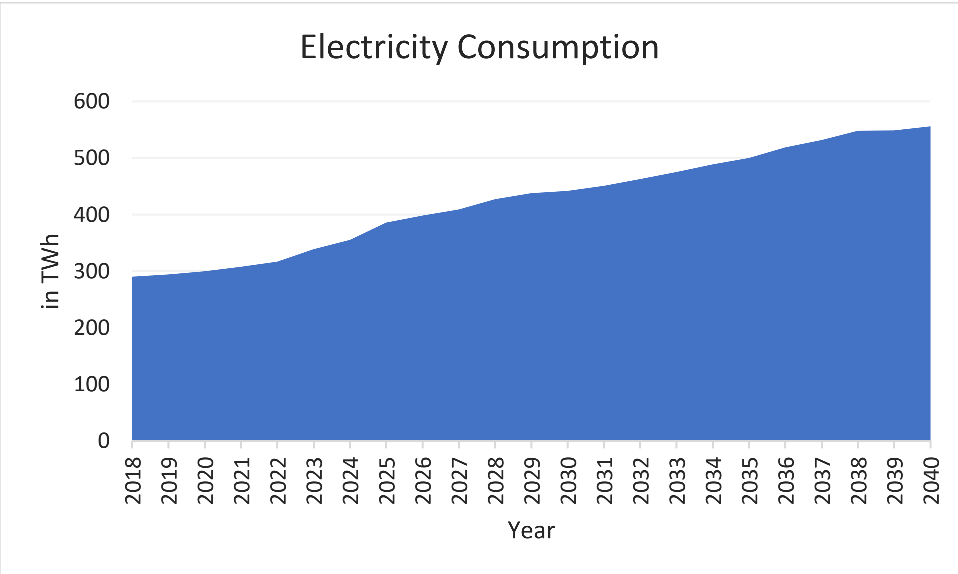


Figure 3-4: Future trends of electricity consumption in KSA (Al Harbi and Csala, 2019)

Electricity generation capacity was forecast to experience an annual growth rate of 5% between 2018 and 2040. In 2018, it was nearly 85 GW, an 8.7% increase of that in 2017, and it is expected to reach 122 GW in 2025, rising to 158 GW by 2030 and 243 GW by 2040 (Al Harbi and Csala, 2019) (See Figure 3-5).

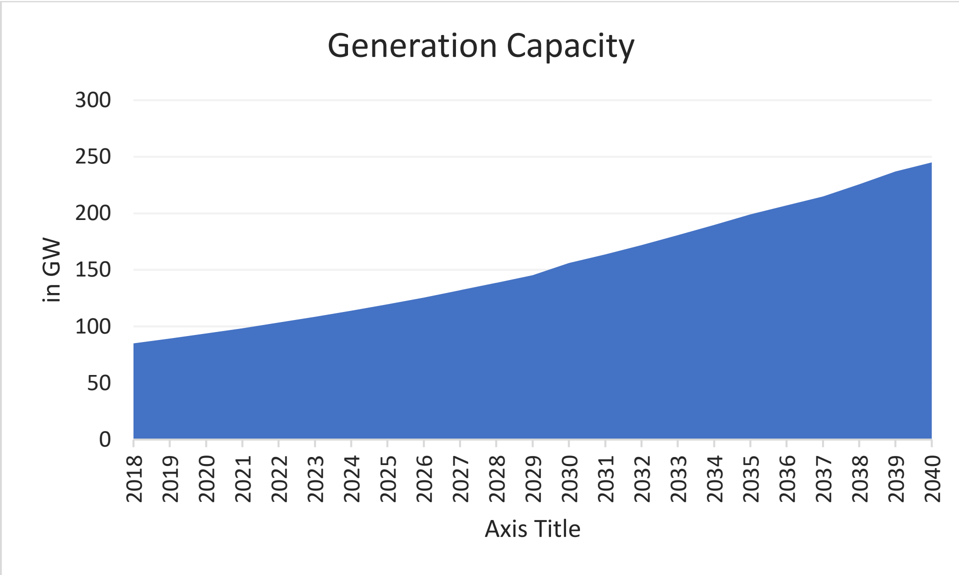


Figure 3-5: Future trends of electricity generation capacity in KSA (Al Harbi and Csala, 2019)

Figure 3-6 depicts the forecast rise in electricity power generation between 2018 and 2040. The annual growth rate of is 3.2%, with generation predicted to reach 489.5 TWh in 2025, 575.3 in 2030, and reaching 746.5 TWh in 2040 (Al Harbi and Csala, 2019).

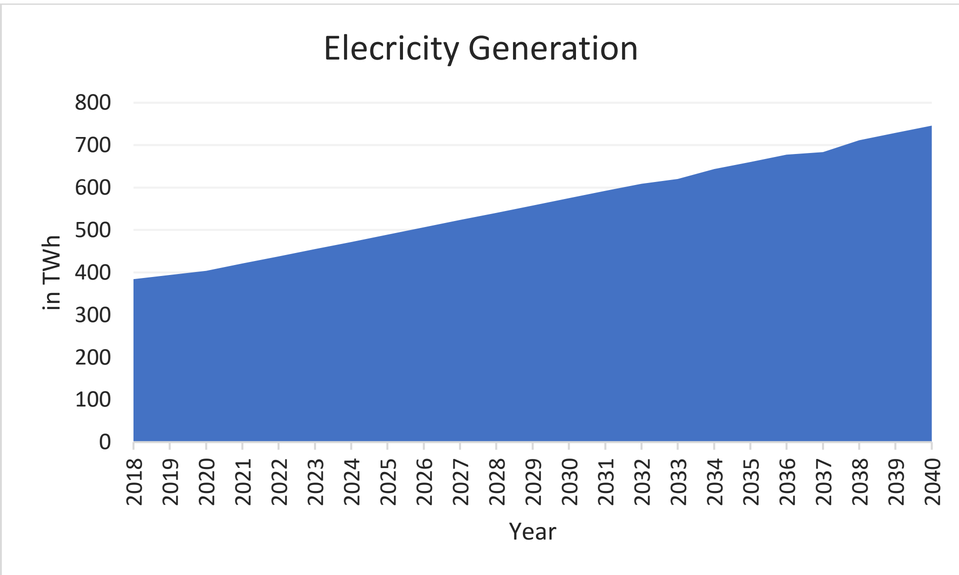


Figure 3-6: Future trends of generated electricity energy in KSA (Al Harbi and Csala, 2019)

The main supplier of electricity, the Saudi Electricity Company (SEC), has managed to boost its generation capacity to meet demand, but economic growth and demographics continue to pose a threat to the sector. However, as demand increases, the Kingdom will need to install more than 4 GW of electricity generation capacity each year (Al-Maamary et al., 2017), the largest electric power generation expansion in the MENA region (KACARE, 2017). Efforts must also be made to address energy demand as power generation and consumption are interrelated and must be balanced (OBG, 2018). The Kingdom's power sector has a tremendous opportunity to adopt innovative technologies, such as renewable energy to meet future demands, but consumer-level energy-efficiency programmes, focusing on households, industry, and the commercial sector must also be implemented.

3.4 Building Regulations

Building regulations establish guidelines for the design and construction of buildings in order to protect public safety and health. They also include standards to preserve fuel and power, and to provide facilities for people, especially those with impairments, to access and navigate buildings**.** The Ministry of Municipal and Rural Affairs (MoMRA) is the principal government body responsible for building regulation in Saudi Arabia, and the National Committee of the Saudi Building Code (NCSBC) operates under its auspices. Prior to 2007, the concept of sustainable building was virtually unknown in Saudi Arabia and made little impact on building practices (Al-Surf et al., 2014). However, the Saudi Green Building Council (SGBC) was established in March 2007, with the aim of promoting and facilitating green building practice in the Kingdom. Its remit includes increasing public awareness, providing training and education, encouraging manufacturers and suppliers of building materials to provide environmentally responsible products, providing green building specifications, and promoting an international-standard green building rating system which meets local environmental needs (Al Surf et al., 2014).

One of the main goals of the SGBC was to develop the Saudi Building Code (SBC), with the aim of protecting residents from building-related hazards such as structural collapse, fire, and other dangers. A number of codes were studied during the development of the SBC, including codes from the US, Canada, Australia, and European and Arab Codes. However, the International Code Council (ICC) was chosen to be the base code for the Saudi Building Code (SBC, 2018). The Saudi Building Requirements currently consist of 18 codes which cover most aspects of the building life, with some codes still under development. However, only those regulations relating to energy-efficiency and the requirements for residential buildings will be reviewed in detail in this section.

3.4.1 The Saudi Building Code

In general, the SBC is divided into two categories. The first sets minimum requirements for engineering specifications in the design, construction, operation, and maintenance of buildings. The second provides detailed information on design and construction procedures. The code includes general requirements (SBC201), structural (SBC301), electrical (SBC401), mechanical (SBC501), energy (SBC601), sanitary (SBC701), and fire systems requirements (SBC801) (SBC, 2018). The code's scope and facility classification are based on occupancy type. Various parties' duties in implementing and enforcing the code are also identified by the code. The SBC includes the Saudi Energy Conservation Code (SECC), based on the International Energy Conservation Code (IECC) and established in 2007, which includes codes for all buildings except low-rise (SBC601) and (SBC602) for low-rise buildings (i.e. residential buildings). The code has been mandatory for government buildings since 2009 (Al-Homoud and Krarti, 2021), and, in the year 2010, all new buildings were required to meet its thermal insulation standards (SASO, 2014). However, the uptake of other provisions was inconsistent, so deadlines for the SBC's phased application across all sectors were announced by Royal Decree on Jan 2017; this included a deadline of August 2021 for rental apartments and residential buildings (See Table 3-3).

Table 3-3: Phases of SBC Implementation

Phase	**Description**	**Implementation**	
		from	***to***
1	The code is applied to the following buildings : government and administrative buildings, high buildings (towers – more than 23 m), hospitals, hotels	Royal Decree issue date (Jan 2017)	End of Aug 2019
2	The code is applied In addition to what was applied in the first phase on the following buildings: mosques, sport buildings, educational buildings, commercial buildings, communication towers, industrial buildings, buildings less than 23 m, high-rise buildings	End of 1st Phase	Aug 2020
3	In addition to the above buildings, the code is applied to Wedding lounges, Cinemas, theatres, medical centres, rental apartments, residential and recreational buildings	End of 2nd Phase	Aug 2021
4	In addition to previous buildings, the code must be applied to airports, banks, post, media, and broadcasting buildings	End of 3rd Phase	End of Jul 2022
5	At this phase , the code must be applied to all types of buildings	End of 4th Phase	Jul 2023

The Kingdom declared its intention to build smart and sustainable buildings in 2011 and allocated funding of around US$ 39.9 billion to support this (Ventures Middle East, 2011). In October 2012, the Saudi Council of Engineers established the Green Building Chapter to raise awareness about green building design through conferences and other educational events to help promote the concept; however, according to Ghabra (2017), the chapter's activities were limited and had little impact on energy policies or building regulations. Given the fact that the SBC has only just been applied to residential construction projects, where it can be seen and assessed, it remains to be seen how thoroughly it will be applied and how effective it will be.

3.4.2 Building Energy Conservation Code (SBC602)

The Saudi Energy Conservation Code (SBC602) provides minimum energy-efficiency requirements for low-rise residential buildings and was produced by the Saudi Energy Efficiency Centre (SEEC) under the supervision of the NCSBC in 2007. The SEEC reviewed several international codes during the preparation of SBC602, and it was formulated based on the International Energy Efficiency Code (2003) and the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, ASHRAE. The code covers the design and construction of new residential dwelling units and their systems. For the purposes of this code, "residential dwelling units" include single-family houses, flats, multi-family structures (of three stories or fewer above ground). Buildings with a height of four or more storeys are classified as commercial, regardless of how many of those floors are occupied by residents. It does not include "transient" housing, such as hotels, motels, nursing homes, jails, and barracks, or manufactured housing (SBC602, 2018).

SBC602 provides thermal performance requirements for the residential building envelope that separates conditioned spaces from either exterior conditions or unconditioned spaces. In order to identify suitable requirements for the envelope of any low-rise residential building, the code divides the country into three climate zones according to cooling degree-day (CDD), a measure which quantifies demand for air conditioning. Zone 1 is categorised as extremely hot, with CDD greater than 5,000; Zone 2 is very hot, with CDD greater than 3,500; and Zone 3 is categorised as hot, for remaining cities. Zone 1 is most significant, as it constitutes more than half of the country and covers all the major cities, including Riyadh (AlFaraidy and Azzam 2019) (See Figure 3-7). The code also sets a reference level for indoor conditions for Summer: a dry bulb (DB) temperature of 23.9 °C and relative humidity (RH) of 50%, and for Winter a DB of 21.1°C and 30% RH (SBC602, 2018).

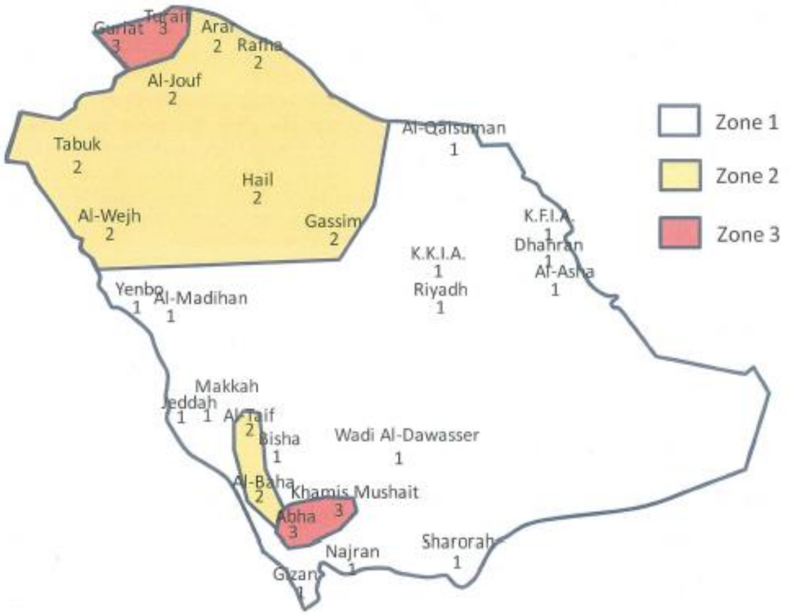


Figure 3-7: Climate zone classification used by SBC (Source: SBC602, 2018)

The code includes three sets of prescriptive building envelope criteria, one for each thermal zone. Each set of criteria is presented as a separate table in Section 5.4 of the code based on the zone classification, and maximum U-value and minimum R-value, the fenestration maximum U-values, and maximum SHGC are provided for roofs, walls, and floors (SBC602, 2018). The minimum performance requirements for energy-efficient buildings were updated by the NCSBC in 2021. The previous and revised versions of the SBC602 are presented in Table 3-4.

Table 3-4. Energy conservation requirements in SBC602 (Source: SBC, 2021)

Item	Energy-efficient building requirement
Wall U-Value ***(U: heat transfer coefficient [W/m²․K])***	***Previous Version:*** Wall: 0.342/0.397/0.453 for zones 1, 2,3 ***Updated Version*:** Wall: 0.403/0.454/0.511 for zones 1, 2,3
Roof U-Value ***(U: heat transfer coefficient [W/m²․K])***	***Previous Version:*** Roof: 0.202/0.238/0.273 for zones 1, 2,3 ***Updated Version:*** Roof: 0.272/0.340/0.397 for zones 1 ,2 ,3
Door U-Value *(W/m²․K)*	2.839 for all zones
Window Overall U-Value *(W/m²․K)*	2.668 for all zones
Window Type	Aluminium frame with thermal breaks or PVC
Internal Shading	Vertical blinds/drapes closed weave light colour
Glass Type	Double glazed with 12mm air space
External Colour	Light
Solar Heat Gain Coefficient *(SHGC)*	For all zones ≤ 0.25
Surface Reflectance Index *(SRI)*	Light colour with SRI ≥ 50
Water Absorption for Insulation Materials	≤ 0.3%
Continuous Insulation	Continuous across all building envelope
Ventilation	54.5 L/s

Infiltration in Fenestration	≤ 1.5 L/s/m²
Infiltration for Doors	≤ 1.5 L/s/m² (for sliding doors) ≤ 2.5 L/s/m² (for swinging doors)
Lighting Power Density	10 W/m² ground floor, 6 W/m² first floor
Equipment Power Density	2.0 kW ground floor,1.0 kW first floor
Vertical Fenestration Area	≤ 25% of the wall area
Minimum Energy Efficiency Ratio- EER	EER ≥ 11.8

According to SBC602, envelope design must take into account both external and internal loads, as well as the benefits of daylighting. As illustrated in Figure 3-8, solar gains, conduction loss across an envelope's surface, and infiltration are examples of external loads, whereas heat gains from lights, equipment, and people are examples of an internal load.

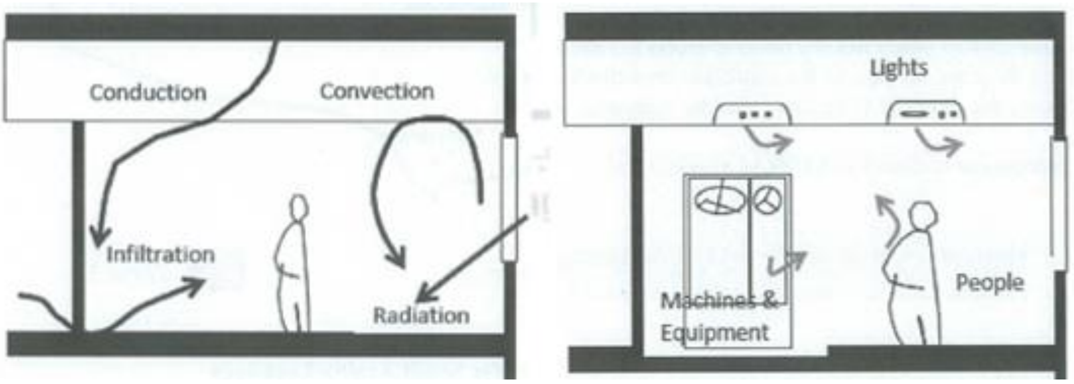


Figure 3-8: Envelope external loads (Left) and internal loads (Right) (Source: SBC602, 2018)

A user manual provides the technical background and intent behind various requirements of the code. The NCSBC have taken precautions to avoid ambiguities, omissions, and errors in the document, but previous studies have suggested that users might find information or requirements are subjected to more than one interpretation or may be incomplete (Ghabra, 2017). The user manual is, however, advisory only and is not considered as a mandatory part of the code. The requirements related to administration and enforcement of the code are also only advisory.

3.4.3 Comparative Analysis of Building Regulations in the GCC Region

The recent trends in the GCC region suggest that there is a growing awareness of the need to drive the construction industry toward sustainability, and GCC countries have made significant progress in terms of green buildings in recent years. The United Arab Emirates (UAE) and Qatar are leading this drive towards sustainability and have the greatest share of green buildings in the MENA region. There has been a remarkable increase in the number of LEED registered buildings in the region as a whole in the last few years, particularly in the GCC. Around 1170 buildings in the GCC region were LEED certified as of 2014, with 70% of these in the UAE. Saudi Arabia came in third with 12%, just behind Qatar with a share of 15% (Asif, 2015).

Sustainability has become one of the priorities in the GCC region, and influential stakeholders in the building sector, including policy makers, investors, contractors, and building professionals, are now looking to develop more eco-friendly buildings (Asif, 2015). The UAE and Qatar have taken significant steps forward by designing their own green building grading systems, the Pearl Rating System (PRS) and the Global Sustainability Assessment System (GSAS) respectively, to manage the energy, environmental and socio-economic aspects of modern construction more effectively. Saudi Arabia is also attempting to position itself in the building industry to take advantage of new sustainability trends within a framework that responds to local requirements. As Haase and Amato explain:

> *Different countries have developed their specific vision of how to incorporate sustainable development particularly to the built environment. Special focus should be put on the building envelope design since the local climate requires customized solutions…. The building envelope ought to be affordable, durable, energy-positive, environmental, healthy, comfortable, and intelligent* (Haase and Amato, 2006).

Studies have also shown that the adoption of building regulations and codes which work with rather than against harsh climates, such as those in the GCC area, could reduce energy demand by up to 70% (Ghabra, 2017, Myrsalieva and Barghouth, 2015). In spite of this, a report in 2012 found that only the UAE and Qatar had developed exclusive building codes to address sustainability and standardisation issues in building construction (Ventures Middle East, 2012). Saudi Arabia has now followed them, but Bahrain and Oman have yet to meaningfully engage in green building construction (Construct Arabia, 2012). Table 3-5 compares and evaluates the major building regulations, practice methods, and rating systems in the Gulf region in order to comprehend the opportunities, challenges, and the innovative approaches which are being adopted.

Building energy-efficiency standards, if effectively enforced, can act as a powerful incentive for the construction sector, including architects and developers, to begin implementing sustainable and energy-efficient solutions into building projects. The GCC energy-efficiency regulations were generally developed with the assistance of external professionals and academic institutions, and they focus primarily on the building envelope (Meir et al., 2012). However, with a particular reference to the SBC601/2, the regulations are based on international standards; thus, they might not be tailored to Saudi Arabia's unique built environment. In addition, according to Ghabra (2017), energy efficiency is not explicitly addressed in these building codes. For example, the regulations determine minimal standards for the thermal properties of the building envelope, such as the SHGC and U-value; however, the envelope design elements and their impact on energy performance are not considered (Ghabra, 2017).

In addition to the lack of clear benchmarks for energy reductions, the absence of effective enforcement of these regulations undoubtedly impairs their effectiveness. The SBC, for example, has required thermal insulation for all new buildings since 2010, as it has been demonstrated to lower energy demand in villas by 30-40% (Aldossary et al., 2015). In spite of this, new buildings are still being constructed without adequate insulation (Lahn et al., 2013). As standards are still optional or poorly enforced, an obligatory regulatory framework is needed in order to ensure sustainable practices are implemented in all structures (Myrsalieva and Barghouth, 2015).

According to conclusions from the study conducted by Ghabra (2017), the main building design challenges in the Gulf region can be categorised into two levels: regulatory and climatic. This implies that there is a need to develop and implement a compulsory regulatory framework with the aim of delivering energy-efficient buildings. Furthermore, if energy efficiency in residential buildings is to be accomplished, local building energy-efficiency methods in the region generally, and in Saudi Arabia specifically, should employ an integrated, holistic, cross-disciplinary design approach (Ghabra, 2017).

Table 3-5: Comparison of some GCC countries regulations (Source: Ghabra, 2017)

SHGC: Solar Heat Gain Coefficient, U-value: Thermal transmittance, SC: Shading Coefficient, VLT: Visible light transmittance

Document	Compliance Approach	Implementation	Thermal Properties of Building Envelope	Design Consideration	Energy Performance Targets	Notes
SBC 601/2 *(Saudi Energy Conservation code for Residential Buildings)*	Prescriptive and Performance	Mandatory for some buildings (*As from 2017 and expanding to cover all type of buildings in 2023*)	SHGC and U-value for windows U-value for opaque elements based on glazing ratio and CDD	None	None	Reference to ASHRAE Standards 90.1-2007 for the thermal properties
GBRS *(Dubai Green Building Regulations & Specification)*	Prescriptive and Performance	Mandatory to governmental buildings, voluntary public, and private buildings	SC, VLT and U-value for windows U-value for opaque elements based on glazing ratio	Considerations for external shading devices	None	Specific to Dubai's climatic conditions and needs
PRS *(Pearl Rating System – Abu Dhabi)*	Performance	Minimum requirements are mandatory for all buildings, additional requirements for governmental buildings	Considered in the Building Performance Rating Method outlined in Appendix G in the ASHRAE Standards 90.1-2007	Considered as an additional credit points (*not mandatory*). Design measures mentioned include orientation, glazing ratio, ext. shading	A minimum 12% performance improvement compared to the baseline building performance as per the ASHRAE Standards 90.1	Provides a prescriptive approach but not relevant for tall buildings
GSAS *(Global Sustainability Assessment System – Qatar)*	Performance	Not mandatory	Inputs for the Energy Performance Calculators	Not known (*Due to lack of availability*)	Baseline reference for Energy Demand Performance for residential buildings = *121 kWh/m²/yr*	Specific to Qatar's climatic conditions and needs

3.4.4 New Building Rating System – Mostadam

Until 2019, all the certified buildings in Saudi Arabia were rated by the US Green Building Council LEED rating system. However, as mentioned above, the international sustainable building rating systems do not take Saudi Arabia’s local climate and environmental characteristics into account. As a result, in October 2019, Saudi Arabia introduced a new green building rating system called ʺMostadam”; this is intended to improve water and energy sustainability and was developed with assistance from the Ministry of Housing (MoH) and Alpin Limited, the sustainable cleantech consulting firm. Mostadam is related to the SBC and was designed to be consistent with the existing legislation. It includes three stand-alone green building rating systems depending on the type of built asset being examined: residential buildings, communities, or commercial buildings. Each rating system has two elements: the first is design and construction, and the second is operational and existing. Mostadam is tailored to Saudi Arabia’s regional needs, local climate, and environmental characteristics (Sustainable Building, 2021), and its green building rating system is intended to create a more sustainable construction industry in Saudi Arabia, as well as improve the overall quality of construction projects in the region.

A recent study by Balabel and Alwetaishi (2021) compared the categories of LEED v4.1 and the Mostadam rating systems for residential buildings and the total points for each category. The findings are set out in Table 3-6. As can be seen, the most important categories for the certification of Saudi sustainable buildings are energy (27), water (24), and health and comfort (14), compared with LEED’s energy and atmosphere (35), materials and resources (19) and indoor environmental quality (16), this being the LEED equivalent of health and comfort.

Table 3-6: Comparison between the categories of LEED v4.1 and the Mostadam rating system (Source: Balabel and Alwetaishi, 2021)

Item No.	Category in LEED v4.1	Total Points	Category in Mostadam Rating System Element (Res. Buildings)	Total Points
1	Integrative Process	1		
2	Location and Transportation	9	Transportation and Connectivity	7
3	Sustainable Sites	9	Site Sustainability	9
4	Water Efficiency	11	Water	24
5	Energy and Atmosphere	35	Energy	27
6	Materials and Resources	19	Materials and Waste	4
7	Indoor Environmental Quality	16	Health and Comfort	14
8	Innovation	6	Education and Innovation	4
9	Regional Priority	4	Region and Culture	7
10			Policies, Management & Maintenance	4
	Total points	**110**		**100**

The points awarded in the Saudi system reflect local cultural, economic and environmental factors, and this accounts for some of the differences. For example, the water efficiency category in Mostadam has a greater effect on the evaluation process than in LEED. This is due to the fact that Saudi Arabia has one of the world's highest levels of water consumption per capita at around 263L (National Water Company, 2021). It is also striking that Mostadam's material and waste category has little effect on the evaluation process compared to LEED. According to Balabel and Alwetaishi (2021), this may relate to the lack of a sustainable construction industry in Saudi Arabia and the technology required to recycle waste material. The region and culture category in Mostadam relates to the importance of privacy and gender separation in Saudi society. Finally, while Mostadam's policies, management, and maintenance category is not included in LEED, it is considered an important category in relation to people's behaviour within Saudi society. Another clear difference between the two systems is the fact that the integrative process category in LEED is not included in Mostadam. This is an early analysis that starts in the modelling and predesign phases. However, it could be argued that the predesign process should be included due to its role in the early identification of the common design weaknesses seen in current Saudi residential stock. The residential building sector in KSA is discussed in more detail below.

3.5 Residential Buildings in Saudi Arabia

This section provides an overview of the Kingdom's existing housing stock, including its size and construction, as well as the main characteristics of household energy-intensive systems. It also summarises the energy performance level within the Saudi residential building sector.

3.5.1 Existing Housing Stock

According to the latest report from Deloitte, the total worth of projects in the GCC region was about US$ 2,564 billion. As illustrated in Figure 3-9, the construction sector is the largest industry, constituting 56% of total industries. The KSA is the leading investor amongst GCC countries, with a 46% share of nearly US$1200 billion worth of projects planned or underway as of January 2019 (Deloitte, 2019) (See Figure 3-9). An analysis of Saudi construction by MoMRA (2016) showed that over the last decade the number of licences issued for buildings has increased dramatically, with most of these for residential and commercial buildings, and significant growth in future demand in the residential sector is predicted as the population is increasing at a rate of 2.2% per year (GAS, 2021).

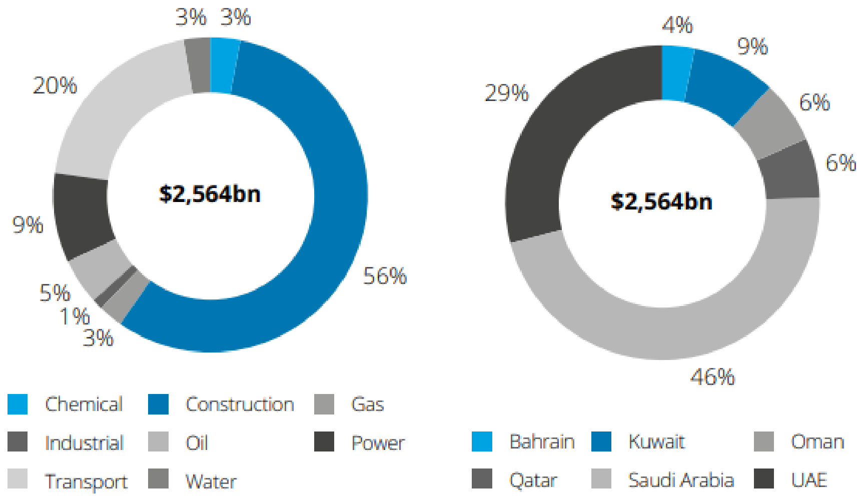


Figure 3-9: Projects distribution in the GCC by industry (Left) and by country (Right) (Source: Deloitte, 2019)

According to the US-Saudi Business Council (USSBC), the real estate sector in KSA led all other sectors during 2019, with nearly $3.2 billion in awarded contracts. This was a 39% growth in real estate compared to 2018 (USSBC, 2020). The residential real estate market was the largest contributor, accounting for 94% of the total, with the remaining 6% coming from commercial and mixed-use contracts (USSBC, 2020). Numerous projects were awarded to build affordable housing units across the Kingdom by the MoH, which was the largest contract awarder, and the residential real estate sector is expected to continue to play a significant role in awarding contracts in the foreseeable future (USSBC, 2020). To fulfil its ambition of increasing homeownership by Saudi nationals to 60% and 70% by 2020 and 2030 respectively, the MoH, in partnership with the Real Estate Development Fund, announced a plan under the 'Sakani' housing development programme to deliver 300,000 residential units for its nationals throughout the Kingdom in 2019 (Vision 2030, 2020).

In 2020, the total volume of residential transactions increased by 25%, and the total value increased by 80% (Durrani, 2021). This relative outperformance can be explained by a marked increase in the take up of mortgages and the delivery of large scale housing schemes. Data from the Saudi Central Bank shows that the value of new residential mortgages for individuals provided by banks and financial institutions increased by 38% in the 12 months to February 2021. New residential mortgage loans for villas accounted for nearly 80% of contracts, valued at $3 billion, with residential apartment and land mortgages accounting for 6% and 4% respectively (Durrani, 2021).

Based on recently reported housing survey results (GAS, 2019), the total number of housing units occupied by Saudi nationals reached 3,681,927 in 2019. The distribution of housing units by type and age, based on historical local housing stock reported between 2010 and 2018, is shown below:

Table 3-7: Distribution of housing units in 2019 (Created by the author- Source: GAS, 2019)

Housing Unit	Distribution by Type		Approximate Age of Housing	Distribution by Age	
Apartment	1,610,408	43.74%	*Less than 5 Yr*	219,172	5.95%
Villas (typically two storeys)	1,095,237	29.75%	*5-10 Yr*	774,335	21.03%
Storey in a villa	284,088	7.72%	*10-20 Yr*	1,140,568	30.98%
Traditional houses	664,991	18.06%	*20- 30 Yr*	906,010	24.61%
Storey in a traditional house	27,203	0.74%	*More than 30 Yr*	641,842	17.43%

As Table 3-7 demonstrates, apartments and villas are the dominant unit types. This was confirmed in a survey carried out by Esmaeil et al. (2019) which showed that villas and flats were the most popular types of housing in the Kingdom. Villas are typically detached single-family residences with two floors and a vacant area surrounding them, while flats are single apartments in structures with multiple units, both types are mainly made of reinforced concrete. On the other hand, bricks, blocks, and in some cases, adobe are used in the construction of traditional houses. Apartments may attract more residents since they are often more affordable than villas. The statistics also reveal that the majority of houses are at least 10 years old, with newly built dwellings (aged less than 5 years) representing only 5.95% of the total stock. The survey data for 2019 showed that 70.3% of housing units occupied by Saudi households had 3 or fewer bedrooms, while 26.6% of houses had 4 to 6 bedrooms. Moreover, the average size of the Saudi household was estimated as 5.86 persons (GAS, 2019). This is consistent with the findings of Alrashed (2015) which revealed that a typical house in Saudi Arabia is a single family villa for 6 inhabitants and usually financed through personal savings and loans. In terms of house tenure, 62.1% of houses were owned by Saudis compared to 35.5% of rented housing units. As operating utility costs are typically paid by the tenants, rather than the original owner, it is expected that rental housing stock will be less energy efficient compared to those intended for personal use for the purpose of minimising the capital cost (Al-Homoud and Krarti, 2021).

With a specific reference to Riyadh, as of 2020, Riyadh's housing stock was estimated to total 1.28 million units, and this is expected to increase to 1.37 million units by the end of 2023 (Durrani, 2021). According to the 2019 Saudi Housing Statistics, the number of housing units occupied by Saudi citizens in Riyadh constituted 23.5% of the total number in KSA at a density of 873 dwellings per square kilometre (GAS, 2019). The most dominant housing type in Riyadh is the villa, comprising about 46% of the total. Furthermore, the average household size in Riyadh is projected at 5.7 people per household (MoMRA, 2019), slightly lower than that estimated by GAS (2019). In terms of housing tenure, more than the half of the houses occupied by Saudi families in Riyadh are owned compared to 40% who rent their dwellings. Also, as before, most of the houses in Riyadh are between 10 to 30 years old, with just 5% of them built within the last 5 years (GAS, 2019).

3.5.2 Existing Housing Characteristics

Saudi residential units are typically large. The average area of a residential site is approximately 625 m^2 and residents are allowed to build on a maximum of 60% of this land (MoMRA, 2017; Aldossary et al., 2015; Taleb and Sharples, 2011). The 2019 Saudi housing survey reported that the primary material used to construct buildings is concrete, accounting for 89.8 % of the total, while housing constructed of block/clay materials constitutes only 10.2% (GAS, 2019). The latter is mainly used in traditional houses. This section draws on the most recent survey data to discuss the application of thermal insulation, AC systems, solar power, and the use of energy-efficiency devices in Saudi residential buildings.

In order to supply electricity to any building in Saudi Arabia, it is compulsory that the landlord must provide evidence from the local authority confirming that the building is constructed according to the original approved layout plans and accords with MoMRA rules (Aldossary et al., 2017). Despite this, data from the SEEC indicates that more than 70% of existing residential buildings lack thermal insulation for either the exterior walls and/or the roof (SEEC, 2021). The establishment of the SBC and the requirement for thermal insulation in all new buildings are encouraging indicators of a commitment to sustainable development; however, there is a lack of appreciation among some building sector stakeholders. For example, a recent SEC survey reported that only 580 out of 15000 new buildings (15%) had applied the compulsory thermal insulation (Asif, 2015). The situation is even worse in some parts of the country. In 2014, City of Jeddah, for instance, was listed as the poorest in its compliance with thermal insulation requirements, where only 52 out of 5200 buildings were erected with compulsory requirements (Asif, 2015). Al-Homoud and Krarti (2021) ascribe the lack of thermal insulation in Saudi buildings to the loose energy-efficiency rules and low costs of energy, and there is evidence that contractors have failed to comply with requirements despite repeated warnings from the SEC (Aldossary et al., 2014).

The Saudi Household Energy Survey indicated that window air conditioners (71.3% of the total) and split systems (25.8%) were the most commonly used heating and cooling systems in Saudi homes (GAS, 2019). Older buildings are more likely to have window air conditioners, but split air-conditioning units have become increasingly popular in Saudi homes in recent years, both in new construction and in renovations. This trend is projected to increase energy efficiency due to reduced air infiltration, a key contributor to energy inefficiency resulting from the loose sealing of window air-conditioning systems in older housing units (Al-Homoud and Krarti, 2021). Moreover, the adoption of energy-efficiency controls such as smart thermostats has been quite limited in housing units (Al-Homoud and Krarti, 2021).

All housing units in Saudi Arabia are powered by electricity and electric heating is the primary means of heating water. However, the 2019 Household Energy Survey indicated that only about 1.6% of households use solar energy in their homes. Although the use of energy saving lamps (i.e. CFL and LED) is growing, with a total share of 35.1%, incandescent lamps (48.7%) are still the most common lighting fixtures in Saudi housing units. The survey results also showed that the majority of households (63.70%) do not have power savers to rationalise consumption (GAS, 2019).

3.5.3 Energy Consumption of Residential Buildings

Saudi Arabia has experienced dramatic growth in urbanisation in the last three decades, driven by substantial rural-urban migration, high fertility rates, concentration of economic activities in urban areas, and international labour migration. The corresponding expansion of infrastructure is vast, particularly with regard to residential construction. However, when comparing Saudi building designs to those of other countries, the issue of energy efficiency has not been given serious consideration (Ghabra et al. , 2017; Felimban et al. 2019). As a result, the building stock consumes around 75-80% of the country's electricity production (ECRA, 2018). Residential buildings in particular are consistently responsible for the largest share of the electrical energy used in the country, as illustrated in Figure 3-10. The electricity tariff for the residential sector in Saudi Arabia is divided into two segments, according to SEC (2021):

- (Tariff A, 0.048 USD/kWh) for those buildings consuming up to 6000 kWh/month
- (Tariff B, 0.08 USD/kWh) for those buildings consuming more than 6000 kWh/month

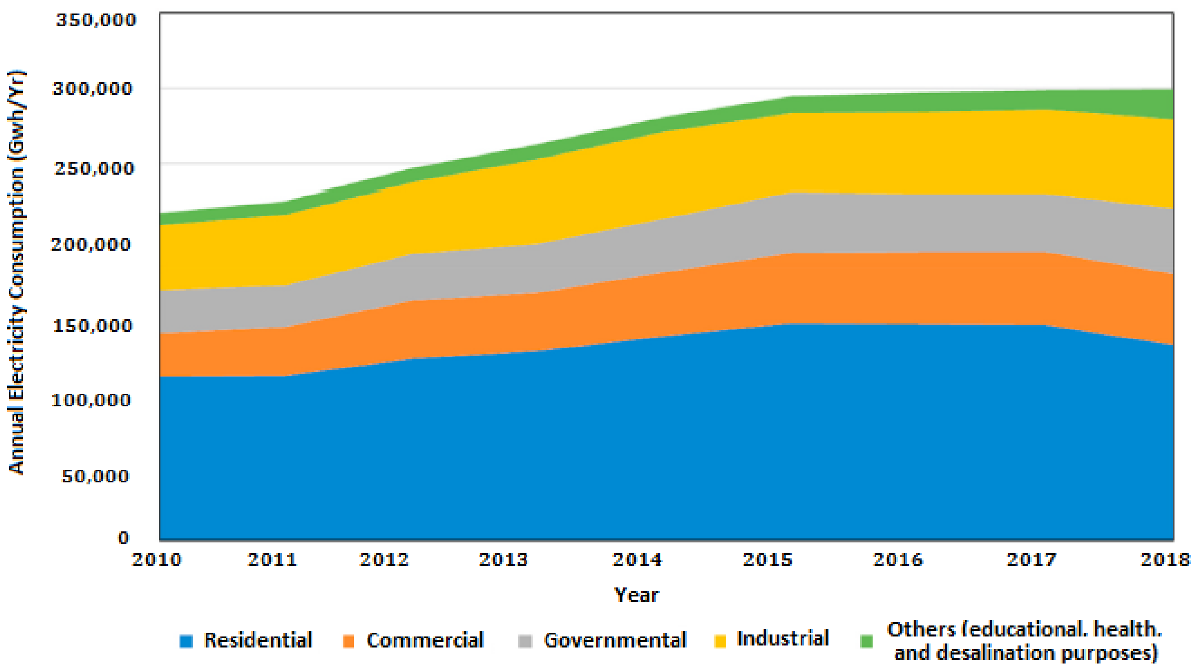


Figure 3-10: Sectoral energy consumption 2010-2018 (Source: ECRA, 2018)

Compared to the global average of less than 27%, the proportion of household electricity consumption in KSA is extremely high (Esmaeil et al., 2019). Several authors have claimed that residential buildings currently consume about half of the overall energy consumption of the building stock due to defects in design and construction (Abd-ur-Rehman et al., 2018; SEEC, 2018; Hijazi and Howieson, 2018; KAPSARC, 2020). The electrical energy consumption rate per capita increased from 6.9 MWh in 2007 to 9.6 in 2017 (IEA 2020), and it is still increasing each year, leading Saudi Arabia to be ranked 15th in the world in terms of energy consumption per capita (Alardhi et al., 2020). According to the EIA (2016), worldwide residential energy consumption is expected to rise by an annual average of 1.4% between 2012 and 2040, and given that cooling loads are already relatively high in KSA, urgent intervention is needed to maximise energy efficiency (Felimban et al. 2019).

According to Al-Homoud and Krarti (2021), the average annual energy use intensity (EUI) for Saudi dwelling units is 249.5 kWh/m², although it can reach as high as 314 kWh/m² in some regions and as low as 184.2 kWh/m² in others. This corresponds to an annual average energy cost index (ECI) of 18.75 USD/m² and represents 5-20% of a typical Saudi household's annual income (GAS, 2019). Table 3-8 summarises the electrical energy consumption per unit area in Saudi residential buildings, specifically villas, based on studies conducted since 2004. A discrepancy in values for the same type of construction can be seen, even within the same climatic zone. This suggests that further research is required to arrive at values that will aid policymakers to make appropriate decision to improve energy efficiency in all its technical, economic, and environmental aspects.

Table 3-8: Previous studies on energy consumption per unit area in villas (Source: Alardhi et al., 2020)

Building Location	Climate Zone	Area (m^2)	Yearly Consumption (kWh/m^2)	Reference
Dhahran	1	525	249.5	Ahmad (2004)
Riyadh	1	525	227.4	Alaidroos and Krarti (2015)
Jeddah	1	428	170	Alrashed and Asif (2015)
Dhahran	1	428	135	
Riyadh	1	428	119	
Riyadh	1	418	162.1	Yousefi et al. (2017)
Riyadh	1	688	110.2	
Dhahran	1	345	150	Alrashed and Asif (2014)
Dhahran	1	428	142	Nilsson et al. (2014)
Riyadh	1	418	100.1	Aldossary et al. (2014)
Qassim	2	533	84.2	Esmaeil et al.(2019)
Guriat	3	428	98	Alrashed and Asif (2015)
Khamis Mushait	3	428	61	

The consumption per dwelling unit area might be the most commonly utilised standard measurement to evaluate the energy consumption in buildings for one year. This measurement can sometimes be called the energy use intensity (EUI) or building energy index (BEI) (Tahir et al., 2015). These indices are important indicators of the energy performance of a building's design or operation (Ma and Cheng, 2016). However, energy usage is affected by a wide range of factors including weather conditions, building attributes, and human behaviour. Esmaeil et al. (2019) performed a statistical analysis to evaluate the electricity consumption patterns in the surveyed dwellings in the Qassim region (Climatic Zone 1). They assessed the average shares of annual consumption as follows: lighting (8.5%), residential appliances (14.7%), water heaters (10.3%), and AC (66.5%). Meanwhile, analyses using parametric data suggested that the type of building had no substantial effect on energy consumption, with the exception of the hot summer months, when villas use more energy (Esmaeil et al., 2019). Overall, they found that occupant behaviour, meteorological conditions, and the technical characteristics of both building envelopes and air conditioning temperature settings, all have a significant impact on residential energy usage (Esmaeil et al., 2019).

Remarkably, AC systems alone are responsible for over 50% of the total domestic electricity demand in Saudi Arabia and up to 70% of electricity consumption in residential buildings, making them the single largest consumption source (Alrashed and Asif, 2012; Mujeebu and Alshamrani, 2016; SEEC, 2018). Figure 3-11 shows the distribution of end-use energy consumption for Saudia Arabia's residential building sector in 2018.

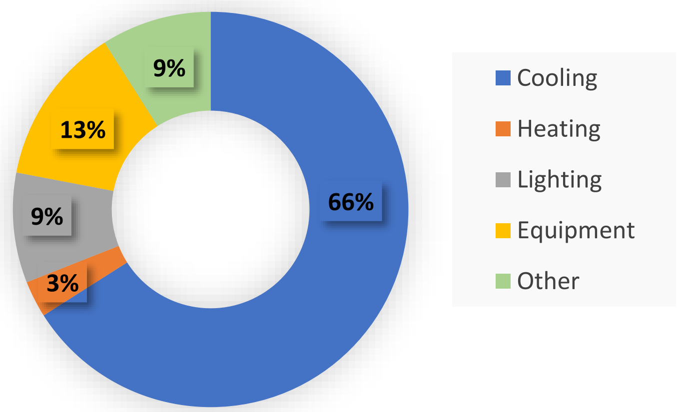


Figure 3-11: A breakdown of the 2018 end use energy consumption for the residential sector. (Source: Krarti and Howarth, 2020)

A typical villa's cooling load ranges from 40 to 71% of its total energy consumption, depending on the local climate (Alaidroos and Krarti, 2015). This was confirmed by an analysis of electricity consumption in 2015 which showed how monthly consumption follows the average ambient temperature, reflecting the importance of AC in the summer months when electricity demand is double that in winter (See Figure 3-12).

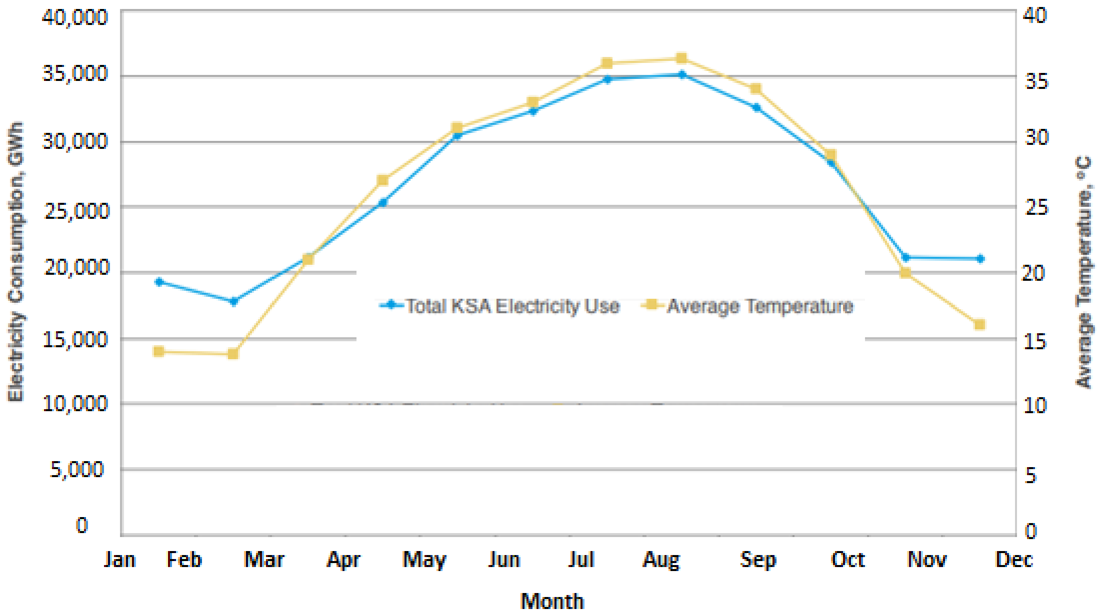


Figure 3-12: Monthly electricity consumption and average ambient temperature (Source: SEC 2015)

3.5.4 Issues in Current Building Practices

Building sustainability has been recognised as a necessity around the world, and the use of sustainable construction methods is essential for the preservation of natural resources for future generations; however, there continues to be a lack of energy-consciousness in the developing world, including in Saudi Arabia (Al Surf, 2014). Although the Kingdom is preparing itself to take advantage of emerging building sustainability trends, the application of sustainable techniques and measures in building construction is still mostly considered as a luxury option for those who have the financial capacity to afford them (Al Surf, 2014). Aldossary et al. (2015) claim this is mainly the result of a lack of public awareness of the benefits of sustainable construction and the environmental and economic cost associated with current building practices.

One reason for the high levels of energy consumption within buildings is the fact that energy efficiency has not been a high priority during any of the different phases of the life cycle of Saudi buildings (design, construction, and use). This is primarily due to relatively low energy costs (Esmaeil et al., 2019; Ghabra, 2017); however, factors such as low quality building envelopes, large areas, and occupant behaviour also contribute to the issue (AlFaraidy and Azzam 2019). Furthermore, the fact that citizens do not have adequate financial and material support to acquire energy efficient housing exacerbates the inefficiency within the Saudi housing market (Fasiuddin and Budaiwi, 2011). According to recent surveys, the energy-efficiency level of KSA buildings remains poor, owing in part to difficulties in the implementation of standards and regulations (Krarti et al., 2017; Alrashed and Asif, 2015; Shenashen et al., 2016). Furthermore, current buildings still lack energy-efficiency measures, such as thermal insulation, and remain heavily dependent on air conditioning to provide a suitable indoor environment, a factor that contribute to the issue of high energy consumption (Taleb and Sharples, 2011). However, the current energy cost reforms may encourage the private sector and householders to invest in more energy-efficient systems to decrease their consumption and lower the operating cost for existing and new structures (Krarti et al., 2020).

The failure of most building design to take account of the prevailing climate means a majority of the building's energy consumption is dedicated to maintaining thermal comfort in the indoor environment. In addition, important factors such as the surrounding and site characteristics, building materials selection, architectural design, and orientation are still not given serious consideration (Ghabra et al., 2017). For example, concrete remains the primary building material, despite its poor thermal behaviour in hot conditions (Marzouk et al., 2014). This lack of regard leads to buildings with poor indoor climates, which has a negative impact on comfort, efficiency, and health (Madhumathi and Sundarraja, 2014). The main concern has been on whether these materials have a high thermal mass (Sinha et al., 2013). The effect of envelope depends on the thermophysical properties of materials which affect the rate of heat flow in and out of building, hence affect the indoor thermal conditions and comfort of occupants (Marzouk et al., 2014). These thermophysical properties of materials used in building industry in Saudi Arabia were not given serious attention. Moreover, investigating building materials and their related embedded energy has been an essential part in sustainable building development.

The construction industry, including architects, real estate developers, and construction firms, can be strongly encouraged to begin integrating sustainable and energy-efficient solutions into buildings if mandatory energy-efficiency regulations properly enforced. At present, only new buildings are covered by current national standards, which is why a mandatory regulatory framework is necessary in order to ensure that all buildings implement sustainable measures (Myrsalieva and Barghouth, 2015). This could constitute a strong driving force for the construction industry. Local municipalities are usually responsible for enforcing laws, they, however, often lack the financial and human resources (Ghabra, 2017). Professionals' skills, knowledge, and expertise will need to be upgraded in order to properly inspect and review site plans, design, construct, and renovate buildings in accordance with energy-efficient specifications. These capabilities are still lacking in most of the Gulf Region in general and Saudi Arabia in specific (Ghabra et al., 2017).

Another issue relates to the lack of available land for sustainable construction. The lack of property tax in Saudi Arabia, prior to 2016, could be the reason why large pieces of land can still be found in the inner suburbs of the city. This means that any party could acquire or occupy relatively large pieces of land regardless of its purpose or use. This stands in the way of development, and there has been an increase of more than 50% in the price of land in recent years (Al-Surf et al., 2014). As a result, while the cost of land generally constitutes one third of the cost of a building in Europe, it now makes up 50% of the cost in KSA (Fattah, 2013). This is why authors like Ferris-Lay (2011) argues that the cost of land is a leading constraint which makes it difficult for individuals and developers in Saudi Arabia to build affordable and sustainable housing.

Furthermore, the late enforcement of the implementation of SBC requirements to residential buildings construction projects has played a significant role to the issue of high energy consumption. The high levels of energy consumption in the residential sector work against the economic and environmental goals of Saudi's Vision 2030 (Nurunnabi, 2017). However, the benefits of energy efficiency remain largely untapped in the country due to a number of factors, including a lax enforcement of existing regulations, substantial energy subsidies, and a lack of financial mechanisms (Al-Homoud and Krarti, 2021). Embedding sustainability in the construction sector is an ambitious goal which calls for novel types of governance and processes of decision making, which bring together an array of stakeholders (Nurunnabi, 2017). In fact, government bodies and building professionals should pay more attention to the in-use stage in a sustainable way (Al-Surf et al., 2014).

3.6 Energy Policies and National Initiatives

The government of Saudi Arabia has made reducing building energy consumption a priority in order to reduce overall energy usage and refocus its economy away from oil dependency. As Al Surf (2014) notes that this provides a significant opportunity to reduce energy consumption in the building sector in general, by developing a sustainable industry in the hot climate of Saudi Arabia and taking urgent and serious steps. As Myrsalieva and Barghouth comment *"the most direct path to improving efficiency is likely through mandatory regulations and standards as opposed to behaviour changes which might take years or decades to make impact."* (2015, p.13). Accordingly, the government has established a number of organisations and programmes that support research and development in this area.

3.6.1 The Saudi Energy Efficiency Centre (SEEC)

As part of the Kingdom's efforts to improve the management and efficiency of electricity generation and consumption, a temporary three-year National Energy Efficiency Program (NEEP) was launched in

2003. NEEP ended in 2006, but, a year later, the Ministry of Petroleum and Mineral Resources, with the support of other government bodies, recommended that a permanent national entity should be established to build on previous experience and to sustain and unify energy-efficiency efforts under one roof. The Saudi Energy Efficiency Centre (SEEC) was established in 2010 as a result of this recommendation. Since then, SEEC has been in charge of the Kingdom's demand-side energy-efficiency efforts, with the goal of improving domestic energy efficiency and coordinating all related activities between government and non-governmental stakeholders (Oxford Energy Forum, 2014).

3.6.1.1 The Saudi Energy Efficiency Program (SEEP)

The Saudi Energy Efficiency Program (SEEP) was launched by SEEC in 2012 with the aim of increasing the Kingdom's energy efficiency through the design, support and implementation of initiatives and their enablers. The subcommittee responsible for the programme's scope focused on three main sectors: buildings, transportation, and industry, as they account for more than 90% of the national energy use, and five enablers: regulations, energy services companies, funding, governance, and awareness (Krarti et al., 2017). Data suggests that the programme is beginning to have an effect; despite the fact that the population and housing units continue to grow, energy use in the residential sector has decreased. Consumption in the sector stood at 130,428 GWh in 2018, a 10% reduction on the 144,513 GWh consumed in 2015 (Al-Homoud and Krarti, 2021).

3.6.2 The Ministry of Housing (MoH)

In 2007, the General Housing Authority was formed to boost home ownership, increase the supply of houses and residential land, and develop a comprehensive strategy for housing in the country. The MoH was established in 2011 in order to strengthen the government's role in housing policy and provision (MoMRA, 2016). Since then, the Ministry has been the biggest awarder of contracts, contracting both local and international contractors to construct affordable housing units across the Kingdom (USSBC, 2020). The aim was to build 2.32 million new residential units by 2020 to meet the needs of the growing population, and 33% were completed by January 2019 (Mujeebu and Alshamrani, 2016; Sakani, 2021; Alrashed and Asif, 2012). Furthermore, in 2018, a new building code (i.e., SBC602) was established and adopted in all housing projects of the MoH.

3.6.2.1 White Lands Tax Law

The MoH is also the implementing authority for the new White Lands Tax Law which was passed by the government in 2016. This imposes a 2.5% annual land tax on the value of land (MoMRA, 2019). As landowners have previously chosen to hoard property rather than develop it, the existence of so-called "white lands" has contributed significantly to the growing housing shortage, particularly for young people. The term "white lands" describes any vacant land located in 'populated areas': those zoned for residential or for dual residential and commercial use. The law has been developed to address this issue, and it is intended to alleviate housing shortages by increasing the supply of developed land, making residential land available at reasonable prices, and fighting monopolistic practices. Riyadh is one of the first three cities where the law will be put into action by the MoH.

3.6.3 The Nationally Determined Contributions (NDC) Initiative

A number of strategies have been introduced by the government to reduce CO_2 emissions and improve energy efficiency (AlFaraidy and Azzam, 2019). The Nationally Determined Contributions (NDC) initiative was proposed as a part of the government's plan to reduce carbon emissions in line with its commitments under The Paris Agreement (2015). It aims to achieve these by reforming energy and economic policies, accelerating economic diversification, and supporting policy adaptation (Wogan et al., 2019). The NDC's 2030 goal is to eliminate 130 million tons of CO_2 emissions by promoting energy efficiency and renewable energy technologies, starting by raising the cost of local fuel for industrial firms and encouraging them to use energy-efficient equipment (Krarti et al., 2017; Matar, 2016). In 1990, Saudi Arabia's carbon dioxide emissions were 172.85 million tons, increasing to 625 million tons in 2018, mainly from fossil fuel products and industrial operations (Tiseo, 2020). However, the country's carbon emissions from fossil fuels alone are now estimated to be around 118 million metric tons, according to the Carbon Dioxide Information Analysis Center and the United States Environmental Protection Agency (CDIAC, 2019; EPA, 2020). In fact, the cost of international utility fuel production is estimated to be $0.1678 per kWh, while the current Saudi government subsidies for electricity tariffs are around $0.048 per kWh, implying that $19.1 billion of $128.9 billion is spent on energy subsidies (AlHashmi et al., 2021). According to the Climate Action Tracker (CAT), the Saudi 2030 emissions reduction target is rated as "critically insufficient", both when compared to modelled emissions pathways and with its fair-share contribution to climate action (CAT, 2020). This indicates that the country's current policies and actions will not meet the Paris Agreement's 1.5°C temperature limit. In addition, Wogan et al. (2019) forecast that GHG emissions would rise by 70% above levels reported in 2015 based on current economic and energy policies, so the country will need to set a more ambitious targets and implement further policies to support them if it wishes to meet its international climate commitments (CAT, 2020).

3.6.4 National Renewable Energy Program (NREP)

The Climate Transparency Organisation (2018) reported that KSA had low performance in renewable energy power generation (almost 0% compared to the 24% with G20 countries). Previously, growth in the industry was hindered by institutional ambiguity and fragmentation (Yamada, 2016); however, Vision 2030 identifies renewable energy as one of the pillars of economic diversification away from oil, and a major step towards achieving Saudi Arabia's transformation goals was taken by launching, in 2017, a strategic initiative known as the National Renewable Energy Program (NREP) (Ministry of Energy, Industry and Mineral Resources of Saudi Arabia, 2019). The country is now investing in renewable energy plants, and, in early 2019, the government announced a new renewable energy target of 27.3 GW by 2023 and 57.8 GW by 2030 as part of its Vision 2030 strategy. These new targets are significantly higher than the previous ones, issued in 2016, which aimed for 9.5 GW by 2023. Progress to date has, however, been slow, with only about 0.4 GW of renewable energy capacity installed by 2019 (CAT, 2020).

Despite this slow rate of progress, Saudi Arabia has the potential to be a global leader in clean energy, especially at harvesting solar radiation (IEEFA, 2018). The solar sector is emerging as part of Saudi Arabia's economic diversification plans under Vision 2030, and the King Abdullah City for Atomic and Renewable Energy (KACARE) planned to add 4% of renewable energy to the national energy mix by 2020 (Jadwa, 2016). In line with the SEC's commitment to the Vision 2030 objectives of promoting renewable and sustainable energy to support the national economy and conserve natural resources, in 2019, ECRA introduced regulations that govern the integration of small-scale solar power systems into the national distribution grid (ECRA, 2019). Through these regulations, the authority aims to provide an environment that encourages consumers to install small photovoltaic systems, to determine the controls and provisions for linking these systems to the distribution grid, the regulatory requirements, and the financial considerations, including determining the net billing for surplus energy which is exported to the distribution system. The guidelines which accompany the regulations provide consumers with the necessary information and take care of their financial interests in relation to solar energy systems.

Mainly, the regulations identify two capacities for possible solar systems and offer a very affordable price to connect the system to the distribution grid in order to receive benefits from SEC. According to Yamada (2016), reduced production costs of solar panel have driven the launch of the solar industry in the Kingdom. The SEC now offers additional financial incentives by compensating eligible consumers for the surplus energy generated or exported by their installed systems. Table 3-9 sets out the cost of connecting a solar system to the power grid and the financial return paid to consumers in the residential sector (in USD/kWh).

Table 3-9: Financial consideration of small photovoltaic systems (ECRA, 2019)

Financial costs paid to distribution provider for Grid connection	
Solar System Capacity (kW)	**in (USD)**
≤50	*147*
≥50	*480*
Financial return paid to customers for surplus energy generated or exported by installed systems	
Category	**in (USD/kWh)**
Residential	*0.019*
Non residential	*0.013*

3.7 Summary

This chapter mainly provided an overview on Saudi Arabia's residential buildings stock and indicated the dire need for energy efficiency in those buildings to alleviate the high pressures posed on the national energy sector and the increasing demands for housing. Recently, the Saudi government issued new regulations and standards with the aim of decreasing the amount of energy used in the construction industry. However, even though initiatives and green building codes may be starting to make an impact in the Kingdom, issues such as the inefficient building design, loose regulation enforcement, and lack of appreciation toward the building regulations still persist and progress will be limited until there is a way of forcing developers to embrace them, either through financial incentives or tougher legislation. Sustainable measures should be applicable not only at the design stage of the building, but also during the in-use stage, the operation, and maintenance. Without immediate intervention and support from all stakeholders, the national power projections reflect a very alarming image of the country's future. The research methodology to ensure energy efficiency in residential buildings in Saudi Arabia will be described in the following chapter.

Chapter Four: Research Methodology

4.1 Introduction

Each research seeks to contribute to the body of knowledge within its field through study, survey, observation, experimentation, analysis, and evaluation (Saunders et al., 2009). Research, as defined by Saunders et al. (2009), is an organised and systematic way of finding out things, thereby increasing one's knowledge. The term "systematic" suggests that research is based on logical relationships, not just beliefs, and will involve an explanation of the methods used to gather the data, justify the results obtained, and clarify the limitations. The term ''finding out things'' suggests that a researcher will have a clear purpose or set of things to find out, such as an answer to a question or a solution to a particular problem (Saunders et al., 2009).

A good place to start is by defining and clarifying the main concept and terms concerning a research study. According to Johnson and Clark (2006), the development of knowledge and its nature are the focus of a research philosophy. Also, they explain that a researcher's philosophy relies on theoretical principles, important assumptions, and beliefs, which fundamentally affect the research process. The choice of research philosophy greatly depends on the research question(s) the researcher seeks to answer; however, as Saunders et al. (2009) note, it is rare for a particular set of research questions to fall neatly into only one philosophical domain. The research design can be described as the general plan of how you will go about answering your research questions. The term ''methodology'' refers to a way to systematically resolve the research problem, which considers the implications of all the approaches through which the research is to be undertaken, whereas the term ''method'' is simply the tools or techniques used to answer the research questions and collect data (Howell, 2013). Within one methodology, the researcher can apply several different methods to explore the research hypothesis. Similarly, a research method may involve the application of various research techniques. For example, a researcher can adopt a quantitative method using a questionnaire technique while another can employ interviewing as a part of a qualitative method (Howell, 2013).

This chapter presents the methodology adopted to meet the aim of this research. The overall structure is shown in Figure 4-1, and the sections which follow explain the research design, the methodology selected, and the specific methods and techniques used in this study. A justification for their selection is also provided. A flowchart is presented at the end of the chapter to provide a clear visualisation of the research process and the sequence of activities involved.

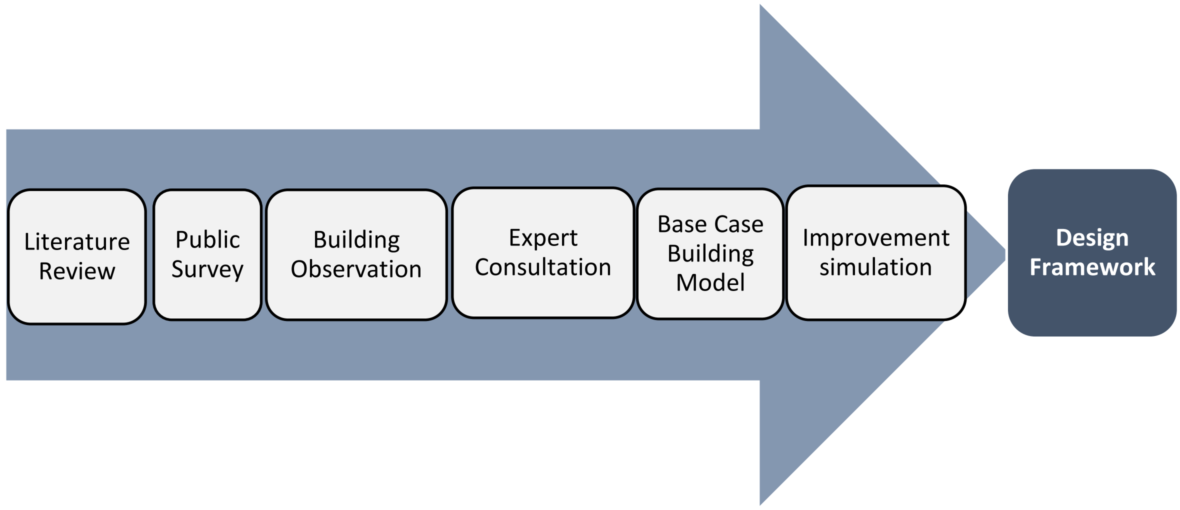


Figure 4-1: Methodology Structure (Created by the Author)

4.2 Research Design

The choice of research design is heavily dependent on the research questions and may be categorised into multiple stages to ensure that the main research aim and objectives are met (Johnson and Clark, 2006). The conceptual structure developed for this study involves four stages, each utilising a specific approach to address the research question and meet the specified objectives. These stages are summarised in Figure 4-2 and described in more detail below.

Stage One involved identifying the factors affecting the development of sustainable residential buildings in Saudi Arabia as well as the high energy consumption experienced in the residential sector. A public survey was employed and analysed to address this issue. Stage Two explored the physical factors influencing energy consumption in residential buildings and involved visiting and observing actual buildings. Therefore, this stage employed a case study approach to address some of the research questions and meet related objectives. During the third stage, experts in the construction industry in Saudi Arabia were consulted to investigate and evaluate the most effective and efficient design strategies with respect to Saudi Arabia's climate and cultural context. A list of potential strategies and solutions to address the factors identified in the previous stages was then created. The fourth stage involved a simulation process in which potential strategies were applied to a base case building in order to identify the most energy-efficient solutions. This was achieved by comparing the overall performance of the improved building models with the base model. Data gathered through this approach contributed to the development of a proposed energy-efficient framework for Saudi residential buildings.

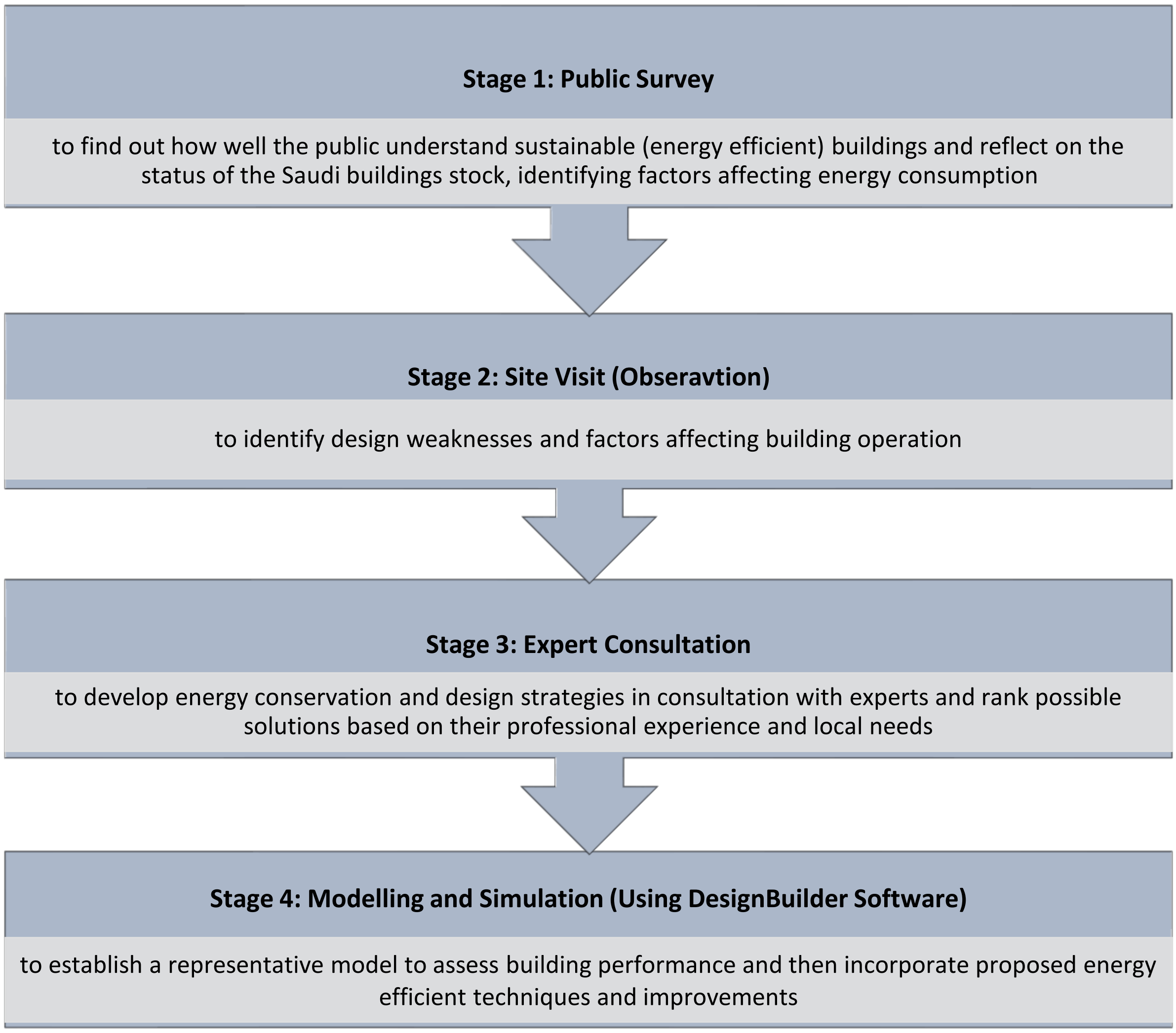


Figure 4-2: Methodology Stages (Created by the Author)

This study aims to identify the causes of high energy consumption in the Saudi residential sector and propose solutions to enhance building energy efficiency. This required an assessment of aspects such as average energy consumption, architectural style, and the socio-cultural barriers which hinder the development of sustainable residential buildings. In order to examine these different issues, a mixed methods approach was adopted, employing both quantitative and qualitative approaches to facilitate deeper analysis and provide a clear statistical picture of the current situation. Table 4-1 identifies the key differences between quantitative and qualitative research methods.

The combination of the two methods has been widely used amongst researchers and has proven to be fruitful in many different fields in which both lexical and numerical data are to be considered. According to Saunders et al. (2009), the term ''mixed method'' is commonly employed to denote a fusion of both qualitative and quantitative techniques for data collection and analysis which can be used either simultaneously or sequentially depending on the research questions. The mixed method enables the use and integration of diverse techniques and strategies in the data collection process such as questionnaires, interviews, observations, and experimentation (Johnson et al., 2007). The following sections describe and justify the methods employed in this study to answer the research questions.

Table 4-1: A comparison of qualitative and quantitative methods (Source: Ali, 2018)

Point of Comparison	Qualitative Method	Quantitative Method
Scientific Explanation	Inductive in nature	Deductive
Data Classification	Subjective	Objective
Purpose	to gain understanding of underlying reasons and motivations. To provide insight into the settings of a problem, generating ideas and/or hypothesis for later quantitative research. To uncover prevalent trends in thought and opinion.	To quantify data and generalise results from a sample to the population of interest. To measure the incidence of various views and options in a chosen sample.
Sample	Usually a small number of non-representative cases. Respondents are selected to fulfil a given quota or requirement.	Usually, a large number of cases representing the population of interest. It involves randomly selected respondents.
Data Collection	Observation, semi- and unstructured interviews, focus groups, conversation, and discourse analysis.	Structured interviews, self-administered questionnaires, experiments, and content or statistical analysis.
Data Analysis	Non-statistical	Statistical
Outcome	Explanatory and/or investigative. Findings are not conclusive and cannot be used to make generalisations.	Used to recommend a final course of action. Findings are conclusive and usually descriptive in nature.

4.3 Research Stages and Description

For the purpose of this research, two methods were utilised as an investigative approach:

- Public survey – to statistically identify the significant corroborating data (such as dwelling type, area, architectural style, consumption patterns, occupants' behaviours, public perception of sustainable buildings and the SBC, and socio-cultural barriers that hinder sustainable development of residential buildings).
- Physical building visit – to identify design weaknesses leading to poor energy performance which cannot be provided by the survey method. Aspects including architectural design weaknesses, potential issues with the building envelope design, and on-site sustainable energy integration strategies, if applicable, were observed through study of the building layout plans. The visit was also required to gather actual data on annual energy consumption.

Furthermore, the identification of the energy performance issues required the use of simulation software to model the base case building. Therefore, the physical observation of the selected representative building and the modelling process formed an essential part of this research. Once the energy consumption problems had been diagnosed, a framework for achieving an energy-efficient design of the residential buildings in Saudi Arabia was developed. This is presented in Chapter 7. To facilitate this process, two approaches were adopted to support the development of sustainable residential buildings:

- Consultations with experts to develop effective building strategies and solutions with due consideration to occupants' needs, cultural requirements, and the hot climate conditions.
- Model simulations to define an energy consumption level for the studied case and validate the proposed improvement strategies.

4.3.1 Stage One: Identification of Factors Influencing Energy Consumption in Saudi Arabia's Residential Sector – by Public Survey

In order to satisfy the needs and requirements of the Saudi population, it was essential to evaluate their level of knowledge concerning sustainability, energy conservation measures in residential buildings, and the economic and environmental importance of adopting low energy housing in Saudi Arabia. Also, in order to determine an average user profile for residential buildings, it was important to understand how occupants operate their residences. The barriers to the construction and adoption of energy-efficient buildings also needed to be identified, along with the factors that lead to such high energy consumption in this sector. Variables considered at this stage were related to architectural design, including size of building, average number of rooms per unit, HVAC system operation, and cultural practices which affect building design.

The survey method was chosen to gather data in order to evaluate the factors affecting residential energy consumption and analyse the public's overall perception of sustainable buildings. Surveys are the most common strategy used to collect data to determine precise estimations of the prevalence of significant factors (Huang, 2006; Aldossary, 2015). The survey, therefore, tends to be used for exploratory and descriptive research and is usually associated with the quantitative and deductive approach (Saunders et al, 2009). The following research objectives were addressed at this stage:

1. Identify the factors influencing energy use in the Saudi residential sector
2. Identify the level of public awareness and engagement with the principles of sustainable building
3. Identify the socio-cultural barriers that hinder the implementation of sustainable residential buildings and the application of energy-efficient technologies
4. Identify the level of policy and regulatory engagement in Saudi Arabia

4.3.1.1 Public Questionnaire Design

A comprehensive range of data linked to building design, site characteristics, socio-cultural issues, and public perceptions was sought in this survey. As a result, the questionnaire was the main technique used to conduct the public survey, which was designed and hosted online. The online distribution technique was selected as this is quicker and less costly than manually distributed surveys (Huang, 2006; Aldossary, 2015). The questionnaire targeted a broad research population, with a wide range of ages, levels of education, incomes, and regional locations, in order to obtain representative data and ensure a range of perspectives across Saudi Arabia were covered. To ensure a wide distribution and large scale coverage, the snowball sampling technique was employed. According to Saunders et al. (2009), snowball sampling, where one respondent passes it to another and so on, is commonly used when it is difficult to identify members of the desired population. Using this technique in the distribution process proved satisfactory as a total of 822 responses were received with a completion rate of 76 % (628 respondents).

According to Saunders et al. (2009), the design of the questionnaire affects both the response rate and the reliability and validity of the data collected. They suggest the following steps to ensure the maximum response rates, validity, and reliability (Saunders et al., 2009).

- Thoroughly planned and executed administration
- Individual questions to be designed carefully
- Questionnaire layout to be clear and pleasant
- Clear explanation of questionnaire purpose
- Pilot testing

This questionnaire was designed and hosted on a sophisticated web platform called SurveyMonkey. This web tool is now commonly used by professionals and researchers (Gordon, 2002) and was employed in this study for a number of reasons, namely: simplicity, ease of survey design and storage, variety of questions types, skip logic, answer choices, response collection, and the abilty to download and statistically analyse results.

The questionnaire consisted of 40 questions in total, divided into the following three sections:

- questions about demographic data and the main properties of the respondents' dwellings (Qs 1 -10)
- questions related to energy consumption patterns and occupants' behaviour (Qs 11-27)
- questions about respondents' perception of sustainable buildings and energy efficiency measures EEMs (Qs 28-40)

The questions were carefully developed to address the following aspects of the research:

- The main factors causing high energy consumption in residential dwellings
- Evaluating levels of reliance upon HVAC systems and operation patterns
- Exploring people’s perception of sustainability and willingness to invest in sustainable dwellings and technologies
- Identifying socio-cultural barriers affecting architectural design and the hindering development of sustainable residential buildings

The questions were designed to be easily understood and straightforward to answer to avoid guessing or estimation. Since the answers to the questions were either multiple choice options or selected from a list of possible responses, the normality test and related parameters were not considered as the answers may not be treated as continuous data. Before distribution, the questionnaire was piloted by selected group to gain helpful feedback, to ensure the context was clear to the public and the questions were easy to understand in order to avoid any misleading interpretation.

The average time for completing the survey was about 10-12 minutes. As Arabic is the national language in Saudi Arabia, the questions were written in both Arabic and English. The time-frame for gathering responses to the public survey was set to a maximum period of 40 days which was proved sufficient for the distribution and collection of questionnaire responses. Setting a limited time for this stage is justified by the time restrictions associated with doctoral study and the need for allowing time for conducting the other methods of this study. A copy of the questionnaire can be found in Appendix A, in Arabic and English languages.

4.3.2 Stage Two: Building Visit and Observation

In order to meet the aims of this research, it was necessary to seek information that could not be obtained through the public survey. As a result, the case study research method was also adopted in order to investigate specific phenomena in much greater detail and depth (Flyvbjerg, 2006; Ali, 2018). This was achieved by visiting an existing occupied residential dwelling, observing the building style and design, investigating energy consumption patterns, and collecting building data. The data collected in this way was used to identify architectural design weaknesses, building envelope design, and any on-site sustainable applications being used. It also provided an opportunity to identify occupants’ habits that may result in energy loss or high energy consumption. The findings and insights from this approach were used to ascertain the extent to which energy consumption in residential buildings in Saudi Arabia could be reduced in future. The main purpose of this stage was to address the following objectives:

1. Understanding how dwellings in Saudi Arabia are designed architecturally, the materials commonly used in their construction, and identifying any design weaknesses
2. Identifying energy consumption patterns in kWh/Year for typical residential houses in Saudi Arabia given the country's climatic conditions.
3. Identifying occupant behaviours and dwelling operations which negatively affect energy consumption.

4.3.2.1 Location and Selection of the Case Study Building

This study focuses on the prevailing climatic zone in Saudi Arabia, Zone 1 (See Figure 3-7), which comprises almost 60% of the total area of the country (SBC, 2019). The capital city, Riyadh, is located within Zone 1, and it has seen the highest rate of population growth and urban development in recent years. In addition, as the capital city, Riyadh is a high priority in the eyes of the Saudi government and is considered the origin of the Saudi 2030 Vision. For these reasons, Riyadh was selected as the location for the site visit and the base case model.

Criteria for the selection of the case study building included age of the building, built area, type of design, building typology, and availability of essential data. It had to be occupied to allow for data gathering on areas including building specifications, user profiles, and energy used. It also had to be a representative example that reflects the most popular type of residential buildings in KSA. Based on findings from the public survey in Stage One, a detached two-storeys building (i.e., villa) was selected. The building sample should reflect similar characteristics in relation to architectural design, total area, and construction materials used.

Therefore, data in this stage heavily rely on the examination of a building sample that tends to share some similar characteristics such as architectural design, total area, and construction materials used. This will be identified based on findings from the public survey (i.e. Stage One).

4.3.2.2 Data Collection

During the visit, information on the way the residence is operated throughout the year, the exact uses of the house, occupants' habits which affect energy usage, and cooling systems used were obtained. Occupant behaviour is a very significant factor affecting residential energy consumption and it was important for it to be considered at this stage. Data collection targeted the following items:

- Architectural layout and construction plan
- Annual and monthly electricity bills
- House occupant profiling (provided by the household)
- Relevant data for establishing a model of the building

A timescale was established to gather the required data within a limited timeframe to enable a base model building to be developed.

4.3.3 Stage Three: Expert Consultation

Stage One of the methodology aimed to determine the issues contributing to high energy consumption within the residential sector while the purpose of Stage Two was to evaluate the design and energy efficiency of current residential buildings. Stage Three involved consulting experts in order to seek their professional judgements and recommendations about design techniques and strategies to save energy and to reach a consensus about the most effective measures. Findings from previous stages were the foundations of this stage, and it provided important insights related to the research questions and objectives.

Expert consultation can be considered as an investigative tool for professional problem solving in fields such as engineering, the sustainable development industry, and policy making (Landeta and Barrutia, 2011). This approach has been found to be particularly useful in refining research ideas by the use of a specialised group of people who are interested in the research concept to generate or choose a more specific solution (Robson, 2002). It is an ethical and principal concern in a consultation study that the professionals involved must be anonymous in the preparation and conduct phases (Paliwoda, 1983; Okoli and Pawlowski, 2004; De Vet et al., 2005), and techniques to conduct online consultations which maintain confidentiality have now been established (Gnatzy et al., 2011). In this study, the participation of the expert panel was a vital element in the establishment of the proposed design framework for energy-efficient residential buildings in the Saudi context, and the consultation was conducted online to satisfy confidentiality requirements.

The aim of the expert panel consultation was to evaluate and rank a number of proposed design techniques based on the experts' professional assessment. The consultation was conducted via a survey that incorporated factors concerning architectural design strategies, building envelope design, and on-site renewable energy strategies for Saudi Arabia. The outputs of the consultation process were analysed using a quantitative descriptive method, such as distribution numbers and weighted averages. According to Bailie (2011), many statistical methods can be used if consensus has been achieved, such as interquartile range (IQR), the mean, and the standard deviation method. However, for ranking data, the mean and standard deviation may not be suitable to determine the overall ranking (Shash, 1993). Therefore, the weighted average method was employed to analyse the results.

4.3.3.1 Selection of Experts

The number and type of experts involved in the consultation method was an important element in the success of this study and in achieving the objective of reaching a consensus to inform the framework. Okoli and Pawlowski (2004) argue that it is crucial that the right experts are selected to ensure the success of any study employing such a technique. There is no consensus about the size of the panel in a consultation study. Some authors have recommended keeping the number of experts below 50, as the likelihood of error increases with the size of the panel (Witkin,1995; Aldossary, 2015). However, Clayton (1997) suggested that a range between 15 and 30 experts is an acceptable size, and others have recommended a range between 10 and 18 (Paliwoda, 1983; Okoli and Pawlowski, 2004). In this study, a panel of 33 experts completed the survey. It was essential for this study that the panel covered decision makers, academics, and professionals (Okoli and Pawlowski, 2004), all of whom had experience in the construction industry, with a focus on sustainability, regulations, the availability of raw materials, and challenges and barriers to energy-efficient building development (Aldossary, 2015). The participants were selected from a range of Saudi organisations and authorities, including MoMRA, MoH, engineering consultants, universities, and construction companies or suppliers. They had backgrounds in engineering, construction, and related fields, including architecture, and had between 10 – 32 years' experience (i.e. 19 years on average). The panel comprised decision makers (51.6%) (principally government representatives), private sector building industry professionals (36.4 %), and academics in the fields of building sustainability and energy efficiency (12%) (See Table 4-3).

Table 4-2: Composition of the expert panel (Created by the Author)

Category	Number	Description of Expertise
Decision Makers (Gov. representatives)	**17**	Decision makers working in the government sector, including ministries and planning and monitoring authorities, with experience in the building industry and sustainability. These experts included engineers in architectural, civil, environmental, electrical, mechanical, and construction sciences. Their responsibilities include planning, monitoring, and granting consents in line with local regulations.
Building Professionals	**12**	Experts in this category had a background in building regulations, energy conservation measures, and sustainable design and included engineering construction practitioners, contactors, suppliers, and consultants in building construction and sustainability. Their role lay in linking sustainable buildings with the availability of construction materials and market demands based on their experience working in different sectors.
Academics	**4**	Academics (PhD holders) with experience in the Saudi context and building energy and sustainability. Their role was to provide different perspectives compared with decision makers and suggest new ideas by transferring their knowledge of developed countries' building styles or techniques that might be suitable in the Kingdom. The selected academics were drawn from different universities across KSA to cover the variation of perspectives and suggestions based on regional climatic conditions.

4.3.3.2 Consultation Questionnaire Design

The survey was developed from existing knowledge acquired through the literature review and the findings of the previous stages (Bustamante et al., 2014, and Aldossary, 2015). Firstly, a questionnaire including various energy-efficiency techniques and design strategies was created. It was designed to enable the experts to add additional techniques and design strategies that were not initially covered. The experts were asked to consider the Saudi context and ensure that the techniques and strategies were suitable. As with the public questionnaire, this questionnaire was also designed in both languages, piloted, hosted using the SurveyMonkey platform, and distributed to the participants via an online link. The consultation questionnaire was divided into four main sections, covering architectural design strategies, building envelope fabric, on-site renewable energy techniques, and socio-cultural requirements and building related practices. A brief description of these sections is provided in Table 4-2 and a sample of the questionnaire is attached in Appendix B.

Table 4-3: Expert Survey Sections (Created by the Author)

Section	Type	Description
Architectural Design (*Qs 2-6*)	**Techniques and strategies**	Includes techniques and strategies related to building design, building shape, shading devices, and HVAC systems that aim to assists designers, architects, and civil engineers in designing sustainable buildings.
Building Envelope Fabric (*Qs 7-11*)		Includes techniques related to envelope elements, such as the design of external walls, roof, floor, and external glazing.
On-site Renewable Energy (*Qs 12*)		Introduces some energy-efficiency measures and techniques, such as PV.
Socio-cultural and Building Related Practices (*Qs 13-19*)	**Issues and suggestions**	Proposes solutions to some barriers that negatively influence the design and operation of residential buildings. Also, asks experts about key practices that greatly affect the building industry.

As the aim of the consultation was to reach a consensus regarding the most effective design strategies and techniques (von der Gracht, 2012), the five-point Likert Scale method was employed. The Likert Scale is a rating technique that allows a respondent to indicate the relative importance or significance of a statement, or how strongly she or he agrees or disagrees with it, usually on a numeric scale of between four to seven points (Dillman, 2007; Saunders et al., 2009). The use of this scale enabled conclusions to be drawn from the statistical results of the weighted average based on the five-point scale (Gnatzy et al., 2011). With the aid of the SurveyMonkey analysis tool, the weighted average of each option was calculated (expressed as a score) to rank options from the most preferred to the least preferred one. The idea behind this calculated score is that the top ranked option (1) is given a weight of 5 while the bottom one (ranked 5) is given a weight of 1. For each criterion, the rating average was measured according to the following formula.

$$Weighted\ Average = \frac{x_1 w_1 + x_2 w_2 + x_3 w_3 \dots x_n w_n}{total} \qquad Equation\ (4-1)$$

Where **w** = weight of answer choice
x = number of responses to the answer choice
n= number of choices considered

The experts were also asked to suggest further design strategies and techniques suitable for the Saudi climate and culture that were not covered in the questionnaire. The objective of this was to assess the value of existing design strategies whilst adding new ones based on their perspectives and experience. The outcomes of this stage informed the development of the design framework for sustainable buildings in Saudi Arabia presented in Chapter 7.

4.3.4 Stage Four: Modelling and Simulation

The final stage focused on establishing a representative model of a typical dwelling in Saudi Arabia, assessing its building performance, and then incorporating the proposed energy-efficiency techniques and improvements. Simulations were then run to assess their effectiveness, and the outcomes were used to inform the final framework. Validation of the base case model was also performed by comparing the actual energy consumption data collected with the simulated results from the model. A detailed parametric analysis of the representative model was used to determine the effect of various design and operating measures on total annual energy consumption and thermal performance. The improvements made to the base model were documented based on selected parameters, which were analysed, individually and as a whole set, in order to assess their impact on total energy consumption. For the purposes of this study, the simulation parameters (also called variables) were categorised into Design-related and Operating-related parameters. These are set out in Table 4-4 and explained in more detail in Chapter 7.

Table 4-4: Parameters to consider in the simulations (Created by the Author)

Parameters	
Design- Related	External Wall Construction
	Flat Roof Construction
	WWR
	Glazing Type
	Local Shading
	Airtightness
Operating-Related	Cooling Setpoint Temperature
	AC CoP

The parameters included in the framework were tested to ensure their validity by the use of computer-based simulation tool to ensure that overall energy efficiency goals were achieved. This study ran five simulations, referred to as Simulation 1– Simulation 5 (i.e. the final improved model), to discover the effects of the different variables on building performance. As a part of testing the proposed performance improvements, the requirements for thermal insulation in local authority codes (SBC602 and SEC), which consider the thermal characteristics of building envelope members (wall, roofs, and glazing), were highlighted. In order to draw meaningful conclusions, the sample building was studied under the following four scenarios:

- Not insulated (existing and relatively old buildings i.e., Base Case)
- It complies with the SEC construction specifications
- It fulfils the SBC-602 thermal insulation requirements
- It applies those thermal parameters within the improved case scenario

For the purpose of this study, a setpoint temperature of 20°C was selected to be applied in all scenarios for comparison. The 20°C cooling set point was given by the householder as the frequent base temperature. This is in accordance with other studies that have also selected 20°C as the base line setpoint temperature for their simulation analysis (Alshahrani, 2018; and Alrashed, 2015). Given these justifications, the study adopted 20°C for the study. Furthermore, benchmarking of the annual energy consumption (per unit area) and the carbon emissions of the base case and the improved cases against results obtained by other researchers was performed. Further details about the methods applied is provided in Chapter 7.

4.3.4.1 Selecting the Modelling Software (DesignBuilder)

To model, simulate, and analyse a particular case study using a software tool, it is important to consider the following elements (Ogunrin, 2019):

- Architectural design of the building (form)
- Building envelope (fabric)
- Local climatic conditions
- Occupants' behaviour

DesignBuilder (DB) is a popular, widely available software tool used for modelling and simulating energy-efficient and comfortable building designs, which has been developed to run EnergyPlus simulations on virtual building models (Olaniyann et al, 2013). Numerous studies have highlighted its validity and suitability with regards to building performance studies (Andarini, 2014, Olaniyann et al, 2013, Nowak-Dzieszko and Rojewska-Warchal 2013), including comparative reviews of BPS tools presented previously in Chapter 2 section 2.4. In addition, the following attributes contributed to the selection of DB as the most appropriate tool for modelling and simulating the base case building in this study:

- DB is a user-interface to EnergyPlus which is arguably the most sophisticated simulation software tool available. It has been used by United States Department of Energy.
- DB is more cost effective than other tools, such as IES-VE.
- DB has a good local support and accessible training materials. Beginners and students can learn DB faster than comparable tools.
- DB provides advanced modelling tools in an easy-to-use interface.
- DB's unique data management system enables users to input the most common data at the site, building, block, zone, or surface levels, so that it is then automatically set for all attributes in the levels below that. This significantly reduces the amount of data input and contributes to reducing modelling time and the risk of data input errors.
- DB enables optimisation of renewable energy systems for building energy performance improvements.
- DB has useful built-in features that facilitate energy performance comparisons and detailed modelling of building systems.

DB models are organised in a simple hierarchy. Default data is inherited from the level above in the hierarchy, so, for example, block data is inherited from the building level, zone data is inherited from block data, and surface data from zone data (See Figure 4-3). However, it is possible to change the inherited defaults in any of these levels by selecting and editing the desired input (DesignBuilder, 2020).

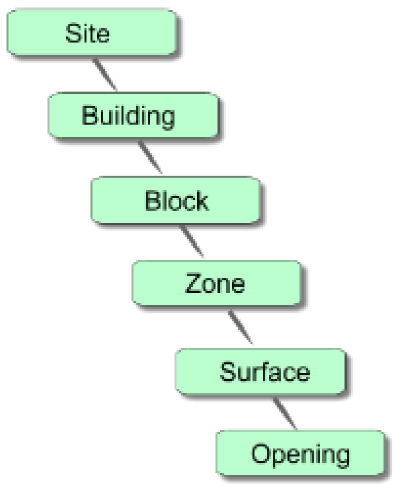


Figure 4-3: Data input hierarchy in DB (Source: DesignBuilder, 2020)

4.3.4.2 Modelling the Base Building

The modelling of the representative building was performed in two phases:

1. **Phase One (Base Case)**

Phase one involved the modelling of the case building using the original layout drawings and plans to construct a three-dimensional model with the aid of DB software. A comparison between the actual electricity bills and the simulated energy consumption was made for the validation of the model. The inputs of each model relied on details such as design features, area of each room and window, the overall orientation of the building, and the materials used for the building envelope. The simulation process was prepared in such a way as to yield periodic energy consumption rates, climate data, and energy consumption for each separate room, as well as to describe the conditions that resulted in energy consumption peaks. The analysis of this phase is presented in Chapter 6.

2. **Phase Two (Improved Case)**

The second phase was carried out to identify energy solutions and address the design weaknesses identified during previous stages of this study, taking into account the SBC criteria and the local context. This phase was also intended to assess the efficiency of the SBC in respect of energy conservation in residential buildings (SBC602) and to validate the improvement parameters which were incorporated into the final framework in terms of the potential energy savings. Therefore, re-simulations of the base case model were performed to assess the potential reduction in energy consumption and to compare the final energy consumption (in kWh/m^2) with previous rates. This phase was conducted based on the findings from the public survey, the building observation, and the recommendations of the expert panel. The analysis of this phase is presented in Chapter 7.

4.3.4.3 Constructing the Model

In order to simulate the thermal and energy performance of a house using DB software, the model parameters must be defined. These describe the physical characteristics of the house (including plan and geometry), construction data, installed equipment or appliances, building purpose and occupancy behaviour, and geographical location and climate (Alshahrani, 2018). In this regard, assumptions were made in order to obtain modelled energy consumption close to the measured values. These assumptions included:

- Ignoring shading from the surrounding homes
- Assuming the air flow was constant at 1 air-change per hour (ac/h) when occupied
- Assuming windows and door were closed. The weather in Saudi Arabia generally is very hot almost from February to November and clouds/rains are intermittently experienced. Cooler air temperatures are only experienced in mountainous southern regions which represent a very small area of the country and out of the study's selected zone. Even though, windows are kept closed to maintain privacy which was identified as a cultural barrier.

- Assuming home was occupied all year round. This is an assumption which can be realistic for Saudi locals living in Riyadh as they reside the house all year and not to leave for reasons such as long holidays. The common culture is that the man of the house is the only one responsible for the providing.

The model was constructed through a four-stage process, beginning with the input of data about the model site (e.g. location and climate), then the definition of the geometrical parameters of the model (e.g. building shape and orientation), the building model data (e.g. construction and openings), and finally, the energy consumption profile (e.g. occupants' behaviour and energy consumption). These stages are explained in more detail below.

1. Definition of the Model Site Data

Model data for the site can be inputted and edited at the site level via the location and region tabs. Under the location tab, site location (country, major city), weather data, daylight savings and energy codes may be specified. The input data for location and climate used for the simulation is given in Table 4-5.

Table 4-5: Data input for location and climate (Source: DesignBuilder- Author's model)

	Value
Program Version and Build	EnergyPlus, Version 8.9.0-40101eaafd, YMD=2021.02.25 00:06
RunPeriod	UNTITLED (01-01:31-12)
Weather File	RIYADH - SAU IWEC Data WMO#=404380
Latitude [deg]	24.70
Longitude [deg]	46.80
Elevation [m]	612.00
Time Zone	3.00
North Axis Angle [deg]	0.00
Rotation for Appendix G [deg]	0.00
Hours Simulated [hrs]	8760.00

2. Definition of the Model Geometrical Parameters

The geometry is described in terms of building shape, orientation, size and types of rooms, and the dimensions of the openings (such as doors and windows). The model takes shape at this stage. Mainly, these data were obtained from the building's visit and observation stage.

3. Definition of the Model Building Data

The building model data can be inputted and edited at the following levels: block (parts of the superstructure), zone (interior spaces), and surface (construction details). The data is organised under the following principal tabs:

Activity: The activity tab provides the ability to input or edit information about how interior space is used. It also includes data for zoning type, occupancy, metabolic rates, domestic hot water (DHW), heat gains through environmental settings, computers, office equipment, processes, catering, operation schedules, and other related uses. During the building visit and observation stage, occupancy data (i.e. number of users, use of appliances, and time of occupancy) were gathered which can affect simulation results.

Construction: The construction tab looks at the properties of the structure and the materials used, such as those for internal and external walls and roofs, and other parts of the building envelope, such as shading and glazing. Users are able to select from a dropdown list of assemblies and a library that allows them to create their own custom assembly along with construction details. The construction tab provides users with the ability to choose components of roofs, walls, floors, surfaces, and opaque building fabric. Every component or assembly is modelled in layers, and each layer is created with editable parameters, such as thermal characteristics and properties. The input data for the case study building were gathered during the visit and observation stage.

Openings: The openings tab is used for selecting windows, vents, doors, holes, and sub-surfaces in the building fabric. The types of openings related to the façade can also be determined when choosing an appropriate façade type. Information concerning the dimensions of internal and external windows can also be selected, including glaze and frame type, shading, and the mode of operations. Input data were provided by the householder.

Lighting: Simulation settings for the lighting are controlled through the lighting tab. Templates are provided to select what load model is desired for the lighting features. Lighting can also be edited by inserting power intensity and selecting luminaire (fixture) types such as surface mounted, recess lighting, or suspended lighting choices. The Lighting type used in the base case building was an LED lighting system with surface mounted fixture.

HVAC: The HVAC tab allows information to be inputted concerning mechanical and natural ventilation, cooling, heating, DHW, humidity control, air temperature distribution, mixed modes, and cost headers. It also provides users with the ability to select heating, humidification, cooling, dehumidification, ventilation, and cycles that can be simulated. The type of HVAC options are EnergyPlus based HVAC modelling and DB allows a detailed HVAC system model view without the need to draw, map out, or control air flow networks systems and node connections.

Outputs: Output data of the design calculations and simulations are controllable under the output tab. There are three output headers. These are design output options for heating, cooling, and simulation. The simulations output header enables users to select the model elements for what output data will be created. Users can select and view the information concerning building zones, blocks, or graphable outputs such as heat transfer, and temperature levels. Periodic reports, such as annual and monthly, can also be generated; these provide a detailed assessment of a number of different parts of the performance of the building to create different simulation variables.

4. Definition of the Energy Consumption Profile

This step defined the result gained from the occupants' behaviour profile, the energy consumption deriving from activities within the house, the schedule of each room as it relates to the usage of appliances, and occupant behaviour when it comes to the air-conditioning system. The calculations of energy consumption were based on real climate data, details concerning type of AC systems, operational methods, as well as the heat gain from equipment use, lighting, occupants, and other profiles. The energy consumption profiles can be created for a chosen period of one single day, or up to one year (Al Shamsi, 2017).

Regarding space allocation, previous literature and survey findings confirmed that a typical Saudi home may be divided into four zones: kitchen, living, guest, and sleeping zones (Monawar, 2001; Alrashed, 2015) . As the power density and heat gain associated with the occupants in these zones vary due to the different functions and activities in each, people heat gain was calculated for each space according to ASHRAE fundamentals (2009). The power densities (in Watt/m^2) for each zone were obtained from a survey on Saudi households conducted by Monawar (2001). The data used for each zone is presented in Table 4-6.

Table 4-6: Data for people heat gains and power densities for the main zones in a typical home in KSA (Source: Monawar, 2001)

Zone	**Sensible Heat (*Watt/person*)**	**Latent Heat (*Watt/person*)**	**Power Density (*Watt/m^2*)**
Living zone	65	30	5
Guest zones	65	30	7
Kitchen zone	80	80	30
Sleeping zone	40	30	7

Internal gains related to equipment and cooking were estimated based on the averages provided by the ASHRAE handbook (2013). These appliances were linked to the occupancy profiles of each space in the building to give a good estimation of an average consumption value. However, it was not possible to link appliances that run on a consistent basis, such as refrigerators, under the occupancy profiles. Therefore, in the absence of complete appliance usage data, overall consumption pattern assumptions were required. Due to the tendency of energy consumption by cooling and heating being influenced by the thermal performance in a building envelope, it is important to differentiate between U-values for materials (such as glass), assemblies (such as windows, which can have frames, air gaps, and others), or elements (such as walls), which may have complex constructions comprising a number of different components. The user profile is presented in Chapter 6- Table 6-4. The schedules of operation were inserted into DesignBuilder interface for the model based on the base case householder's information.

4.4 Methodology Flow Chart

The flow chart of the implementation of the methodology described in this chapter is given in Figure 4-5.

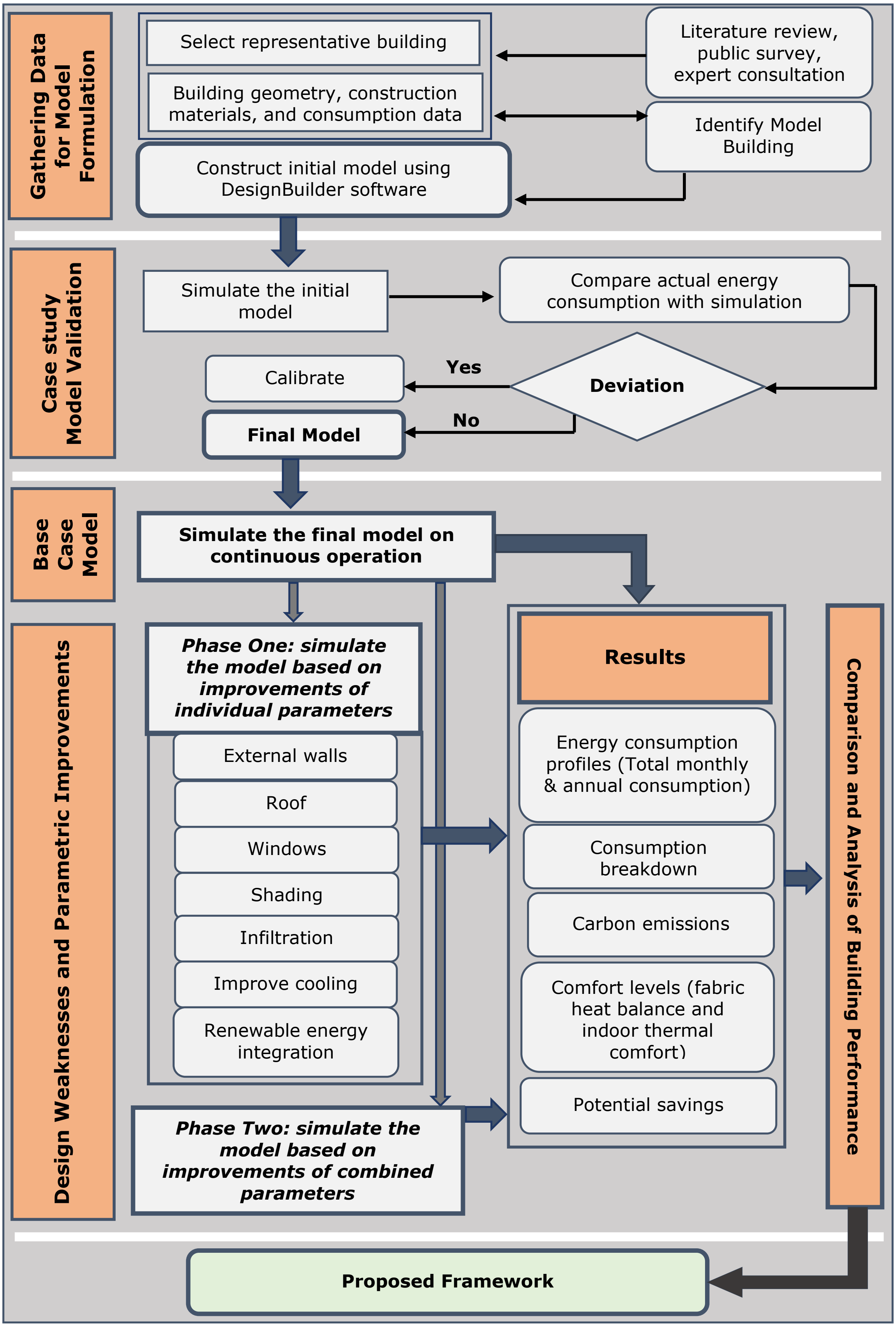


Figure 4-5: Methodology flowchart

4.5 Summary

The four stages of the methodology chapter were designed to ensure that the main aim and objectives can be reached. Each stage, as presented in the flowchart above, utilises specific methods to address particular research questions. This study will use the mixed method approach through the involvement of selected techniques such as public survey, existing buildings visit, experts consultation, and proposing and validating a low energy design framework for residential buildings in Saudi Arabia through the use of DesignBuilder simulation tool. The next chapter presents and discusses the results for the public survey and experts' consultation.

Chapter Five: Public Survey and Experts Consultation

5.1 Introduction

This chapter provides analysis of the results of the public survey and the questionnaire distributed to the expert panel. In relation to the public survey, it begins by identifying the respondents' demographics and the characteristics of their buildings, before going on to explore their behaviour and energy consumption patterns, then assessing their perceptions of sustainability within the residential sector ad their willingness to adopt EEMs. The chapter then turns to the results from the experts' survey (also called consultation) and considers four main themes, architectural design, envelope design, on-site renewable energy, and building applications and practices, before presenting the expert panel's professional recommendations and strategies to energy efficiency consideration within the sector. This is followed by a comprehensive discussion and interpretation of the main findings, focusing on public perceptions and willingness regarding sustainable construction, the factors causing high energy consumption in residential buildings, the barriers preventing the development of energy-efficient dwellings, and the need for greater stakeholder engagement. The chapter concludes by discussing the experts' key recommendations in relation to existing literature and the climate and socio-cultural features in Saudi Arabia.

5.2 Public Survey Results

The aim of the public survey was to explore residents' perceptions of sustainable homes within Saudi Arabia, a developing country known for its high energy consumption and CO_2 emission rates. 822 responses were obtained in total, with a completion rate of 76% (628 respondents). The following sections present the responses received in each part of the survey, beginning with demographic data.

5.2.1 Respondents' Demographics and Building Characteristics

The first part of the survey asked respondents to provide demographic data, including their age, gender, education level, and in which region of the country they were located (See Table 5-1).

Table 5-1: Demographics of the Respondents

Age	%	Gender	%	Education Level	%	Location	%
18-24	9.4	Male	76.4	Secondary or below	11	Central Region	29.8
25-34	36.6			Diploma	14.0	Eastern Reg.	13.9
35-44	34.2	Female	22.8	Bachelor	49.8	Western Reg.	21.2
45-54	12.1			Postgrad (Masters or PhD)	25.2	Northern Reg.	9.4
55+	7.6	Prefer not to say	0.8			Southern Reg.	25.8

As shown in Table 5-1, nearly 71% of respondents were aged between 25-44 years. In term of distribution, the highest percentages of respondents were in the central and southern regions, 30% and 26% respectively. Almost half of the respondents had a bachelors qualification, and just over 25% had a masters' degree or a PhD. More than 76% of participants were male, while fewer than 23% were female. This is due to cultural barriers in Saudi society which make it challenging for male researchers to approach females. This meant that the survey was initially distributed to male acquaintances of the researcher, and, as snowball sampling was used, the male participation rate increased further.

The next questions asked about the main properties of the respondents' dwellings, as building characteristics such as type, size, and number of occupants are considered to play a role in energy consumption and building performance. The responses are shown in Figure 5-1.

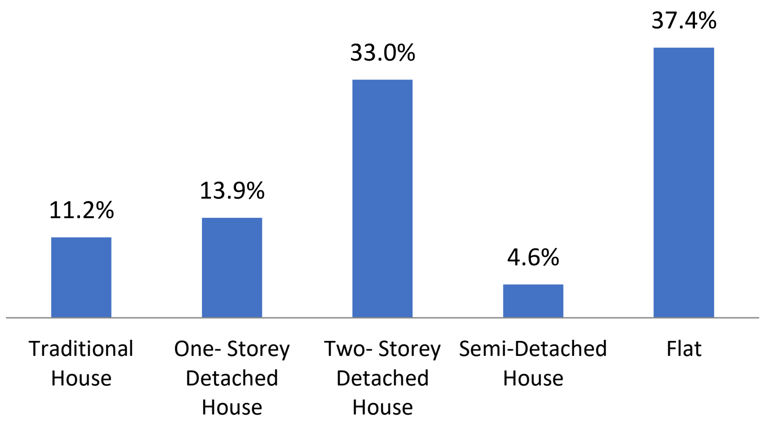


Figure 5-1: Respondents' dwelling type

The dominant types of dwelling were flat (37%) and two-storey detached house (33%). However, for the purposes of this study, only detached two-storey dwellings will be considered, as the study aims to identify energy efficiency solutions which can be applied to whole buildings. Flats are commonly located in large buildings made up of many units, often developed for investment purposes, and identifying energy-efficient solutions for this type of building is beyond the scope of this study.

Respondents were also asked whether they were responsible for paying utility bills (See Figure 5-2).

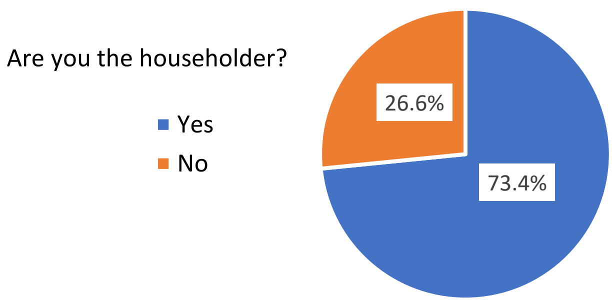


Figure 5-2: Respondents who are responsible for paying house bills

Just over 73% of respondents indicated that they were responsible for bill payments. This might contribute to more accurate answers to questions about dwelling properties and energy consumption.

Respondents were also asked about the age and overall size of their home. As illustrated in Figure 5-3, almost half of respondents (46%) live in old buildings (over 10 years), almost 31% in homes considered recently built (from 5 - 10 years), and less than 23% in new houses (less than 5 years old).

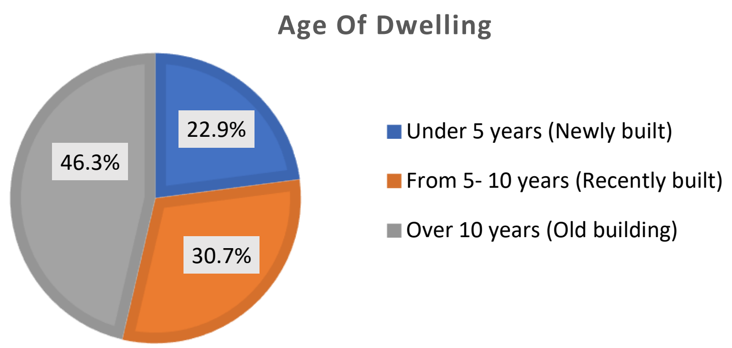


Figure 5-3: Age of respondents' dwellings

In terms of overall size, just over half of respondents (57%) live in properties which cover between 150 m^2 to 500 m^2. Fewer than 10% live in properties over 700 m^2 (See Figure 5-4).

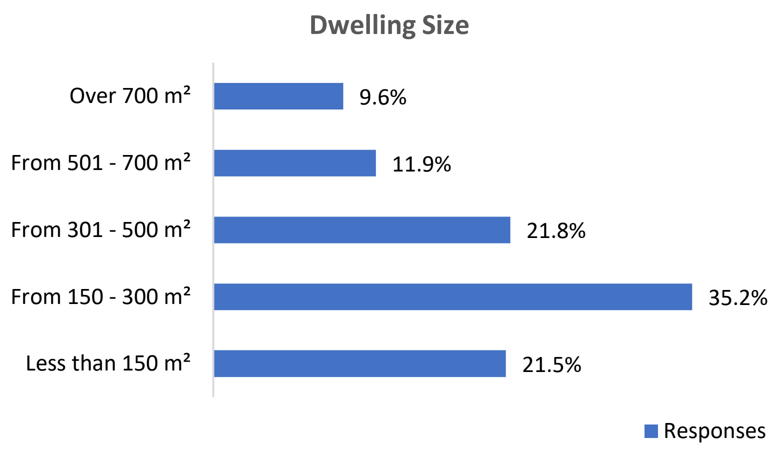


Figure 5-4: Built area of respondents' dwellings

The next questions asked respondents how many members lived in their home and how many bedrooms they had. The responses are shown in Figure 5-5 and Figure 5-6.

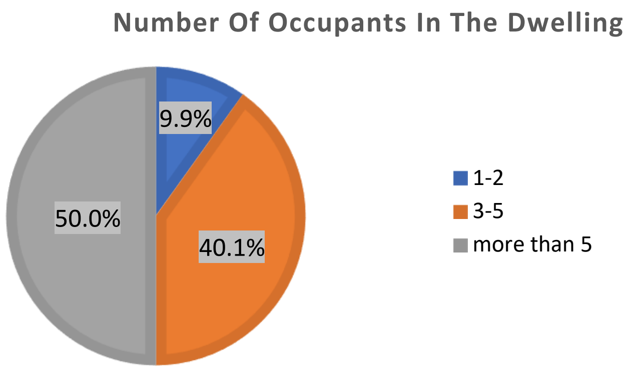


Figure 5-5: Number of occupants in respondents' dwellings

Saudi society is known for having medium to large family sizes, and, as Figure 5-5 demonstrates, 50% of respondents have more than five family members living at home, while families of 3-5 members represent another 40%.

As might be expected in light of Figure 5-5, nearly one third of respondents have five or more bedrooms in their houses, with just over 5% having only one bedroom (See Figure 5-6).

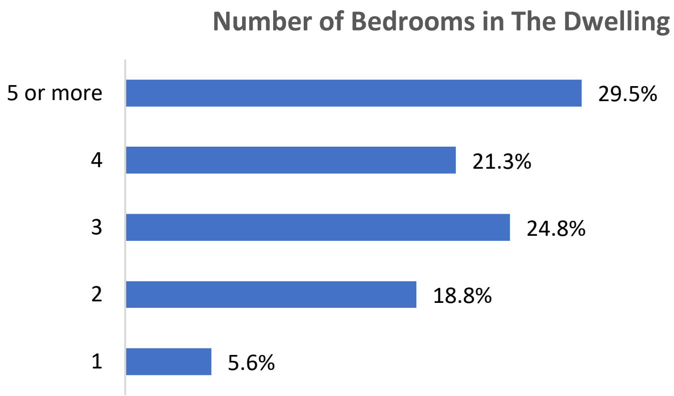


Figure 5-6: Number of bedrooms in respondents' dwellings

5.2.2 Energy Consumption Patterns and Occupants' Behaviour

In this section, respondents were asked about their monthly electricity bills in order to explore their levels of energy use and awareness of energy costs. The first question asked if they knew the amount of their monthly electricity bill (See Figure 5-7).

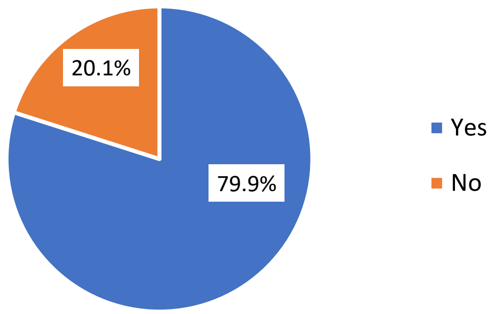


Figure 5-7: Percentage of respondents who knew the cost of their monthly electricity bill

About 80 % of respondents knew how much their monthly electricity consumption cost. This response is slightly higher than the proportion of respondents who said they were responsible for paying household bills (73%), suggesting that awareness of energy costs extends beyond the bill payer. Overall, this indicates that the majority of respondents are well informed about the cost of electricity.

Respondents were then asked to enter the amount of their average monthly electricity bill and to specify whether they thought this was 'low', 'reasonable' or 'high' when compared with their income. The mean value entered was 743.45 SAR (198 USD), and nearly 53 % of respondents considered the cost of the electricity required to operate their homes was high (See Figure 5-8). This finding indicates the need for energy efficiency measures in the residential sector in KSA.

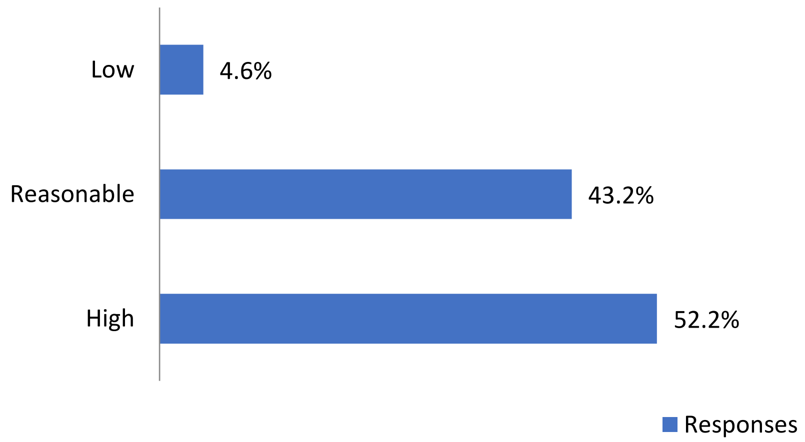


Figure 5-8: Respondents' views of the cost of their bills in relation to their income

Two questions explored house occupancy during weekdays and at weekends, excluding sleep hours. For the purposes of these questions, sleep hours were assumed to be 8 hours. The first question asked how many hours a day the house was occupied by family members during weekdays (Sunday to Thursday). The results are shown in Figure 5-9.

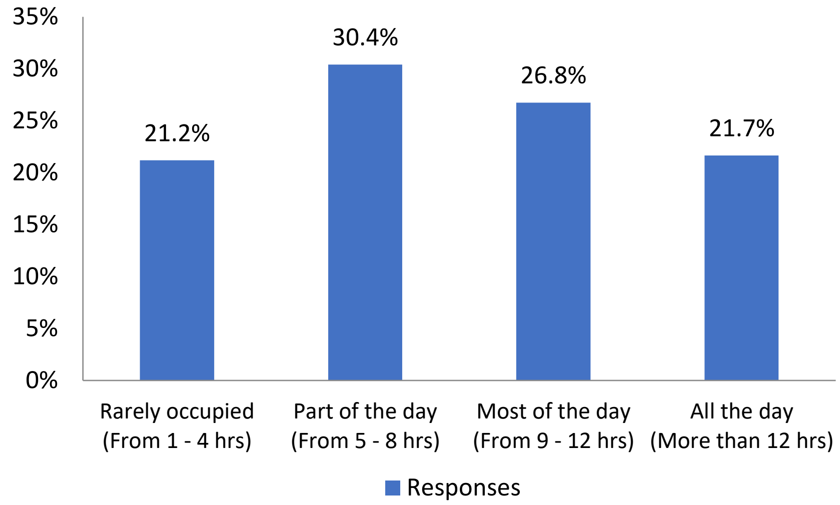


Figure 5-9: House occupancy during weekdays

As Figure 5-9 illustrates, the largest proportion of respondents (30%) indicated that their house was occupied between 5-8 hours per day. This can be attributed to commitments to school and/or work during normal working days. However, just under 50% reported that their home was occupied most or all of the day. In Saudi culture, it is to some extent common perception that providing for the family is the male's responsibility so that the wife stays at home to take care of the house rather than working outside the home, and this socio-cultural aspect appears to be reflected in this finding.

The occupancy patterns at the weekends follow a similar trend to weekdays profile, when people tend to go out for recreational purposes or visiting relatives. As Figure 5-10 shows, almost 61% of respondents reported that their house was occupied for part or most of the day, i.e. from 5 to 12 hours.

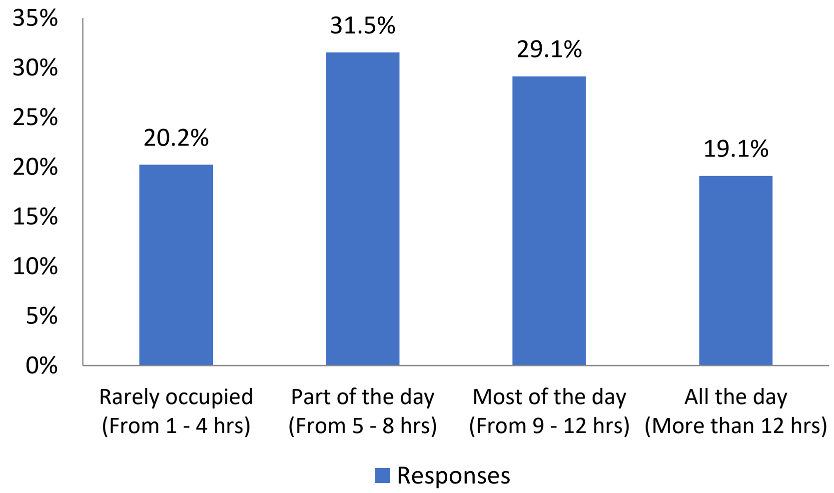


Figure 5-10: House occupancy during weekends

The next question asked respondents which of the appliances in the house consumed the most electricity. The results are provided in Figure 5-11.

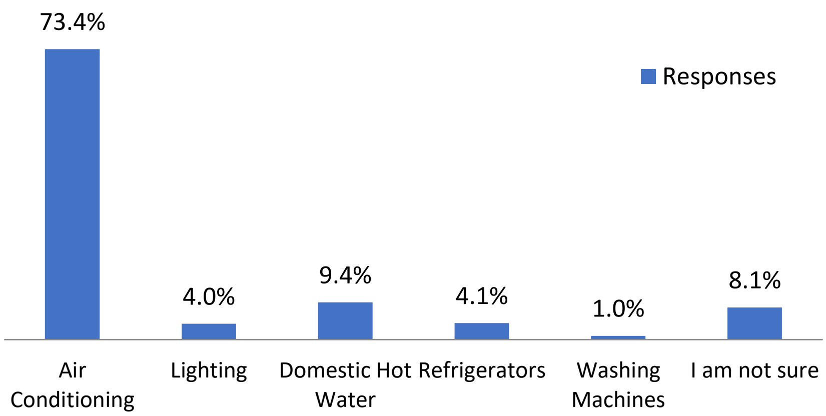


Figure 5-11: Respondents' views of the most energy-consuming household appliances

As Figure 5-11 demonstrates, the majority of respondents (73%) knew which appliances placed most pressure on operational energy demand. A justification for obtaining this information by the participants could the tendency of operating AC systems continuously due to harsh weather experienced in the KSA, and the number of ACs found in each housing unit, which was found to be 5 units, on average for a single dwelling. This is a positive sign; however, it does not necessarily mean that they also know about sustainability or house efficiency.

In order to explore the use of AC within residential settings, the next question asked respondents about the type of cooling system used in their homes. As Figure 5-12 shows, the vast majority of respondents (86 %) use air conditioning to cool their houses. This is no surprise given the climate in KSA where the average ambient temperature in summer is 45°C.

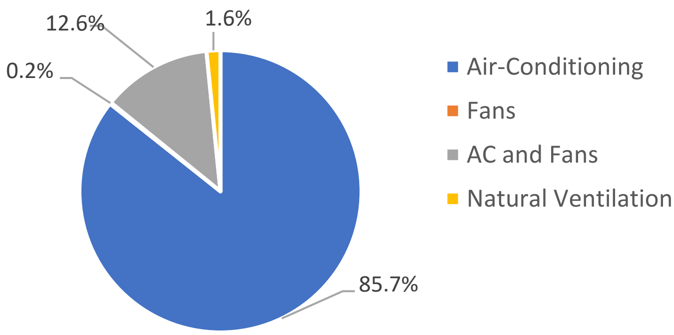


Figure 5-12: Types of cooling systems used in respondents' dwellings

The weather of the KSA generally consists of 2 seasons – winter (Dec-Feb) and summer (Mar- Nov). Hot temperatures are experienced almost all year. However, extreme summer conditions are experienced form April to Oct. Hence, the main focus of this study is the summer conditions. The following questions asked about the type of AC system installed, the rooms in which AC usage was highest, and the frequency of AC operation during the summer. The results are shown in Figure 5-13, Figure 5-14, and Figure 5-15 below.

As Figure 5-13 illustrates, the most common types of air conditioning are window AC (32.2%) and split AC (29.5%), or a combination of both (32.6%). As the results suggest, these types can be operated separately or in combination, and both appear to be popular in housing across the KSA.

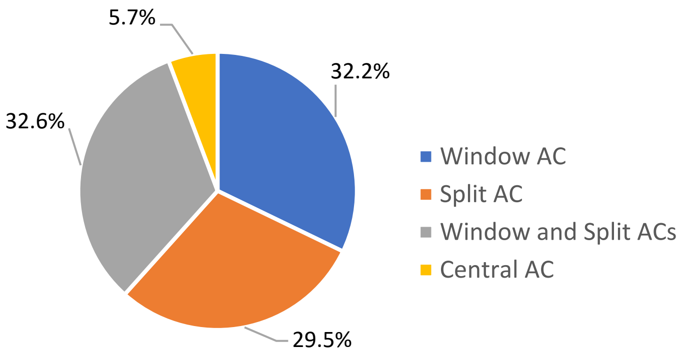


Figure 5-13: Types of AC used in respondents' dwellings

In terms of the rooms which created the heaviest demand on AC operations, 74% of respondents identified both bedrooms and sitting rooms (as shown in Figure 5-14). Only 1% identified guest rooms. This may reflect the fact that guest rooms are typically only used to accommodate overnight guests and may only be needed once or twice a month in most cases.

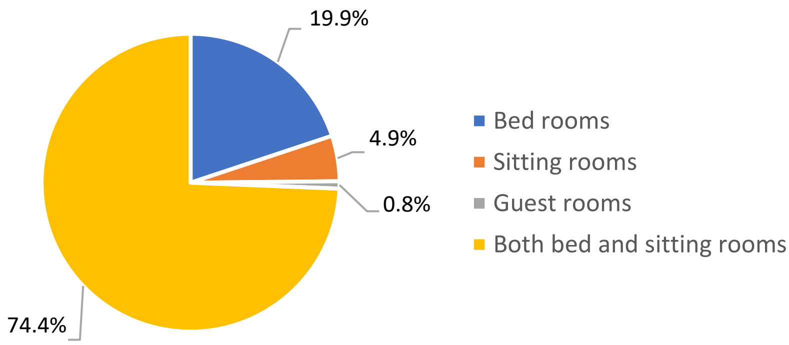


Figure 5-14: Rooms of high AC operation

As Figure 5-15 demonstrates, 90% of respondents reported using air conditioning between 10 to 24 hours a day in summer seasons (both day and night times). This reflects the very hot climate conditions in KSA during the summer months.

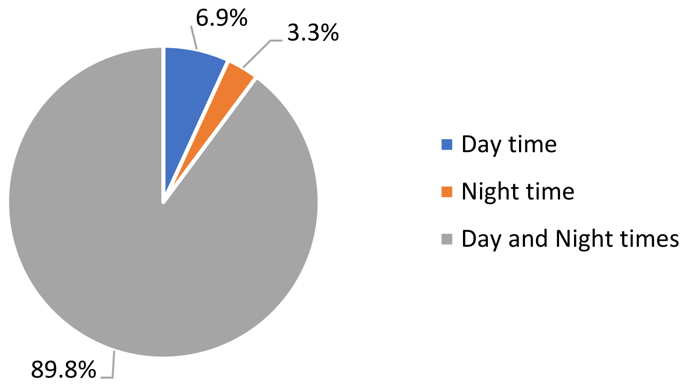


Figure 5-15: Frequency of AC operation during Summer

As one of the objectives of this survey was to conceptualise occupants' behaviour and energy awareness, the next set of questions explored respondents' behaviour in relation to cooling and lighting their homes. Respondents were first asked what they do if they feel cold during AC operation, and their responses are depicted in Figure 5-16. More than half of respondents reported that they lower the AC cooling setting and 39% turn it off.

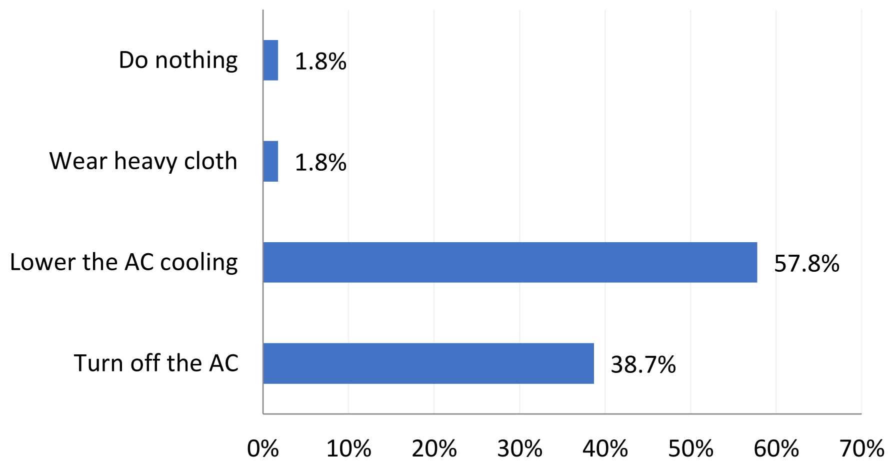


Figure 5-16: Occupants' reactions when feeling cold during AC operation

Respondents were then asked if they turn off the AC when leaving the house or the room. As Figure 5-17 indicates, 88% reported that they always do this, with a further 11% saying they sometimes do so. A follow-up question then asked respondents why they turned the AC off. Almost 48% reported that this was done to reduce the cost of the monthly electricity bill and just over 38% said it was for health and safety reasons. Just 6% of respondents said they turned off the AC to reduce energy consumption for environmental reasons (See Figure 5-19).

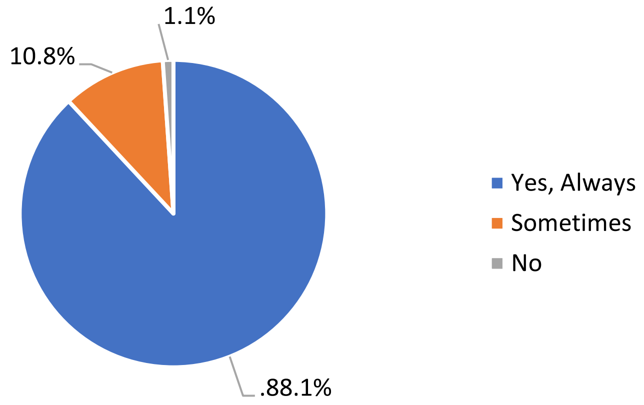


Figure 5-17: Percentage of respondents who turn off the AC when leaving the home or the room

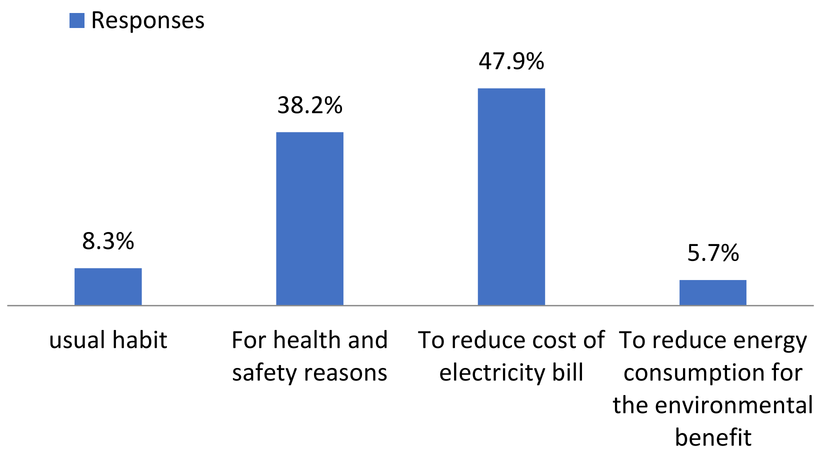


Figure 5-18: Reasons for turning off the AC when leaving the home or the room

The next question asked respondents how often they turn the lights on during daytime, given the fact that sunshine typically provides adequate lighting in daylight hours. As Figure 5-18 demonstrates, almost 58% of respondents reported that they rarely or sometimes use lights during daytime, with just over 12% saying they always did so.

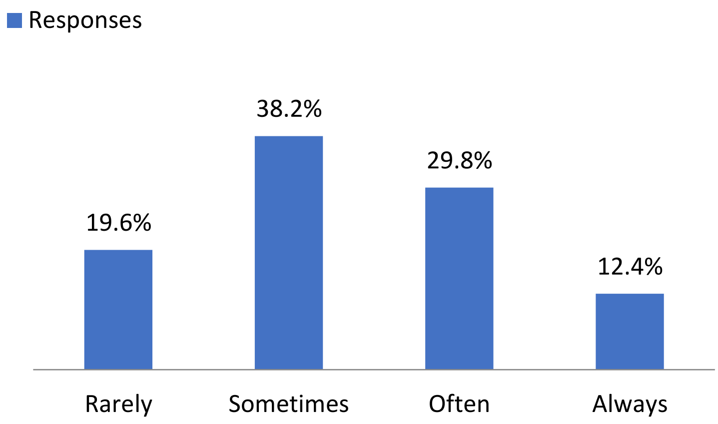


Figure 5-19: Light operation during daytime

Allowing fresh air to pass through the house is considered as a healthy household practice (Aldossary, 2015). This can be achieved by opening windows to allow the natural air exchange process. As a result, the next set of questions asked respondents how often they opened their windows and the reasons for doing so. Respondents were also asked about reasons which prevented them opening their windows. As Figure 5-20 illustrates, just over half the respondents (53%) reported that they sometimes open their windows while just under 8% never do this.

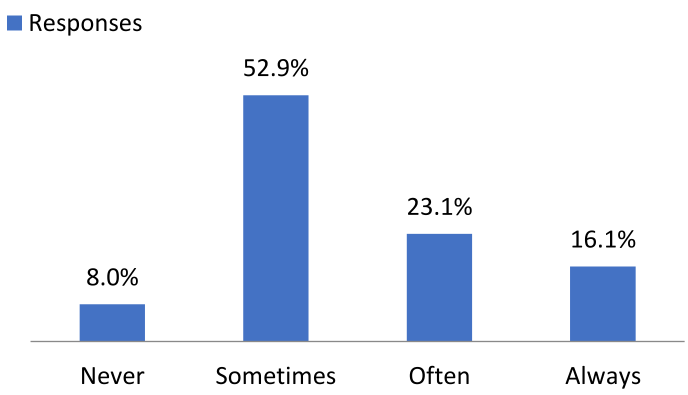


Figure 5-20: Frequency of window opening

The most common reason for opening windows was to refresh the indoor air (86%). Less than 2% of respondents said they opened their windows to cool the house, as the external air temperature is likely to be lower only in moderate temperature regions of the country (i.e. mountain regions) (See Figure 5-21).

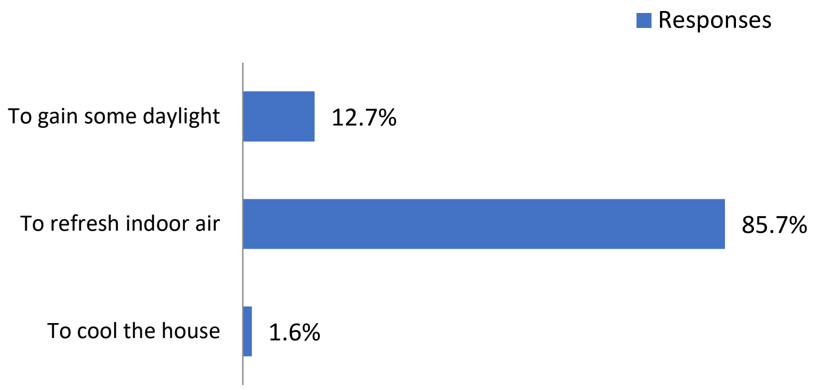


Figure 5-21: Reasons to open the windows

Respondents were then asked to identify the reasons that prevented them from opening their windows. As Figure 5-22 displays, almost 43% of respondents identified the country's harsh climate (hot outside weather), with just over 29% saying that they kept windows closed to prevent dust entering.

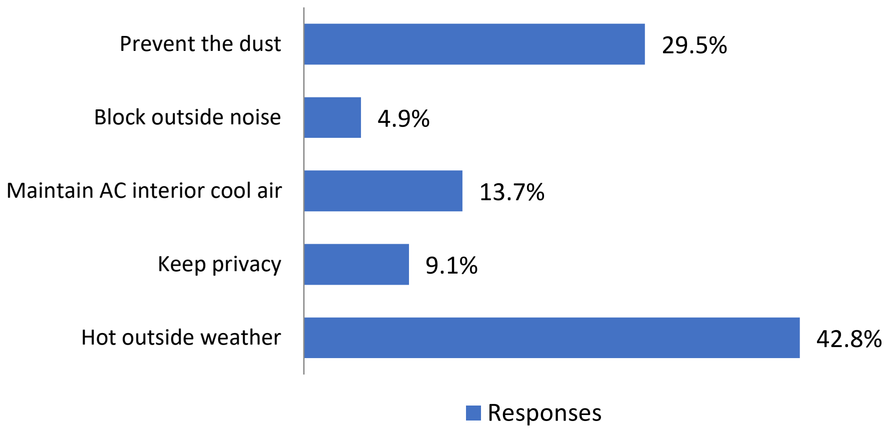


Figure 5-22: Reasons preventing occupants opening the windows

5.2.3 Respondents' Perceptions and Willingness

A fundamental objective of the survey was to arrive at an accurate and detailed assessment of people's awareness of and willingness to adopt sustainability measures in their homes. As a result, the next section asked about respondents' knowledge of sustainability and the use of energy efficient materials within their homes.

The first questions asked if respondents were aware of sustainable, green, or energy efficient buildings. As Figure 5-23 demonstrates, almost three-quarters of respondents said they were not aware of these. This suggest that a lack of awareness about sustainability may reinforce the non-sustainable practices during building use such as using lighting during day times and continuous AC operation.

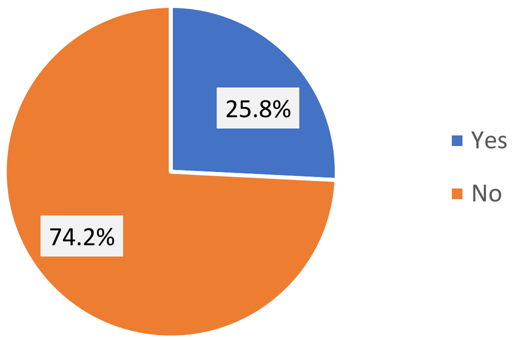


Figure 5-23: Proportion of respondents who are aware of sustainable buildings

The next question asked if respondents were aware of insulation materials and their role in buildings. The results here were more encouraging, as Figure 5-24 shows, with 61% of respondents saying they knew about thermal insulation materials and their role in reducing energy consumption.

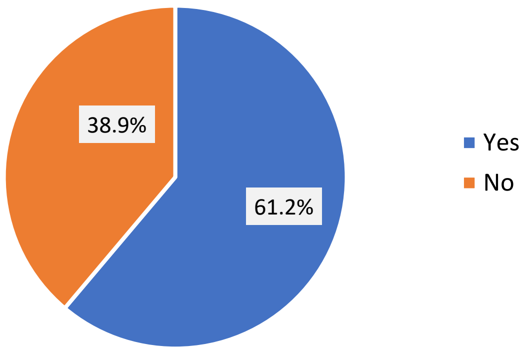


Figure 5-24: Proportion of respondents who were aware of thermal insulation materials

A follow-up question asked if respondents' houses were thermally insulated. As can be seen in Figure 5-25, 43% reported that they were not insulted while 26% were unsure. Of the 628 respondents, only 197 live in insulated houses (31%). Comparing these results with those in the previous question suggests that knowing about insulation materials does not necessarily mean applying them within the home**.**

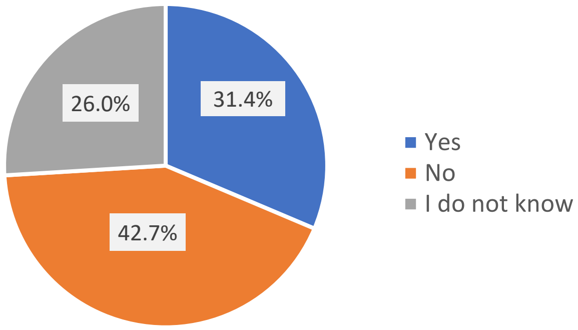


Figure 5-25: Percentage of respondents living in thermally insulated dwellings

The next question asked about window glazing. Respondents with single glazed windows represented almost 47% of the sample compared to just under 52% with double glazing, as shown in Figure 5-26.

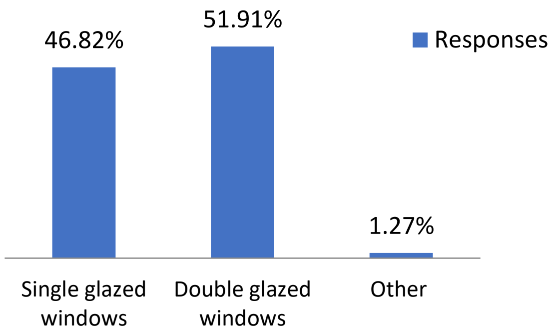


Figure5-26: Types of glazing used in respondents' windows

The next set of questions explored whether respondents would be willing to pay more for an energy-efficient home. As Figure 5-27 demonstrates, exactly half of respondents (50%) confirmed their willingness to pay more for energy-efficiency, while just over 37% were not sure. Just over 12% said they would not be willing to pay more.

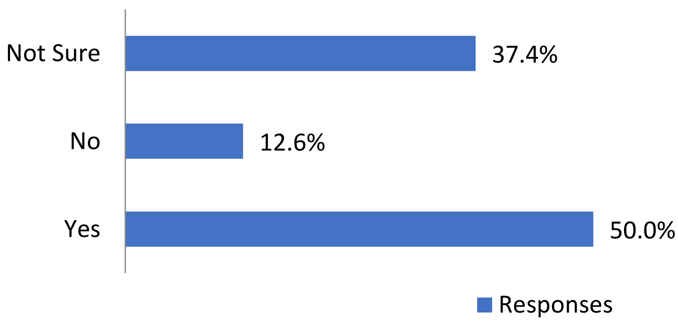


Figure 5-27: Percentage of respondents willing to pay for a more energy-efficient house

Two follow-up questions asked respondents to give reasons for their answer. Of those who were willing to pay more, 67% selected both ‘to reduce the cost of electricity’ and ‘to reduce energy consumption for the benefit of the environment’ as their main reasons (See Table 5-2).

Table 5-2: Reasons for willingness to pay for a more energy-efficient home

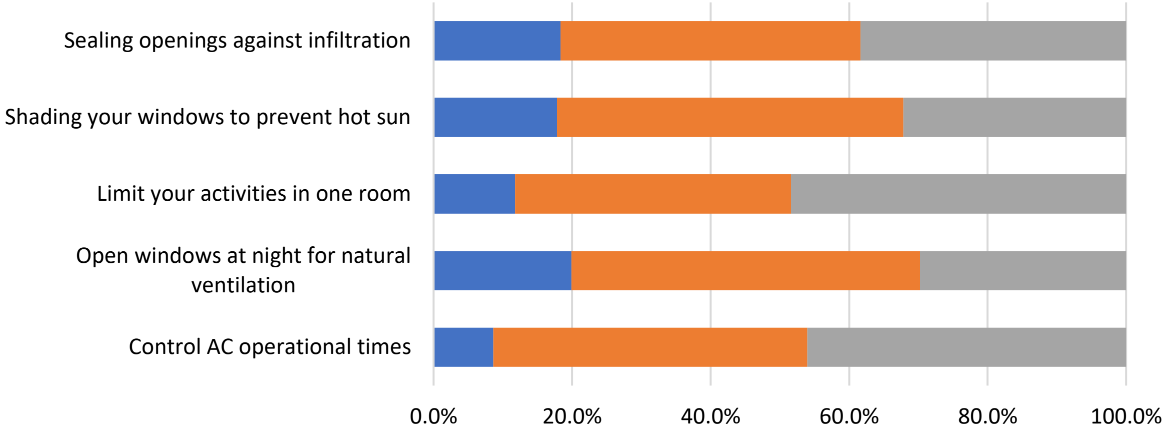
Answer Choices	Responses
To reduce the cost of electricity	28.3%
To reduce energy consumption for the environmental benefit	4.5%
Both of the above	67.2%

As Table 5-3 shows, 32% of those who were unwilling or not sure about paying more for an energy-efficient home stated that they could not afford the cost of sustainability applications. Furthermore, 60% of respondents were either unsure about the effectiveness of sustainable technologies or were not familiar with such subjects.

Table 5-3: Reasons for not being willing to pay for a more energy-efficient home

Answer Choices	Responses
Not sure of the effectiveness of energy-efficient technologies	26.0%
Not familiar with sustainability and energy saving subjects	33.6%
The cost of electricity consumption in my house is not high	8.0%
I cannot afford applications of sustainability	32.4%

The next question asked how much effect a number of measures could have on energy saving without compromising occupants’ thermal comfort. Respondents were asked to indicate whether these would have ‘No effect’, ‘Little effect’ or a ‘Considerable effect’. The results are shown in Figure 5-28.



	Control AC operational times	Open windows at night for natural ventilation	Limit your activities in one room	Shading your windows to prevent hot sun	Sealing openings against infiltration
No effect	8.6%	19.9%	11.8%	17.8%	18.3%
Little effect	45.4%	50.3%	39.8%	50.0%	43.3%
Considerable effect	46.0%	29.8%	48.4%	32.2%	38.4%

Figure 5-28: Respondents' views of the effectiveness of the suggested energy-efficiency measures

As can be seen, limiting activities to one room (48 %) and controlling AC operational times (46 %) were considered to be most effective in terms of reducing energy consumption. By contrast, opening windows at night for natural ventilation was thought to have little or no impact on energy reduction.

In order to assess respondents' actual commitment to reducing energy consumption in their homes, the next question asked if they had tried any of these measures. As Figure 5-29 demonstrates, 13% reported that they had tried all of them, 64% had tried some of them, while 23% had not.

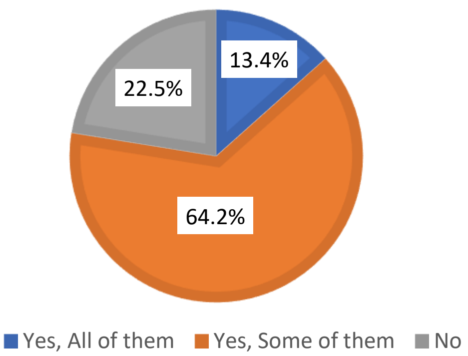


Figure 5-29: Percentage of respondents who attempted the suggested efficiency measures

Respondents were then asked if they had noticed any difference in their energy consumption costs when trying any these methods. The majority (53%) said they had noticed a positive difference in their electricity bill. However, 42% of respondents did not notice any improvement, suggesting that these measures are not sufficient to reduce consumption in the hot Saudi climate (See Figure 5-30).

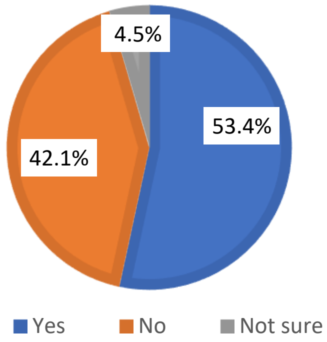
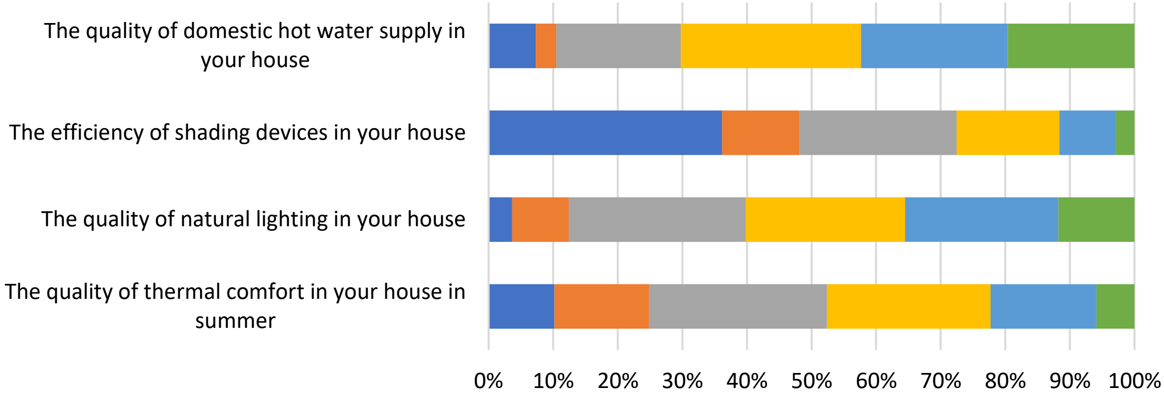


Figure 5-30: Percentage of respondents who noticed a difference in their energy consumption costs when attempting the suggested efficiency methods

The next question asked respondents to rate the quality of the following features in their home: thermal comfort in the summer, natural lighting, shading devices (if used), and the domestic hot water supply. These items were selected as they all influence building energy performance. Respondents were asked to rate them using a five-point scale from Poor to Excellent. As illustrated in Figure 5-31, the majority of respondents confirmed that they were satisfied with the domestic hot water supply (70%) and the quality of natural lighting in their dwellings (60%). Given the importance of effective shading in reducing solar heat gain, it is striking that 36% of respondents reported that shading devices were not applicable (i.e. not utilised in their homes) and another 36% assessed the quality of their shading as either poor or fair. Respondents' views of the quality of internal thermal comfort in their homes was as follows: 42% assessed it as poor to fair while 48% assessed it as good to excellent.

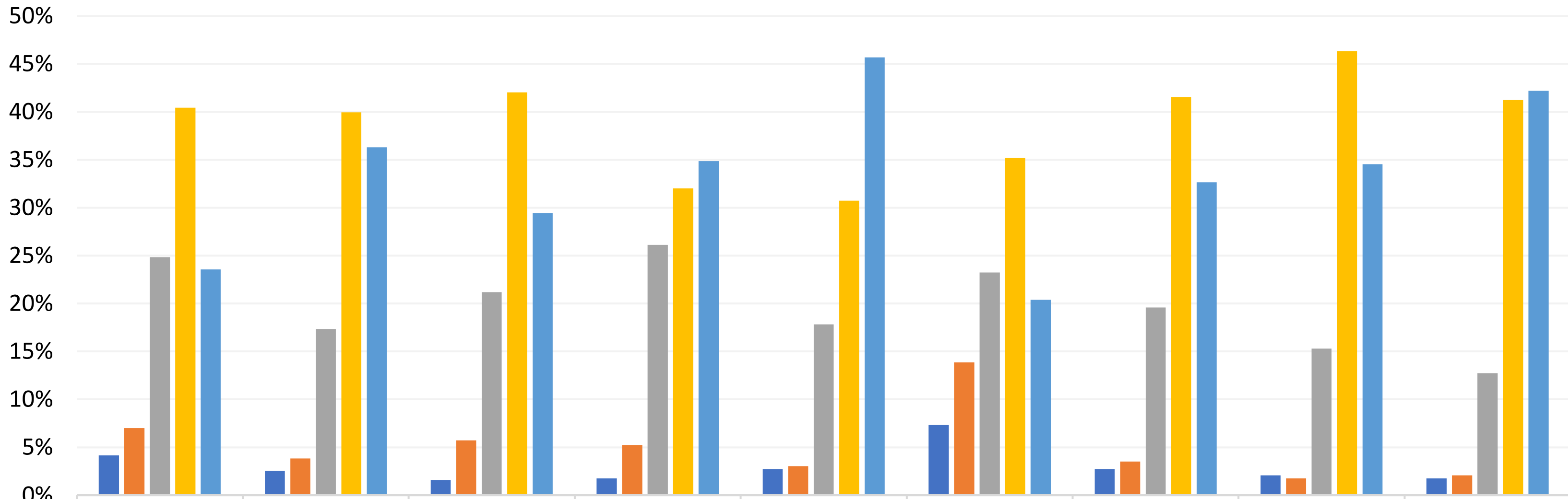


	The quality of thermal comfort in your house in summer	The quality of natural lighting in your house	The efficiency of shading devices in your house	The quality of domestic hot water supply in your house
Not Applicable	10.2%	3.7%	36.2%	7.3%
Poor	14.7%	8.8%	11.9%	3.2%
Fair	27.6%	27.4%	24.4%	19.3%
Good	25.3%	24.7%	15.9%	27.9%
Very Good	16.4%	23.7%	8.8%	22.8%
Excellent	5.9%	11.8%	2.9%	19.6%

Figure 5-31: Respondent's views of the quality/ efficiency of factors influencing building energy performance

One of the objectives of the survey was to elicit information on what the public currently understood concerning sustainable building practices in residential buildings with a focus on energy saving. To this end, a number of questions were used to test the public's views of sustainable buildings, the availability of sustainable products, such as PV panels, the cost of construction materials, and the role the Saudi government should play in promoting more sustainable construction. The intention behind these questions was to identify issues that may hinder sustainable residential development in KSA. The responses to these questions are shown in Figure 5-32.

As Figure 5-32 demonstrates, over 64% of respondents agreed or strongly agreed that households have no awareness of low energy or sustainable buildings. A larger proportion of respondents agreed or strongly agreed that a shortage of sustainable products in the Saudi market is affecting sustainable development (76%), that there is a shortage of skilled labour or technicians (71%) and that the escalating prices of sustainable construction materials and products is affecting the development of a sustainable housing sector (67%). There were similar levels of support for greater government action to support sustainable construction. A large proportion of respondents agreed or strongly agreed that future dwellings must be designed according to sustainable criteria made compulsory by the government (76%), that the governmental sector (such as MoMRA, ECRA, and MoH) should introduce further legislation to promote sustainable construction (74%), that it should regulate the housing market and establishments to promote sustainable building (81%), and that the government should offer incentives to encourage sustainability practices and sustainable buildings (83%). However, there was less support for the idea that the sizes of future dwellings should be reduced to fit the number of household members, with just over 55% of respondents agreeing or strongly agreeing with this. The high levels of support expressed here indicate an overwhelming willingness among members of the public to accept and adopt sustainable buildings; however, the results suggest that some aspects will experience slower acceptance/adoption, especially those related to reducing the size of houses or the number of rooms.



	The households have no awareness of low energy or sustainable buildings	There are shortages of sustainable products on the Saudi market such as Photo-voltaic cells	One of the reasons influencing development of sustainable buildings is the lack of trained labours and technicians	One of the reasons influencing development of sustainable buildings is the escalating prices in construction materials and products	Future dwellings must be designed according to sustainable criteria established as compulsory by the government	The sizes of future dwellings in Saudi Arabia should be reduced to fit the household members	The government should take serious steps to introduce rules to adopt sustainable buildings in Saudi Arabia	The government should regulate the housing market and establishments to promote sustainable buildings	The government should offer incentives to encourage sustainability practices and sustainable buildings
Strongly Disagree	4.1%	2.6%	1.6%	1.8%	2.7%	7.3%	2.7%	2.1%	1.8%
Disagree	7.0%	3.8%	5.7%	5.3%	3.0%	13.9%	3.5%	1.8%	2.1%
Neutral	24.8%	17.4%	21.2%	26.1%	17.8%	23.3%	19.6%	15.3%	12.7%
Agree	40.5%	40.0%	42.0%	32.0%	30.7%	35.2%	41.6%	46.3%	41.2%
Strongly Agree	23.6%	36.3%	29.5%	34.9%	45.7%	20.4%	32.6%	34.6%	42.2%

Figure 5-32: Respondents' views on a number of issues related to sustainable construction

The penultimate question asked respondents if they were aware that painting the exterior of a building with light reflective paint may reduce the building energy consumption by reducing AC operational load. As Figure 5-33 shows, almost 57% reported that they were aware of this.

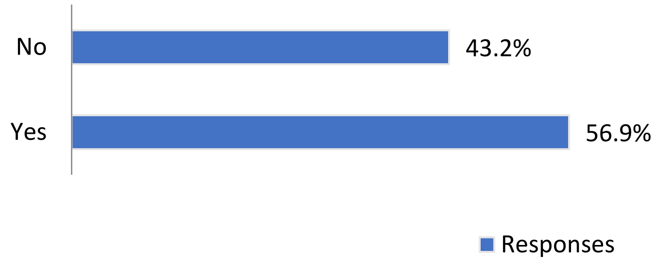


Figure 5-33: Percentage of respondents who knew about solar reflective paints

To conclude the questionnaire, the participants were asked whether they thought current residential buildings in Saudi Arabia met sustainability and energy saving standards. The majority (57%) thought that Saudi houses did not comply while 36% were not sure (See Figure 5-34).

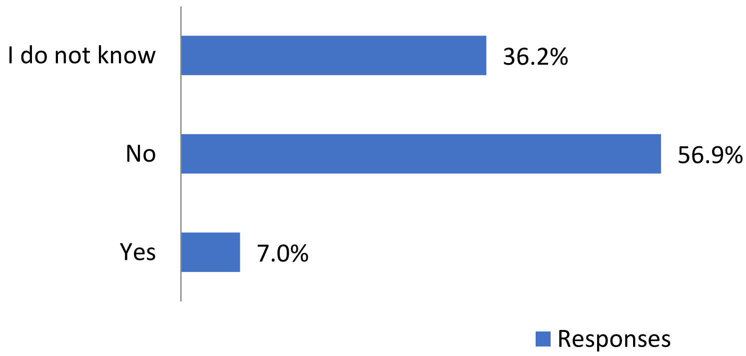


Figure 5-34: Percentage of responses regarding Saudi houses' compliance with building codes

5.3 Expert Survey Results

The next section reports the results of the expert panel consultation. This was conducted as a survey that covered a range of factors concerning architectural design strategies, building envelope design, and on-site renewable energy strategies for Saudi Arabia, taking into account socio-cultural considerations. The questionnaire comprised 19 questions, divided into four main sections: a) architectural design techniques and strategies (Questions 2-6), b) building envelope design techniques and strategies (Questions 7-11), c) on-site renewable energy strategies and cultural issues (Questions 12-13), and, finally, d) analysis of building applications and practices in KSA (Questions 14-19). The first question asked for respondents' demographic details (organisation, subject field, position, years of experience, city, and contact e-mail); these are not reported here to protect the respondents' anonymity, but the composition of the expert panel is explained in Chapter 4 (See 4.3.3.1).

5.3.1 Architectural Design

Building shape and orientation play a significant role in the design phase and, subsequently, influence energy consumption. As a result, the second question asked the experts to rank five techniques associated with building shape and orientation according to their effectiveness in enhancing residential building performance, using a scale from 1-5. As Figure 5-35 demonstrates, orienting the building to the south was ranked as the most effective option while minimising the building size was considered least effective. The weighted score for all five options is presented in descending order in Figure 5-36.

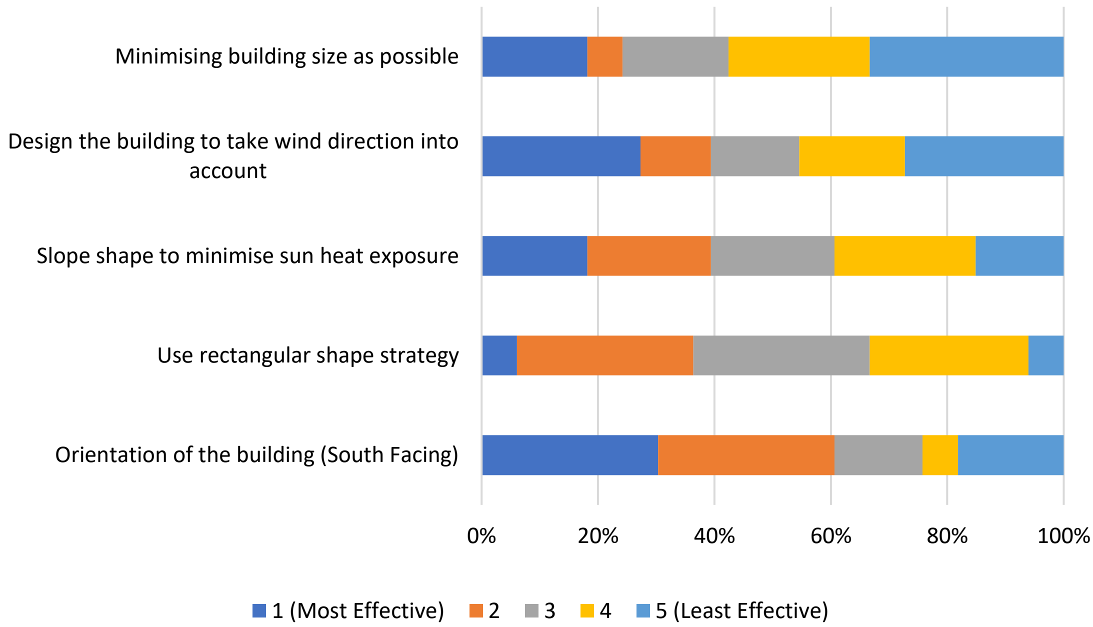


Figure 5-35: Expert's views of the effectiveness of selected building shape and orientation techniques

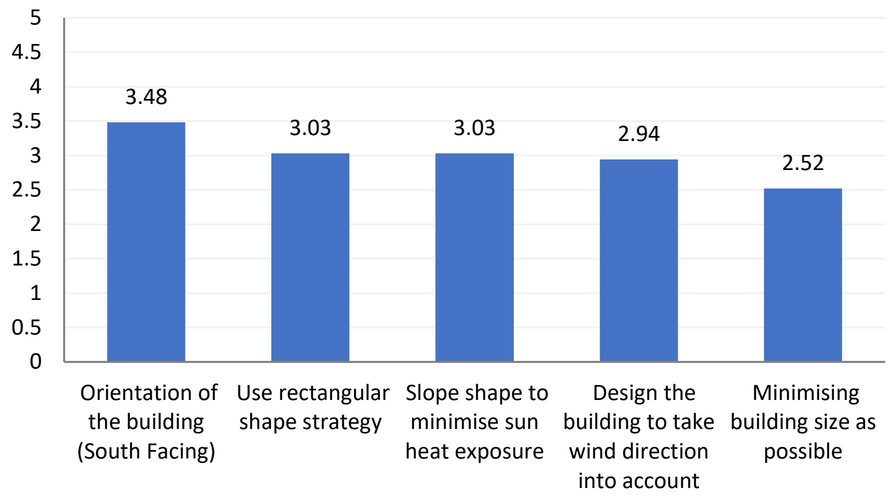


Figure 5-36: Ranking of building shape and orientation techniques in descending order

The experts were then asked to rank five commonly used window design techniques from an energy efficiency perspective. As Figure 5-37 shows, reducing the window area was judged to be the most effective technique to enhance residential building performance (with a score of 3.39 out of 5), followed by reducing the number of windows (3.09). Reducing the size and number of south-facing windows was considered the least effective option, with a weighted average of 2.48.

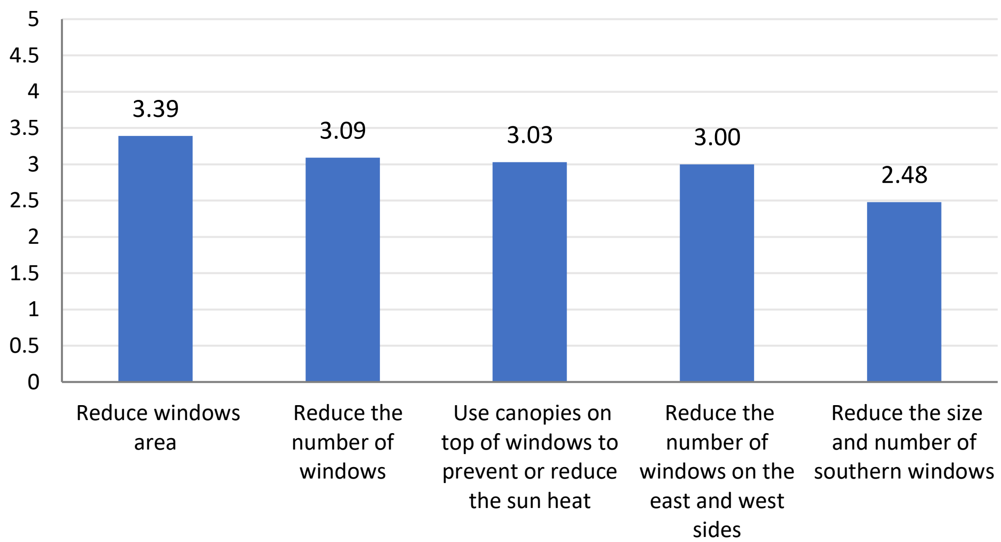


Figure 5-37: Experts' final ranking for window design techniques

As shading design and devices may help to reduce energy consumption in buildings, the experts were then asked to rank five shading techniques currently used or applied in Saudi residential buildings. As shown in Figure 5-38, the use of efficient courtyard landscaping to provide shade around the building was selected as the most effective technique (3.48 out of 5), closely followed by using internal and/or external shutters for windows to prevent unwanted solar gains (3.42). The option judged to be least effective was the use of a horizontal canopy to create shade.

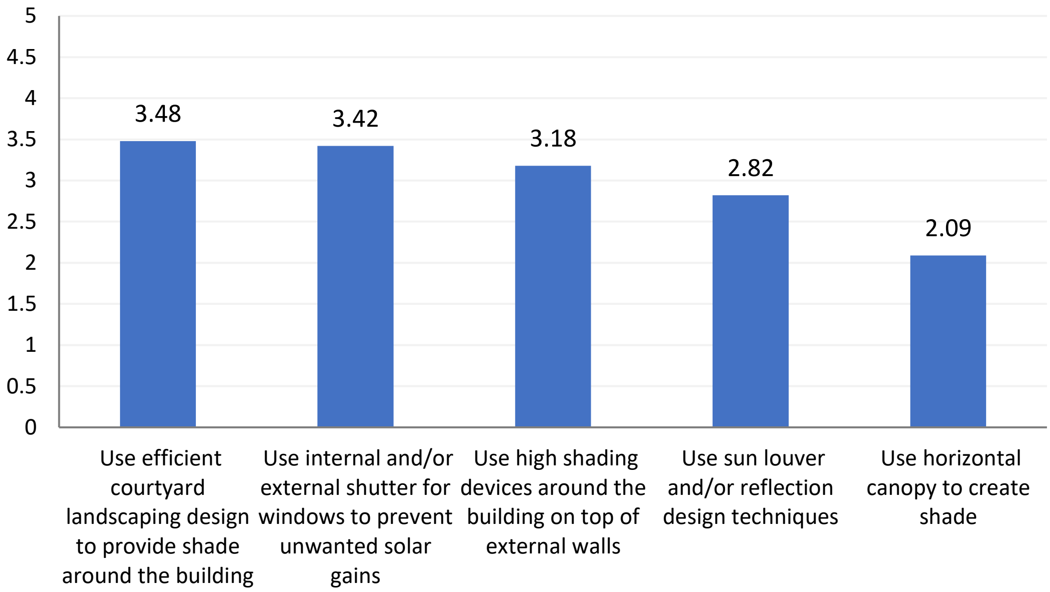


Figure 5-38: Experts' final ranking for shading design and device techniques

Given the fact that HVAC systems dominate energy consumption in residential buildings, the experts were then asked what they would normally apply (or do) to minimise the load from HVAC operations. A number of options were provided, along with a free-text box to enable respondents to offer alternatives. As Figure 5-39 illustrates, almost half of the experts (49%) selected dividing the internal rooms in the building into zones to create separate cooling and/or heating units and only using rooms when the need arises, followed by using air conditioning sensors to regulate the indoor temperature and/or control the cooling setpoint temperature (30%). By contrast, using ground heat exchange techniques and other ventilation techniques, such as natural ventilation or fans, attracted little or no support, with just 9% and 0% respectively. The ground source was included because there has been some interest in some studies, although very limited, toward benefiting from ground heat as a cooling technique. Also, it was added to see if this option is viable in the country in the experts' point of view. Other techniques suggested by the experts were using vegetation around the house, incorporating PV panels, and setting the cooling temperature at 25°C for most of the operation time.

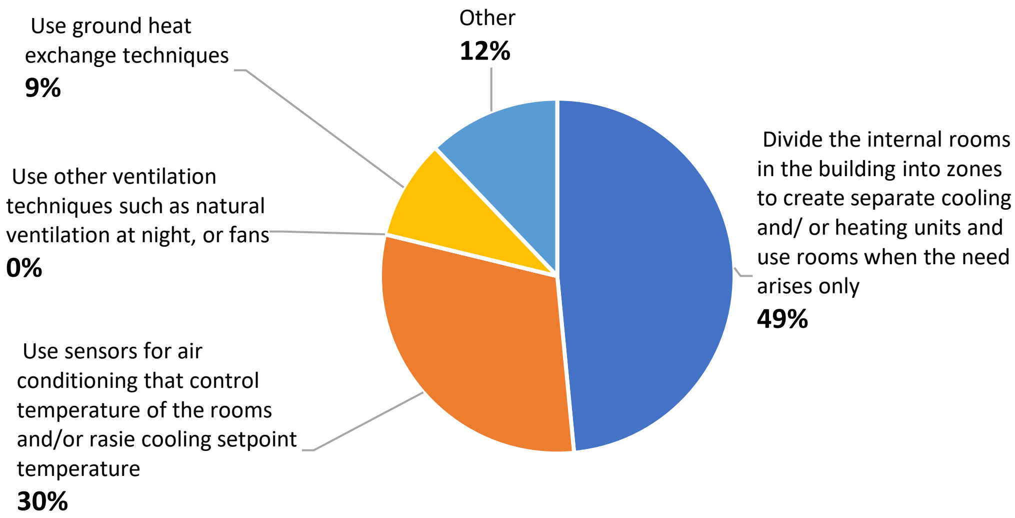


Figure 5-39: Experts' views of the most effective options to minimise the load from HVAC operations.

The expert panel were then asked to select the most effective natural ventilation techniques currently used in Saudi residential buildings from a list of five. They were also provided with space to offer alternative options. As shown in Figure 5-40, the use of efficient window designs to ventilate the building was selected by 40% of the panel, followed by designing an open plan interior in order to provide internal airflow (30%). Techniques such as using ventilation towers or designing rooms with two windows to promote airflow attracted only 6% and 15% respectively. However, these proposed techniques might be applicable only to regions of lower temperatures where cooler air prevails such as those in southern mountainous cities, namely Asir and Albaha regions. The experts also suggested other techniques such as planting trees adjacent to the building, increasing windows number for each room, and using exterior water surfaces to cool the air.

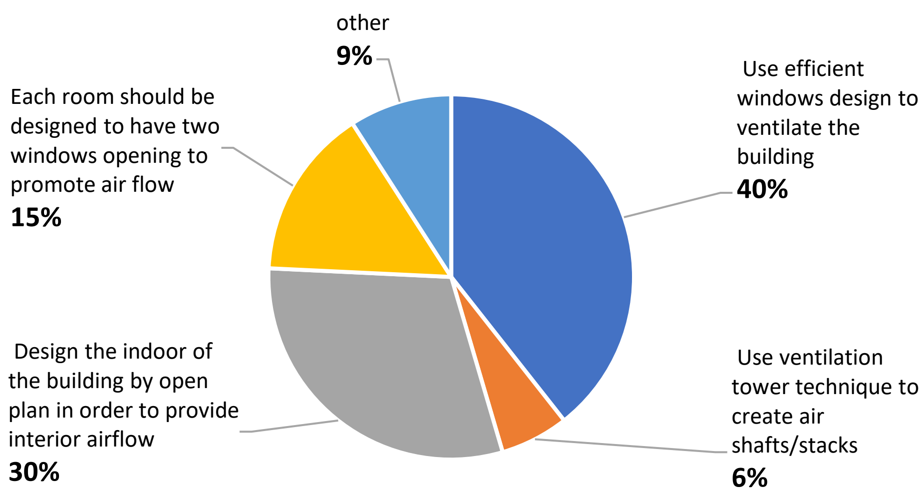


Figure 5-40: Experts' views of the most effective natural ventilation techniques

5.3.2 Building Envelope Design

As discussed in Chapter 2, the building envelope is considered one of the most significant factors in relation to energy saving in residential building operations, if not the most significant. As a result, the next section of the survey sought the experts' assessment of a range of techniques and materials used in building envelope design, giving consideration to their availability and effectiveness in terms of energy saving. These techniques were derived from current practices taking into account the Saudi context and the local climate conditions (mainly focusing on the summer season).

The experts were first asked to review a list of most popular roofing strategies used in Saudi Arabia and indicate which of them they would use to improve insulation in the roof. They were also offered the opportunity to add alternative options. As Figure 5-41 demonstrates, almost 58% of the responses were directed to designing the external roofs above the concrete structure with efficient insulation materials and concrete tiles. The second choice was adding green grass above the concrete structure of external roofs to increase the insulation, attracted just over 21% of the responses. Techniques such as creating a cavity between the concrete structure and the top layer of the roof to allow ventilation at night and prevent direct heat from the sun and designing the external roof to include rain insulation and wood materials above the concrete structure were the least popular options, selected by just over 15% and 3% respectively. It was also suggested to use other techniques such as external roof- surface insulation and reflective coatings.

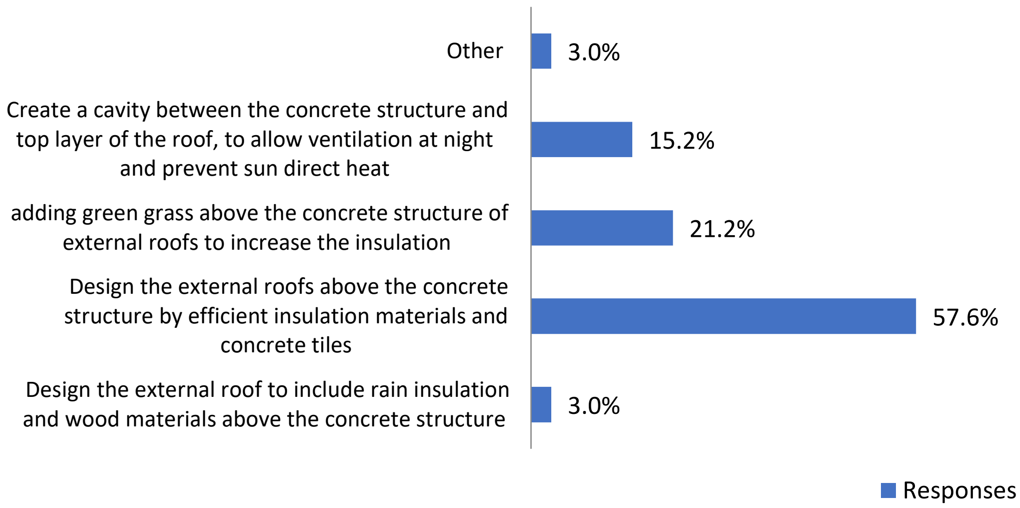


Figure 5-41: Experts selection of roof design techniques

The next question adopted a similar approach with regard to building floor design and materials. Respondents were asked to select the most effective floor building technique from an energy reduction perspective from a list of four. As Figure 5-42 shows, opinion was almost evenly divided between the four techniques. Using a thick layer of sand and concrete tiles is currently the most popular practice when building floors in Saudi Arabia; however, based on these experts' views, other techniques, including the use of mud, mortar and concrete tiles, natural stones, and wood as an insulation material may need to be considered as effective alternatives.

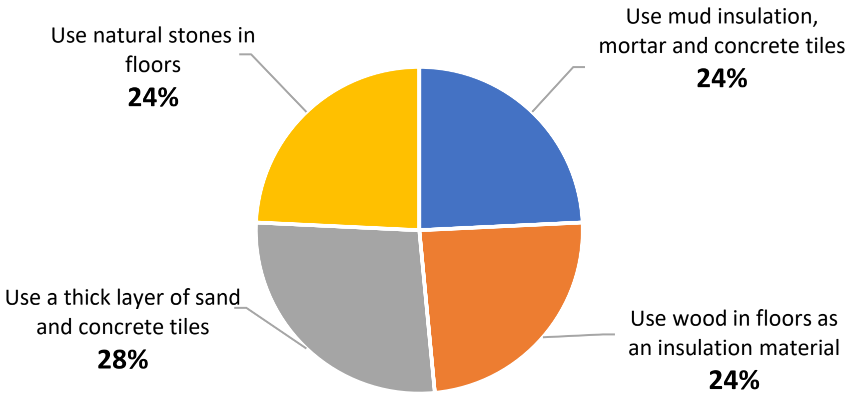
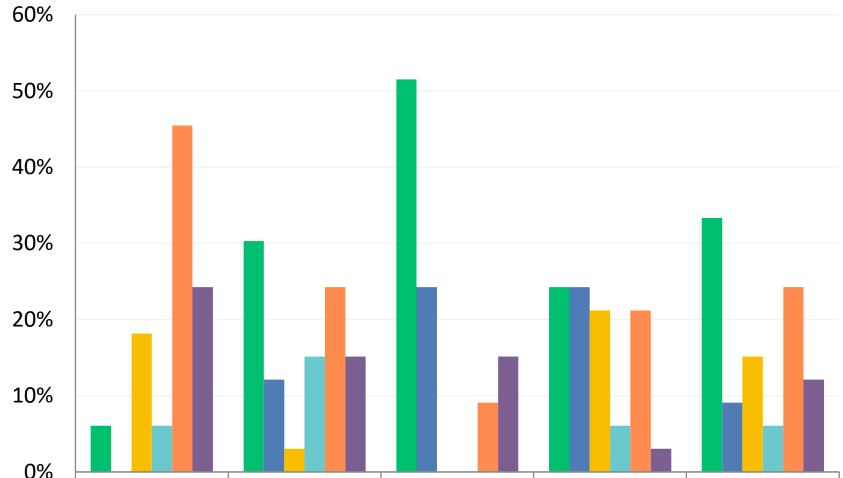


Figure 5-42: Experts' selection of the most energy efficient floor building techniques

The next question explored energy saving in relation to external walls and asked the experts whether five specific techniques are currently in use in residential buildings in the KSA. If respondents selected 'No' they were asked to select one of the following reasons: too expensive, not available, not useful, not necessary, or not acceptable to the client. The results are shown in Figure 5-43.



	Design external walls with mud in order to be highly insulated	Design external walls with solid red- clay bricks	use double skin walls technique in the designing of external walls	Use stone built external walls	Use cavity techniques in external walls
Yes	6.06%	30.30%	51.52%	24.24%	33.33%
No, Expensive option	0.00%	12.12%	24.24%	24.24%	9.09%
No, Not available	18.18%	3.03%	0.00%	21.21%	15.15%
No, Not useful	6.06%	15.15%	0.00%	6.06%	6.06%
No, Not necessary as other means may provide the same benefit	45.45%	24.24%	9.09%	21.21%	24.24%
The client prefers other options even though not effective	24.24%	15.15%	15.15%	3.03%	12.12%

Figure 5-43: Experts' views of which external wall design techniques are currently in use in KSA

As Figure 5-43 illustrates, almost 52% of experts identified using double skin walls to enhance building performance as currently used in the Saudi housing industry. However, just over 24% believe that this technique is an expensive option (suggesting the public might therefore avoid it). On the other hand, there was widespread agreement that designing external walls with mud in order to improve insulation is not currently used in the Kingdom (94% of experts), often with many expressing the view that it is not necessary since other means provide the same benefit (45%), or the client prefers other options, even if they are not as effective (25%). However, there is a clear disparity in the views of the experts regarding the other options. For example, one third identified using cavity techniques in external walls as currently in use, but almost 25% said it was not used because other means could provide the same benefit. Similarly, just over 24% thought using stone built external walls was in current use, but the same proportion thought it was not used because it was too expensive.

The next question explored the expert panel's views of types of glazing design and techniques for external windows. Five techniques were presented and respondents were asked to rank their importance on a scale of 1-5 (where 1 is the most important). As can be seen in Figure 5-44, the most important technique was the use of double or triple glazing with air between glazing panes achieving a weighted score of 4.1, followed by the same technique but with the use of argon gas instead of air (3.5). Increasing the thickness of glazing and using highly airtight windows scored 3.2 and 2.7, respectively. The least important option in the experts' opinion was the use of single glazing (1.6).

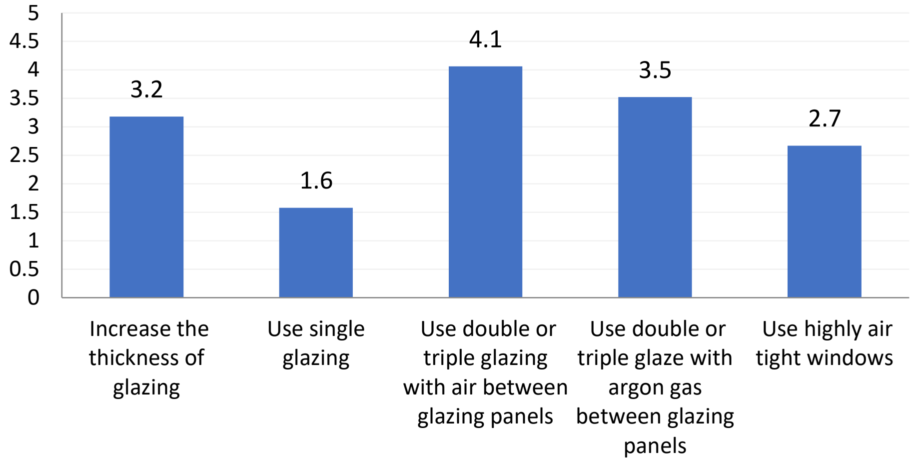


Figure 5-44: The most important window glazing techniques from the experts' perspective

The aim of the next question in this section was to assess the relative merits of a number of building envelope fabric factors and techniques in term of their effectiveness in reducing energy consumption in residential buildings within the Saudi context. The experts were asked to consider 12 different aspects and rate their relative importance on a five-point scale from 'not important' to 'extremely important'. Each degree was assigned a weight in order to calculate each factor's weighted average (also called score), with 'not important' assigned '1' and 'extremely important' assigned '5'. The results are shown in Table 5-4.

Table 5-4: Experts' assessment of the importance of various building envelope design factors

Factor or Technique	Assigned Weight					Weighted Average
	1	2	3	4	5	
	Importance					
	Not important	*Less important*	*Important*	*Very important*	*Extremely important*	
Types of Insulation materials	*1*	*1*	*5*	*8*	*18*	**4.24**
Use modern construction materials which have high insulation and are available in local markets	*2*	*4*	*6*	*6*	*15*	**3.85**
Low thermal conductivity of materials	*0*	*4*	*12*	*7*	*10*	**3.70**
High resistance of materials	*1*	*3*	*13*	*6*	*10*	**3.64**
Use a suitable construction material in terms of coolness retention	*1*	*4*	*12*	*5*	*11*	**3.64**
Thicknesses of building envelope elements	*0*	*7*	*13*	*3*	*10*	**3.48**
Use finishing materials with high R-values	*1*	*7*	*11*	*4*	*10*	**3.45**
Use light colours for external walls	*1*	*6*	*14*	*6*	*6*	**3.30**
Use foam glazing in external windows	*2*	*14*	*8*	*6*	*3*	**2.82**
Use volcanic bricks as an efficient construction material	*7*	*6*	*13*	*3*	*4*	**2.73**
Use plaster for glaze insulation for external windows	*5*	*13*	*8*	*6*	*1*	**2.55**
Use wood in designing the external walls	*20*	*12*	*1*	*0*	*0*	**1.42**

As Figure 5-45 demonstrates, types of insulation materials was rated highest in term of its role in enhancing building performance with a score of 4.24. The use of modern construction materials with high insulation which are available locally came second with a weighted average of 3.85, indicating its significance in building envelope design. Factors such as low thermal conductivity of materials, high resistance of materials, and the use of a suitable construction material in terms of coolness retention shared almost the same degree of importance (scored 3.64 - 3.70), as did thicknesses of building envelope elements and using finishing materials with high R-values (3.48 and 3.45 respectively). The techniques considered least effective in terms of enhancing building performance were using volcanic bricks (2.73), using plaster for glaze insulation on external windows (2.55) and using wood in external walls (1.42). The ranking of these factors and techniques according to their effectiveness is shown in Table 5-4.

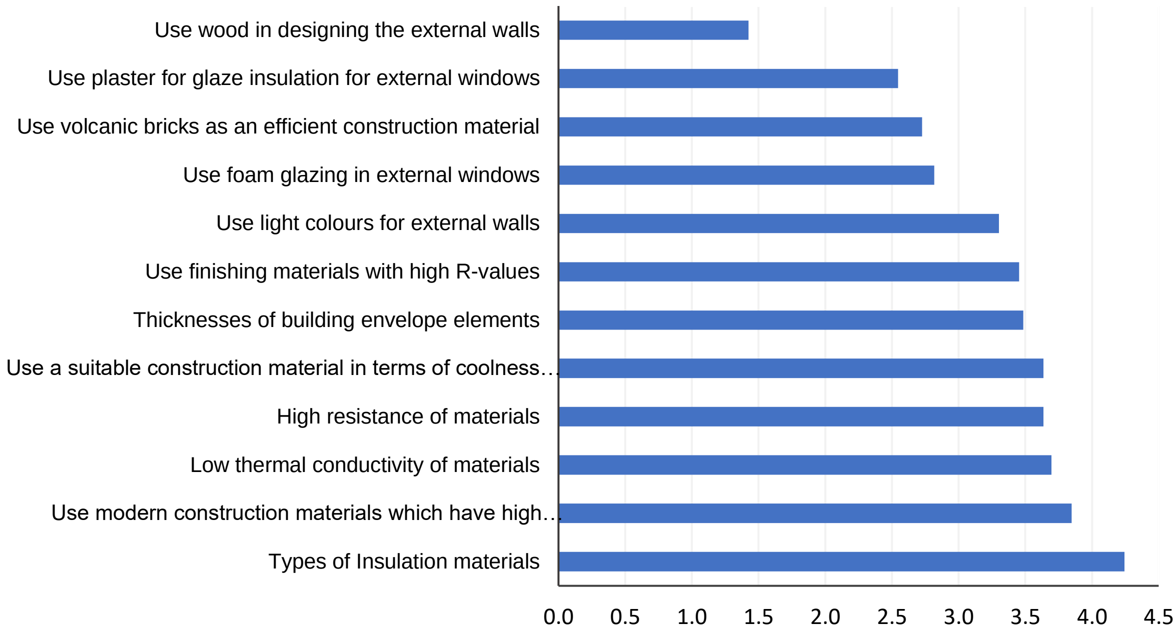


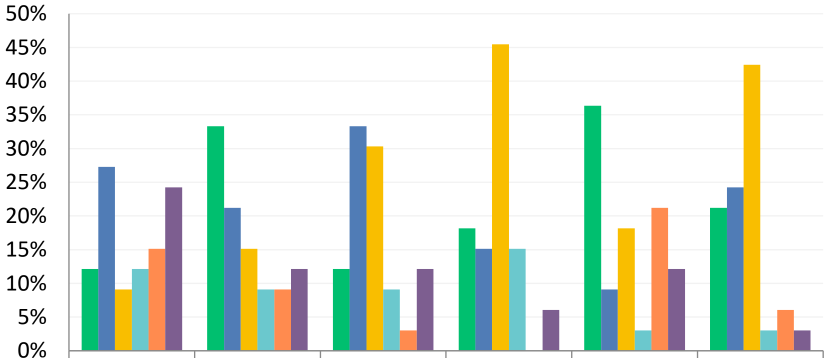
Figure 5-45: Effectiveness of the selected envelope design factors and techniques

5.3.3 On-site Renewable Energy

The third section of the survey addressed renewable energy usage and the socio-cultural aspects that play a role in building performance (Questions 12 and 13). As there are multiple ways of generating energy in buildings from natural sources (e.g. PV cells or wind towers), the experts were asked to indicate whether a number of renewable energy techniques were in use in the Saudi residential buildings, and to identify the barrier if they were not used.

As Figure 5-46 illustrates, just over 36% of the experts thought that using solar water heating technology was currently in use in KSA, while a third identified the installation of east and west oriented PV panels on building tops; however, about 21% thought this option was not used because it was too expensive. Cost was also selected as the most common reason why south facing PV panels were not used (just over 27% of responses) but the view that clients prefer other options was expressed by almost a quarter of respondents (24%). Similarly, almost 88% of respondents thought that the installation of PV on external windows was not currently used for reasons such as its high cost (33%) or lack of local availability (30%). A photovoltaic (PV) window is a daylight-management apparatus with photovoltaic solar cells, modules, or systems embedded on, in, or around a window (Skandalos and Karamanis, 2015). Each PV window consists of several double-sided solar cells that convert both external and internal light into electricity.

Over 40% of expert respondents indicated that renewable energy techniques, such as the use of solar walls and wind energy conversion technologies, were not currently used in KSA because they were not locally available.



	Installation of PV panels on top of the building oriented south facing	Installation of PV panels on top of the building oriented east and west facing	Installation of PV on external windows	Use of solar wall techniques	Use of solar water heating technology	Use of wind energy conversion technology
Yes	12.12%	33.33%	12.12%	18.18%	36.36%	21.21%
No, Expensive option	27.27%	21.21%	33.33%	15.15%	9.09%	24.24%
No, Not available	9.09%	15.15%	30.30%	45.45%	18.18%	42.42%
No, Not useful	12.12%	9.09%	9.09%	15.15%	3.03%	3.03%
No, Not necessary as other means may provide the same benefit	15.15%	9.09%	3.03%	0.00%	21.21%	6.06%
The client prefers other options even though not effective	24.24%	12.12%	12.12%	6.06%	12.12%	3.03%

Figure 5-46: Experts' views of which on-site renewable energy applications are currently in use in KSA

As socio-cultural factors influence occupants' behaviour in buildings and this, in turn, affects energy consumption. The next question asked the expert panel to rank five cultural-related techniques in terms of their impact on building energy performance. These are considered as socio-cultural image of the current practices in domestic houses which were believed to be additional and not of necessity. As before, a scale from 1 to 5 was used (where 1 was the most influential factor and 5 the least). The results are shown in Figure 5-47.

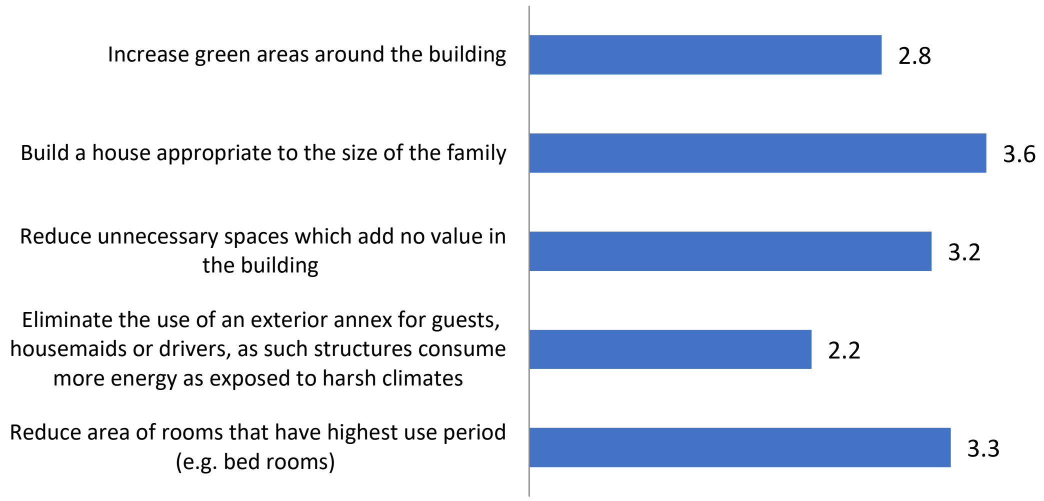


Figure 5-47: The most effective socio-cultural practices from an energy reduction perspective

As Figure 5-47 indicates, building a house appropriate to the size of the family was considered to be the most influential factor from an energy reduction perspective, with a weighted average score of 3.6. The second was to reduce the area of rooms that have longest use period (e.g. bedrooms). Furthermore, reducing unnecessary spaces which adds no value to the building scored 3.2. Increasing the green areas around the building fell in the middle in term of its influence on energy reduction. The least influential practice was judged to be eliminating the use of an exterior annex for guests, housemaids, or drivers (2.2 score).

5.3.4 Building Applications and Practices

The fourth section of the questionnaire addressed aspects of Saudi building practices and applications, particularly the Saudi Building Code (SBC). The experts were first asked if they always use the SBC requirements and/or sustainability elements in their projects. As Figure 5-48 shows, 27% said they always used the code in their projects while 55% said they sometimes used it. Only 18% said they did not use the SBC and/or sustainability elements in their projects.

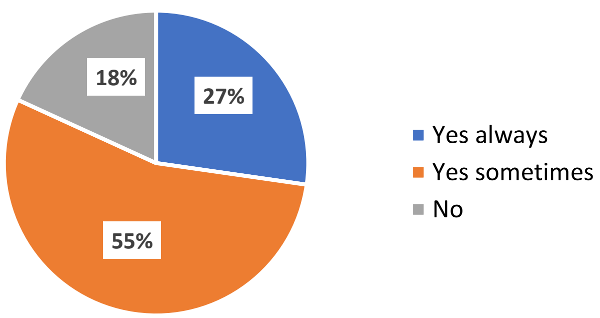


Figure 5-48: Percentage of experts who use the SBC

Experts were then asked if they discussed the option of having the building constructed in compliance with the SBC and/or sustainable design elements with their clients. Just over three quarters (76%) said they discussed this option with their clients, while just under a quarter (24%) do not (See Figure 5-49).

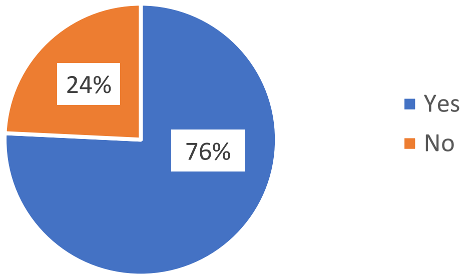


Figure 5-49: Percentage of experts who discuss SBC application with clients

As discussed in Chapter 2, the application of thermal insulation in buildings has a significant effect on the thermal performance of a building. For this reason, the experts were then asked to rank four main selection criteria for insulation materials on a scale of 1-4, where 1 is the most popular and 4 the least popular. Their descending ranking is presented in Table 5-5 indicating that the availability of insulation materials in the market tends to be the major player followed by materials effectiveness.

Table 5-5: Experts' ranking of the factors influencing the selection of insulation materials

Factor	**Rank**	**Score**
availability of insulation materials in local markets	**1**	**3.15**
high efficiency (effectiveness)	**2**	**2.39**
U-value of that material	**3**	**2.33**
cost regardless of the material effectiveness (i.e. cheaper material preferred)	**4**	**2.12**

The next question asked the experts whether they thought residential buildings in general in Saudi Arabia were compliant with the SBC. As Figure 5-50 demonstrates, based on the panel's experience, most residential buildings in the Kingdom are not in compliance with the code.

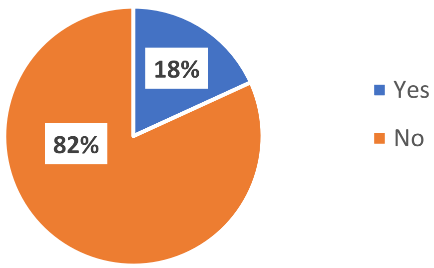


Figure 5-50: Respondents' views on whether residential buildings in general are compliant with the SBC

In a follow-up question, the panel were asked to identify potential reasons why the SBC and/or sustainability elements were not applied in the construction of residential buildings in KSA. Respondents were asked to select options from a list and were able to select more than one option. The results are presented in Figure 5-51. As can be seen, public lack of awareness of the SBC was the leading reason (with over 90% of the responses); this may explain why the second most popular reason was 'not required by the client' (nearly 55% of responses). It is also worth noting that the high cost of compliance was third (27% of responses).

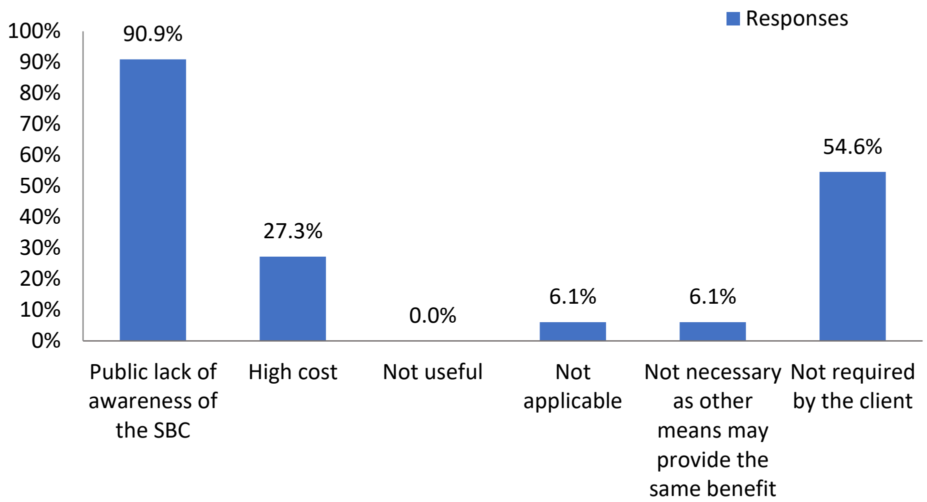


Figure 5-51: Potential reasons for not applying the SBC and/or sustainability elements

5.3.5 Experts' Recommendations

In the final section, the experts were asked to offer their best solutions or suggestions to address the sustainability issues and barriers to the construction of energy-efficient residential buildings in KSA. The strategies to achieve better building performance which received the most support from the experts were:

1. reduce unnecessary spaces in buildings and use these spaces efficiently, as per SBC requirements and design specifications
2. create thermally comfortable indoor environments by considering wind flow and direction for natural ventilation in building designs
3. use thermal insulation materials in external walls and roofs
4. facilitate and simplify access to information about design or energy-efficient measures for clients
5. require engineering consultants and design agencies to comply with the minimum requirements of sustainable building design and/or SBC when meeting clients' need

6. require clients to assign accredited agencies to supervise the building construction process (which has to comply with SBC specifications) in order to get an approval for essential utilities provision (i.e., electricity, water, telecommunication fibres etc)
7. encourage the use of renewable energy sources in building design and operations to generate electricity, e.g. solar systems
8. suppliers should offer self-insulated blocks/bricks at affordable prices to low- and middle-income clients
9. require local market to only import products and materials that meet the specification of the Saudi Arabian Standards Organisation (SASO)
10. ensure the availability of efficient and high quality products in local markets and tackle price manipulation. There should be an official authority to monitor and regulate this
11. government should provide a very strict requirements and standards for buildings so that everyone has to follow it accordingly. These standards must meet all people's needs
12. accelerate the compulsory application of SBC and sustainability requirements to all types and sectors of buildings since
13. the government should lead by example in the field of sustainable buildings as there seems to be a lack of interest in sustainable buildings among local authorities.
14. increase professionals' and contractors' knowledge about sustainable construction
15. educate the public about the importance of sustainability through all channels (i.e., educational institutions, social media, agencies, etc). This was highlighted as being by far the most important step to start with in order to make sustainable development achievable and encourage efficient retrofitting
16. educate public in general and clients particularly of the great long-term environmental and economic benefits of adopting sustainable construction
17. governmental agencies should encourage sustainable practices by offering incentives to clients such as giving discounts to power tariffs and accelerating utilities connection to national grids and alike.

These recommendations and the main findings to emerge from both the surveys are discussed in detail below.

5.4 Discussion

The number of participants in the public has proved sufficient and reflected the common practice in both dwelling and operation levels. The public participants number is higher than that in Aldossary's study in 2015 and Alsurf's in 2014. As for the expert size, it was in line with previous studies recommendations and range. This was explained in Chapter 4. The surveys mainly aimed to identify the relevant features of a typical home in Saudi Arabia in terms of aspects such as type, size, building systems, and user behaviour. they also aimed to explore the Saudi public's views of sustainability in general and energy-efficient buildings in particular. The findings indicate that, in general, the Saudi residential building stock does not meet or comply with sustainability (energy-efficient) standards.

Two groups of barriers to the application of sustainable building methods in Saudi Arabia were revealed by the surveys. The first group is related to uncertainties regarding the economic, technical, and climatic adaptability of sustainable houses in Saudi Arabia. The other group includes constraints associated with cultural, behavioural, technical, and legislative issues. In order to enhance the sustainability of buildings in Saudi Arabia, these factors and barriers need to be addressed. As a result, the experts were asked to suggest the most efficient strategies and recommendations to enhance buildings performance in the KSA. These are discussed in more detail in the following sections, alongside other significant factors which emerged from the data. The first section explores the respondents' perceptions of sustainability and energy conservation in buildings and their willingness to implement energy-reduction techniques, notably those specified in the SBC.

5.4.1 Perceptions and Willingness

As Valkila and Saari (2013) noted, "*To mitigate climate change, technical advances must be accompanied by greater ecological commitment from consumers, i.e., households*". Although 94% of the Saudi population is regarded as educated (Central Department of Statistics and Information, 2013) and most people can access the internet and online media, the findings reveal a huge lack of awareness about sustainability and energy conservation in buildings, regardless of the education level of participants. This lack of awareness may create the perception that there is no scope for energy saving within people's homes, even though only a third of the respondents' dwellings were thermally insulated and the use of single-glazed windows is still, to some extent, a common practice. Another example is that over 40% of respondents in the public survey were unaware of the role of reflective coatings in reducing heat gain and energy consumption. In addition, the figures from the expert consultation suggest that Saudi professionals are less appreciative of these issues. 82% of the expert panel believe that residential buildings in Saudi Arabia are generally not compliant with the SBC and energy conservation requirements, although three-quarters of them still discuss the SBC and/or sustainable design elements with their clients. According to the experts, the main reasons for this are a lack of public awareness of the SBC and the unwillingness of clients to apply them. Furthermore, a lack of interest in sustainable buildings among local authorities was also identified.

This idea that the public are unwilling to accept sustainable buildings is challenged by Algendy (2011) who found that it is highly possible for a society to change traditional building strategies and embrace more energy-efficient structures. It is also called into question by the finding that 50% of respondents in the public survey would be willing to pay more for a more energy-efficient home, with a further 37% unsure. Of those who were uncertain or unwilling to pay more, reasons included uncertainty about the effectiveness of EEMs, inability to afford the costs, low electricity tariffs, and unfamiliarity with sustainability and energy efficiency in general. This suggests that public acceptance of energy conservation could increase significantly if the occupants knew more about the value of EEMs. Effective public awareness programmes would help the public to increase their knowledge about energy conservation and enable them to use more proactive methods to manage cost efficiently and minimise their environmental impact. It is, therefore, imperative to take steps to improve energy savings in the domestic sector and intensify public awareness through public outreach campaigns.

5.4.2 Factors Causing High Energy Consumption

The level of energy consumption in domestic buildings varies from one dwelling to another, but it depends greatly on the design of the building envelope, the type of housing unit, the energy control systems utilised, the occupants' behaviour, and the climate conditions of the local area (Zhu et al., 2013; Pérez-Lombard et al., 2008; Shimoda et al., 2007; Swan and Ugursal, 2009; Hartkopf et al., 2012; Brounen et al., 2012). A number of reasons for the high energy consumption within the Saudi residential sector were identified in the responses, some of which could be addressed in existing homes. However, some issues may not be possible to fix due to the difficulty of retrospectively altering the building, and must instead be considered during both the design and construction stages.

One of the factors identified pertains to the number of rooms and the property area. Larger floor areas increase the energy consumption of per square metre, and, as Hurst et al. (1982) argue, they also may lead to exceed the energy demand level. The survey revealed that more than half of the respondents live in properties with areas of up to 500 m^2. This is in line with Alrashed (2015) who claimed that the average total dwelling area had increased to 500m^2 in the years preceding the study. This average area is large compared with similar dwellings in Europe, and one argument is that providing financial assistance or loans to individuals encourages the construction of larger properties using the maximum permitted area (60% of the plot) (Aldossary et al., 2014). Additionally, the number of rooms found in a property is also high; according to the Saudi Housing Statistics (2019), most homes in the KSA have, for a limited number of family members, more than four bedrooms in the property, and the public survey results showed a significant tendency towards having as many rooms as possible in the house. However, although reducing the size of a dwelling to be proportional with the size of the family has been shown to reduce energy demand (Aldossary et al., 2014b) and it was considered the most effective option by the expert respondents (scoring 3.58 out of 5), the public seem to be divided on this concept, with only 55% of public questionnaire respondents agreeing or strongly agreeing with it.

The number of people per household also affects energy use significantly (Kelly, 2011; Brounen et al., 2012; Kaza, 2010) as does their behaviour and the way they operate their dwellings (Virote and Neves-Silva, 2012; Hendrickson and Wittman, 2010; Romero et al., 2013). 50% of respondents to the public questionnaire indicated that there were more than five occupants in their dwellings, and this accords with recent government statistics which put the average size of the Saudi household at 5.86 persons (GAS, 2019). While people are unlikely to reduce the size of their families to save energy, the findings suggest that other behavioural changes could be made. Although the public survey showed some responsible occupants' habits, such as turning off the AC when not needed or when leaving, some occupants appear to behave irresponsibly. For example, the findings showed that some respondents operate ACs in both bedrooms and sitting rooms when it may have been possible to gather the activities in just one zone. Another example is the use of artificial lighting during the daytime, even though there is abundant natural light. Research has suggested that this may be due to socio-cultural issues, with many houses depending extensively on artificial lighting as windows are mostly closed, or covered with dark drapes, to maintain privacy due to cultural and religious reasons (Mahmud, 2009).

Such behaviour has been facilitated by the fact that electricity costs in KSA have traditionally been low; indeed, the national policy of subsidising the energy and petroleum industry has previously been identified as a significant contributor to high energy consumption in Saudi Arabia (Aldossary, 2015). However, the government initiated a new energy conservation scheme in 2018, and one measure was to remove the subsidy and increase the electricity tariff for all sectors (Al Harbi and Csala, 2019). In the residential sector, prior to 2018, the price for 1 kWh was 0.05 SAR (0.014 USD), whereas it now costs 0.18 SAR (0.048 USD) per kWh, an increase of 260%. Although the tariff is still among the lowest in the world (IEA, 2018), the findings here indicate that it has placed some financial pressure on householders. While the cost of electricity was not a pressing issue in previous years, almost 80% of the public respondents knew what their monthly electricity costs were, and many of them considered them too high compared to their monthly income. This suggests that people may be more willing to consider EEMs if they can be shown to improve their long-term financial stability.

Another issue relates to the fact that in many developing countries, including KSA, modern building design does not usually take account of the prevailing climate. As a result, maintaining an acceptable indoor thermal environment, notably through the use of AC, is responsible for most of a building's energy consumption (Fasiuddin and Budaiwi, 2011). It was encouraging to see that the majority of respondents knew that AC consumes more energy than any other house appliances or systems, and the findings also show a clear tendency amongst the public to move towards mini-split systems, which are more efficient than window type systems. However, this study supports previous literature by showing that it is common practice amongst 90% of public respondents to operate the AC continuously, both day and night, due to the extremely hot weather in Saudi Arabia. Since natural ventilation flow depends on environmental conditions, it may not always provide an appropriate amount of ventilation, and fewer than 50% of respondents said they usually or always opened windows. Reasons for not doing so included hotter outside temperatures and dust, leaving them to depend on mechanical cooling systems to provide a satisfactory indoor environment. This finding is in line with Al Surf (2014), who cites this as an example of unsustainable practices which threaten the country's long-term energy security, and, it is an important area in which to create alternatives in order to reduce current energy demand.

As previous studies have indicated, important factors such as the surrounding and site characteristics, building materials selection, architectural design, and orientation are still not given serious consideration in the context of Saudi Arabia (Ghabra et al., 2017). As discussed in Chapter 2, most buildings are made from reinforced concrete and concrete blocks, despite concrete's poor thermal behaviour (Marzouk et al, 2014), and this finding was endorsed by Mujeebu and Alshamrani (2016) who stated that the thermophysical properties of the materials used in the building industry in Saudi Arabia were not given serious attention. The findings of the public questionnaire indicate that a considerable share of respondents (42%) stated that the quality of internal thermal comfort in their houses was assessed as poor to fair, and this may be due to the ongoing practice of erecting homes without regard to the properties of the materials used and without proper insulation. This is in line with previous literature which reported that new buildings in KSA continue to be erected without proper insulation (Lahn et al., 2013; Asif, 2015; SEEC, 2021). The lack of insulation may be the most significant factor that affects a building's thermal and energy performance.

Furthermore, the age of buildings can also be a crucial factor when considering building performance. While newly built housing units (less than 5 years old) tend to include wall and roof insulation, in addition to double-glazed windows, older buildings (5 to 10 years old) often include only wall and roof insulation, whereas older units (over 10 years old) are typically built without thermal insulation and with single glazed windows (Krarti et al., 2019; Krarti and Howarth, 2020). As the type and operation of the AC systems used also depends on the housing unit's type, age, and location, the age of the building usually defines its overall condition as well as its energy efficiency level. The findings of the public questionnaire revealed that almost half of the dwellings were more than 10 years old (46%) and 47% had single glazed windows. Although previous studies have proved that single glazing is not as efficient as double-glazed windows in term of solar gain, transmittance, and thermal comfort (Wright et al., 2009; Banihashemi et al., 2015), the findings here suggest that its use is still a very common practice.

5.4.3 Barriers Preventing the Development of Energy-Efficient Dwellings

In order to establish energy-efficient dwellings in Saudi Arabia, the key obstacles identified here, and in other studies, must first be overcome. While lack of awareness is clearly a significant barrier, others relate to the perceived costs associated with sustainable construction, the lack of widely available materials, and to the prevailing cultural and religious beliefs within the country. Islam is deeply embedded in the culture in Saudi Arabia, and it informs every part of life; as such, its influence is felt in the design, construction, and operation of residential buildings too (Aldossary, 2015). While barriers that stem from religious beliefs must be taken seriously and shown appropriate respect as stressed by Al Surf (2015), this section attempts to identify a number of obstacles rooted in cultural practices which could be overcome in order to achieve sustainability objectives. These objectives include reducing energy consumption and minimising CO_2 emissions.

The expert respondents stressed that the lack of public awareness of sustainable and energy-efficient buildings in Saudi Arabia is of major concern. This was supported by the public survey, which showed that 74% of respondents were not aware of sustainable, green, or energy efficient buildings. This is in line with Aldossary et al. (2015) who found that the Saudi public were generally not aware of the environmental and economic benefits related to sustainable construction. Similar concern has also been raised by Alyousef and Stevens (2011). In addition, the fact that land prices in Saudi Arabia have increased by over 50% in recent years makes it more difficult for individuals and developers to build affordable yet energy-efficient housing (Ferris-Lay, 2011). Furthermore, according to the findings, a large majority of respondents, in both the public and experts questionnaire, agreed that the escalating prices of construction materials and products has a negative influence on sustainable development in Saudi Arabia. There is a perception that the use of sustainable techniques and measures in building construction is still primarily regarded as a luxurious option in KSA, a finding supported by Aldossary et al. (2015) and Al Surf et al. (2014) who found it was reserved for those with sufficient financial capacity.

The issue of cost, real or perceived, is a significant obstacle in the way of development of sustainable dwellings. This can be seen in the finding that 50% of public respondents were unwilling to pay more for greater energy-efficiency, or unsure of the effectiveness of such measures. Studies from China also support the idea that the high costs of sustainable construction is still a major obstacle from the homeowner's point of view (Xu et al., 2013; Dianshu et al., 2010). The findings also indicate that there is limited access to information on renewable technology performance, reliability, durability, and cost efficiency, hence, the public lacks awareness of their subsequent benefits and may not be confident in adopting such applications. This was supported by the expert panel who indicated that their clients would still tend not to apply or integrate energy-efficient or sustainable measures into their buildings. In situations where the cost of energy is very low, as it was in KSA until 2018, the high initial costs associated with sustainable energy technology are difficult to recover over time. However, as energy prices increase, and homeowners become more conscious of long-term costs, low energy construction becomes a more effective and economical building alternative for the public to consider (Al Shamsi, 2017). Previous studies have suggested that implementing sustainable housing would require strong government, public, and housing industry support (Al-Badi et al., 2011), but funding for energy-efficient buildings, which can reduce the cost differential between them and conventional buildings, has been identified as an effective way to promote their use in the country, and increase their economic and environmental benefits (Alalouch et al., 2016).

5.4.3.1 Cultural and Religious Barriers

Many of the barriers relating to the costs of constructing and operating a home in Saudi Arabia relate to cultural and religious considerations common to most of the GCC countries. This section considers the ways in which certain Saudi traditions and cultures affects the way houses are designed in the Kingdom.

As previously discussed, traditional and cultural factors found in Saudi Arabia can impact the amount of energy consumption in residential buildings. For instance, one of the major cultural aspects found in Saudi Arabia is that the majority of the population are considered family oriented. Most individuals are close to their elderly family members and pay much respect and consideration to them as they are regarded as the wise leaders of the family (North and Tripp, 2009). It has long been a tradition for a number of generations to live in the same household, with the younger generations look after the elderly and giving great honour to them. As a result, the multigenerational Saudi home is much larger in size than the common single-family dwellings (Al Surf, 2015). Furthermore, the general design of a Saudi home follows the module of Islam, including the segregation of female and male family members and guests; for example, the majority of homes are built with two main entrances, one for females and one for males (Al Surf et al., 2014). Additionally, Saudis often participate in social events where large gatherings occur; therefore, many homes include separate rooms for male and female guest. These rooms are generally quite spacious and equipped with lighting and cooling to provide comfort needs. Limiting the number of rooms to one guest room for both genders would be an ideal solution; however, under Saudi religious traditions, this would not be acceptable. An alternative solution that pays respect to Islamic religious beliefs would be to minimise the size of each room to reduce the level of energy used.

It is a Saudi stereotype that building size and area are symbols of a person's status or position in society (Aldossary et al., 2015), and this contributes to the tendency towards building dwellings of a larger area than is absolutely required. Although the experts indicated that building a house appropriate to the size of the family was the most effective way to reduce energy consumption from a socio-cultural perspective, the public respondents were much less receptive to this idea. This supports Aldossary (2015) who explored this issue and found that many respondents would not accept a reduction in building size to consume less energy. However, it may be possible to reduce energy consumption by changing the way rooms are arranged in the house. The findings of the public questionnaire showed that villas, in the shape of a detached two-storeys house, were among the two dominant types of dwelling for Saudi residents, with flats being the other, and this is in line with two subsequent surveys (Esmaeil et al., 2019; GAS, 2019). A very common area of consideration in the design of two-storeys houses is that most guest rooms are located on the ground floor, with seating areas and bedrooms on the higher floors due to considerations such as having elderly guests and privacy (Al Surf et al., 2013). However, seating areas and bedrooms are more commonly used than the rooms dedicated for guests, and experts have indicated that relocating them to the ground level would consume less energy, especially for lighting and cooling. This is because the ground floors are generally more energy-efficient as the upper floor provides a sort of insulation to rooms on the ground floor, reducing the amount of energy required to cool them. However, some may consider this solution is impractical in the case of having elderly individuals. Therefore, altering some traditional aspects of Saudi housing design could reduce domestic energy use.

Privacy is a fundamental part of the design of dwellings in Saudi Arabia, and it is a key consideration in any stakeholder’s involvement, including architects, urban designers, and landscapers (Abu-Ghazzeh, 1996). As part of the culture, privacy (especially for females) is imperative (Mahmud, 2009), and it can be divided into three major areas in respect of residential buildings (Daneshpour, 2011). These include privacy among family members, privacy between genders, and privacy between dwellings and neighbours or the street (Alsurf et al., 2013). In addition to the separate entrances and rooms for different genders, the findings of the public survey indicate that measures are also taken to prevent occupants’ privacy being breached by neighbours or passers-by. Due to the lack of proper building codes prohibiting the construction of high-rise buildings adjacent to low-rise private residences, windows are often kept closed, or blocked with drapes, requiring the use of artificial lighting, even in the daytime. In addition, the majority of outdoor spaces, such as balconies, verandas, and gardens are underutilised because they lack privacy and have become non-functional over time.

5.4.4 Stakeholder Engagement

Changing behavioural patterns and promoting the idea of low energy construction involves a number of factors. These include higher levels of public awareness, policies focused on changing occupants' behaviours, addressing socio-cultural obstacles, and the creation of a system involving a long-term commitment (Jiang et al., 2013). In order for sustainable housing projects to become successful, major support from the public, the government, and the housing industry is required, and previous literature has stressed the importance of high levels of stakeholder engagement to support the reduction of energy consumption and CO_2 emissions, particularly in developing countries (Zhou, 2006; Zhang et al., 2013; Ng et al., 2013). However, the findings from these surveys indicate a general lack of coordinated enforcement and stakeholders engagement, including government parties, developers, suppliers, contactors, and householders, which are hampering energy-efficiency efforts in the sector.

While there are limited energy reduction options for existing buildings, as the most effective methods can only be implemented during the design and construction stages (Alhashmi et al., 2017), retrofitting existing buildings could offer a great opportunity to improve older housing stock. The expert survey explored some of the current options to consider, such as PV system installation, replacing single glazed windows with more efficient glazing, and the use of shading devices, and based on the findings of Aldossary et al. (2014a), using these methods could decrease energy demand by nearly 34%. The expert respondents concurred with the need to retrofit existing buildings. However, a number of obstacles exist which could prevent effective retrofitting, notably the lack of a stable market for sustainable and energy-efficient products. The findings of the public survey confirmed that there is a shortage of energy-efficient products, such as PV panels, in the Saudi market, and a general lack of expertise and skilled labour in the local sustainable construction sector. This supports the findings of Saleh and Alalouch (2015) who stressed that the majority of small-scale construction firms employ a small workforce and have limited capacity for research and development. In fact, there are only a handful of construction companies in KSA that can exploit new types of materials to produce more sustainable building, and the most prominently known contractors do not entertain small project proposals, such as private villas, because of the low profit margins (Saleh and Alalouch, 2015; Al Shamsi, 2017). Given this, it is significant to see that both respondents groups (public and expert) strongly support the establishment of a well-regulated market that promotes sustainable products and greater access to data about energy-efficient applications to raise awareness and motivate involved parties to embrace low energy construction or retrofitting.

Furthermore, one of the main reasons for the low prevalence of energy-efficient buildings in Saudi Arabia is the lack of effective policies and codes. Until recently, there were no regulatory frameworks for energy conservation in buildings (Alardhi et al., 2020), so a large percentage of residential buildings lack even the most aspects, such as proper insulation. The findings here indicate that in the absence of these types of polices, laws, and regulations, the construction industry is not prepared to fully employ these methods. This is in line with Al Shamsi (2017) who found a lack of commitment to energy conservation in the field, and the government must play a stronger supporting role if low carbon and green construction is to be effectively implemented (Timilsina and Shah, 2016). One outcome from the experts' consultation is that the SBC needs some modification to be able to meet the needs of the Saudi population, as it does not discuss or relate to the cultural needs of the unique Saudi context. According to Aldossary (2015), this is because the SBC is rooted in the American building standards with just a little some editing. This is in agreement with Alshahrani's (2018) view that the SBC ignores the Saudi lifestyle at several stages, including at the management code level; in terms of building preparation and proper definition, and at the construction level. Without specific cultural adaption, it is possible that the issues of sustainability may not be resolved, even if the SBC is fully implemented. In this situation, the government will need to decide what specifications may be used in order to achieve sustainable residential buildings and then tailor laws that relate specifically to KSA and the needs of the local population (Saleh and Alalouch, 2015).

For the Kingdom to begin the steps towards sustainability and meeting the goals of sustainable urbanisation, legislation must be enacted by the government which will provide an incentive for the construction industry to shift to low energy construction practices, as advocated by Chapman et al. (2016). The results of both the public and the expert survey showed that a majority of participants agreed that future construction projects in the Kingdom should adopt an energy saving methodology that also helps to decrease CO_2 emissions, and they also agreed that the government should initiate policies that will support sustainable designs for dwellings. Results also indicate that government entities, such as MoH and MoMRA, need to formulate plans on how to create low energy construction policies and to grant permission and introduce mechanisms to oversee these plans to ensure that construction projects actually follow sustainable guidelines. However, this must be done in ways which do not alienate residents or offend sensibilities, for example, by proposing solutions, such as reducing a dwelling's size, which have been found to be unacceptable. Complementary measures, such as incentives, will also be required to encourage the adoption of energy-efficient solutions for new and existing dwellings across Saudi Arabia. As the findings here and elsewhere indicate that high implementation costs pose a significant barrier, offering some sort of financial incentives could be a powerful driver towards the application of efficient building design and retrofitting. This would be in accordance with the recommendation of Ruiz Romero et al. (2012).

The transformation of the energy sector towards renewable and sustainable sources can lower the demand for power generation (Richter, 2013). However, despite the availability of renewable resources in Saudi Arabia, specifically solar, there appears to be little drive to incorporate it into building sector. While the experts thought that using renewable energy technologies instead of conventional fossil fuels would be beneficial, notably for water heating, they identified high installation costs, lack of local availability, and lack of awareness among users, clients, and technicians as significant barriers. This is where the government should play a more active role in enforcing all parties to apply the minimum principles of sustainable and energy-efficient practices in buildings, the nation’s biggest energy consuming sector. Without regulatory bodies taking action and becoming more involved, the construction sector will not be fully motivated to use renewable energy sources in new construction projects. Additionally, without detailed safety regulations that provide technical frameworks and guidance, and adequate training, the technical barrier to the use of this new technology will remain. For example, government agencies should offer educating and training courses to all type of engineers, architects, contractors, and entrepreneurs, as part of a thorough strategy to achieve sustainable development and conserve energy in future, both nationally and globally. According to Aldossary (2015), this lack of expertise and skills may be attributed to the shortage of university curricula in the field of sustainable construction, so this would require some institutions to improve their curricula to address the topic of sustainability in much greater depth.

5.4.5 Experts’ Recommendations

A number of potential design strategies and recommendations for the domestic building stock emerged from the expert panel consultation, and those which received the highest levels of support were considered in the simulation process in the later stages of this study. This section discusses the experts’ key recommendations in relation to existing literature and the climate and socio-cultural features in Saudi Arabia.

The first section of the consultation process concerned the architectural design of buildings, including orientation, building shape, window design, shading, and HVAC systems. Although previous research has indicated a lack of consideration of orientation in building design in Saudi Arabia, the impact that orientation has on a building's life cycle energy cost can be substantial (Abanda and Byers, 2016). In addition, according to Gabril (2014), solar radiation and air movement are the two major criteria of the local climate that guide the form and orientation of buildings to achieve 'the optimum shape'. As the latitude and high solar radiation levels of the Gulf region lead to the highest intensity of solar radiation falling on the east and west facing walls in summer (Wahl, 2017), the experts highly recommended that new buildings in Saudi Arabia should have a south facing orientation and a rectangular shape. Another important strategy for reducing energy consumption they identified is to minimise the number and size of windows. As hot air flows though exterior windows to the inside of the building, occupants require mechanical devices to cool the internal space to a comfortable level. This translates into higher energy costs as more attempts are being made to cool the warmer air. Their final recommendation in this section was the proper use of shading devices and efficient glazing techniques in order to minimise solar radiation and heat gain in the country's harsh hot climate. These professional judgements seem to be consistent with Aldossary et al. (2014) who found that shading, radiation barriers, and reflective colours could be used to reduce solar heat gain.

Another major area of concern in building design is the building envelope. Housing units in Saudi Arabia have largely transformed from vernacular houses to modern housing that relies on air-conditioning to provide cooling. This transformation and heavy reliance on cooling systems plays a significant role in the increasing national energy demand, especially in buildings with no proper insulation. In fact, previous literature has emphasised the importance of using thermal insulation materials in the building envelope and the significant reduction in energy consumption it brings (Granadeiro et al., 2013; Ghabra, 2017; Taleb and Sharples, 2011; Aldossary et al., 2015). The experts in this study highly recommended adding thermal insulations to the entire building envelope to reduce heat gain through the envelope's elements as much as possible. With a particular focus on external walls, they recommended the use of the double skin walls techniques in the construction of new buildings, with insulation being placed between walls. It is noteworthy that their highest ranked criteria for the selection of insulation materials were availability in local markets and their effectiveness, with the cost of such materials of less importance in their expert opinions.

The experts also agreed that incorporating interior open plan design and using efficient window designs could improve indoor air quality and may help to reduce the demand for cooling. However, the use of natural ventilation is only an option in areas, such as the southern-mountain region, which are cooler than other areas of the country. Another solution highlighted by the experts is to divide the building into zones to create separate cooling and/or heating units, and they also advocated the use of HVAC sensors to control the temperature of the room; these are considered an efficient measure to reduce cooling loads, but they are seldom used. And finally, to return to the topic of incorporating renewable energy into buildings, there was agreement amongst the experts that the integration of solar panels, especially on rooftops, can be a very efficient measure to reduce domestic loads.

5.5 Summary

This chapter has analysed the results of the public and the expert panel surveys and discussed the main findings. It has identified the possible factors causing high energy consumption and the barriers that impede the application of EEMs, including socio-cultural factors specific to the Saudi context. Generally, the findings indicate that the Saudi building sector lacks compliance with the national codes and application of EEMs due to a lack of awareness, high costs of applications, and uncoordinated enforcement of regulations. The professionals also stressed that the application of the SBC in construction projects is still at its primary stage, and it would need enhancement and the full involvement of all stakeholders, private and public, to be effective. Overall, this chapter has identified an urgent need to develop sustainable or energy-efficient guidelines for stakeholders to follow and mechanisms to ensure building codes and requirements are enforced. To fulfil this, a combination of educational, legislative, and financial measures is required to stimulate the application of sustainability in the building industry.

The next chapter describes the creation of the base case model and the validation process adopted prior to testing the effectiveness of the experts' recommendations through a series of simulations.

Chapter Six: Base Case Building Simulation

6.1 Introduction

This chapter concerns the case study building model established using DesignBuilder (DB). Having identified the detached two-storey villa as a typical family dwelling in the Saudi context, a representative building in Riyadh was selected and the data required to structure the model was collected. Details of the selected building's characteristics, construction details, occupancy profile, and utility bills are presented first, followed by the input data and design parameters used to create the model. The chapter goes on to report the base case simulation results and assess the building's performance in term of energy consumption, thermal comfort, and daylighting. Finally, the validation process carried out to ensure that the model was close enough to the real-life case is described.

6.2 Case Study Building

As described in Chapter 5 (See 5.1.1), the detached two-storey villa building type was identified as representative of typical Saudi dwellings, based on the findings of the public survey and housing statistics published by the GAS (2019). As a result, a detached two-storey villa which houses a family of six (the average Saudi family size) was identified in Riyadh, and the data required to create a base case model was gathered during an observation visit to the site. The householder provided additional data for the occupancy profile.

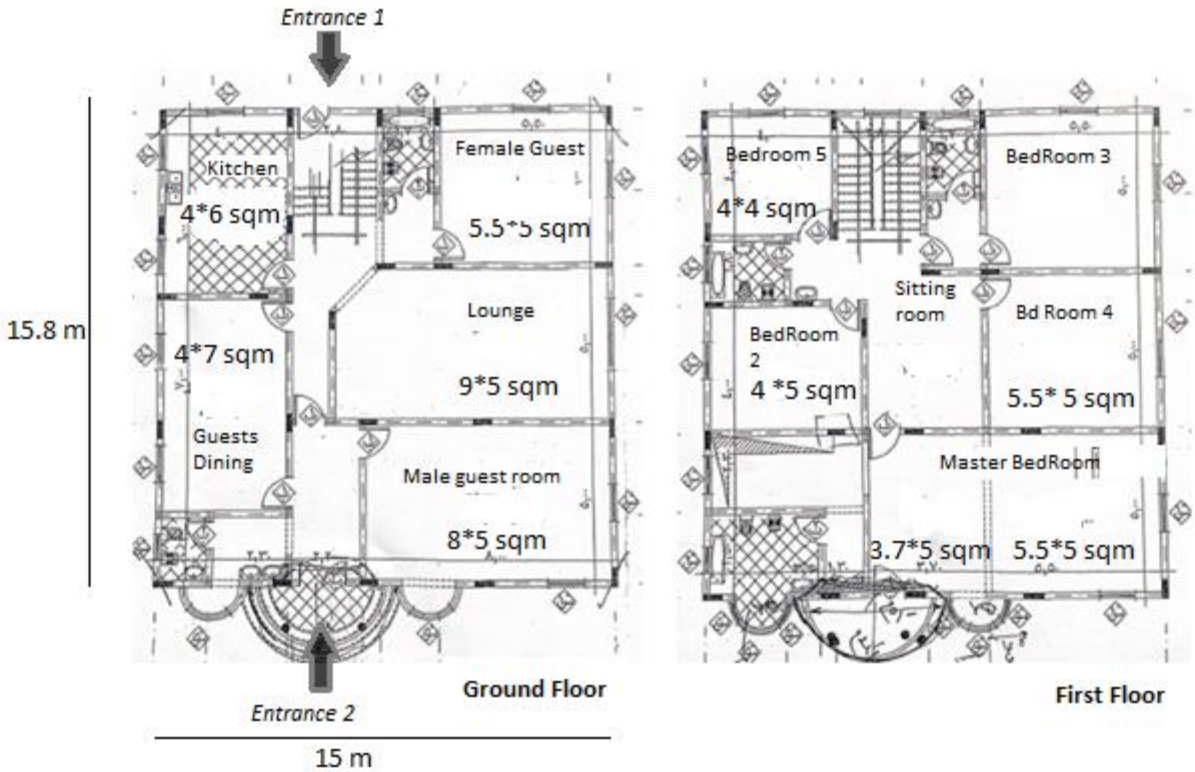
6.2.1 Building Characteristics

The house was built within the last five years. Table 6-1 presents the main building specifications.

Table 6-1: Base case building specifications

Location	*Riyadh*
Façade & Orientation	Front Elevation Eastern Facing
Number of Floors	2
Plan Shape	Rectangular
Total Height	7.0 m
Gross Floor Area	474 m^2 (for 2 floors)
Gross Wall Area	431.2 m^2
Gross Roof Area	237 m^2
Total Area of Windows	41.9 (m^2)
Surface Area to Volume S/V	0.46 (m^{-1})
Glazing Area for each Cardinal Orientation	N (12.6 m^2), E (6.0 m^2), S (14.3 m^2), W (9.0 m^2)
Windows	Single pane windows (SHGC 0.62), U-value (5.78 W/m^2K)
External Walls	U-value (2.15 W/m^2K)
Roof	U-value (2.12 W/m^2K)
Number of Occupants	6
Age of the Building	4 years

Official drawings of the building were obtained from the householder and are provided in Figure 6-1. The U values were obtained from the DesignBuilder construction tab. In this tab, the materials layers and thicknesses were inserted as inputs (as informed by the householder). It is then calculated through the software inbuilt database library and site location. The interior layout of the villa is very common in Saudi Arabia and reflects the Saudi Muslim culture, which maintains a separation between genders. As the figures demonstrate, the ground floor of the building consists of a separate guest room for each gender, a guest dining room, a common lounge, a kitchen, and two toilets. The upper floor includes five bedrooms of different areas (20 m², 25 m², and 50 m²), one office, one sitting room, and three bathrooms.



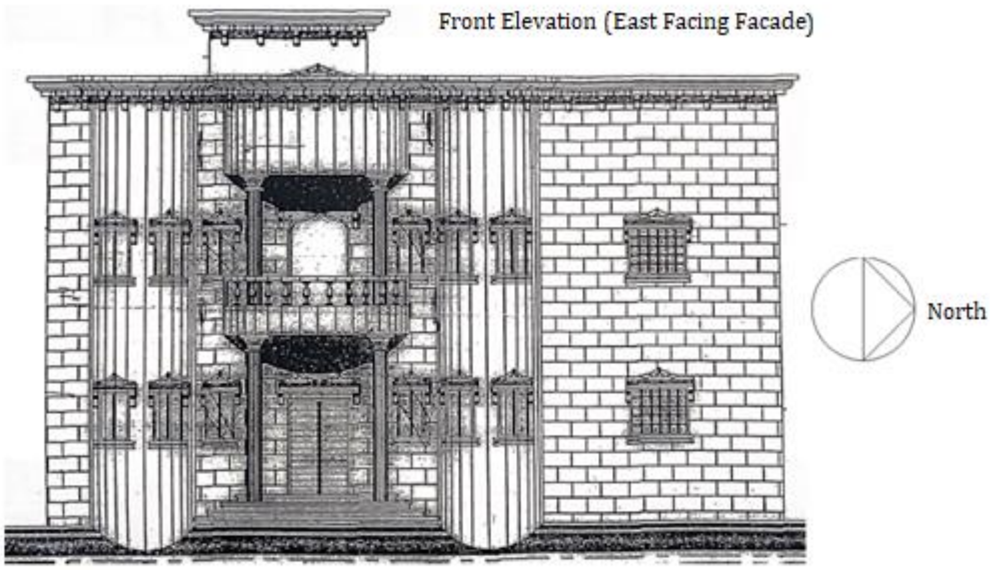


Figure 6-1: Official drawings of the case study building- Zone dimensions (top)- Front elevation (Bottom) (Source: Provided by the householder)

6.2.2 Building Construction Details

Typically, houses in Saudi Arabia are made from reinforced concrete columns and beams and the walls are made of concrete blocks. The villa was built using conventional methods and typical materials in the Saudi context. For example, Kaneesamamkandi et al. (2015) indicated that the walls of residential buildings typically consist of three layers: the external cement plaster, hollow blocks (of different thicknesses depending on whether they are inner or outer walls), and the interior cement plaster. Other common construction materials widely used in KSA and their thermal properties are presented in Table 6-2.

Table 6-2: Thermal properties of traditional materials used in construction in Saudi Arabia (ASHRAE, 2009)

Material	Thickness *(m)*	Conductivity *W/(m.K)*	Density *(kg/m³)*	Specific heat *J/(kg.K)*
Terrazzo tiles	0.025	1.8	2560	790
Granite tiles	0.02	2.9	2650	900
Mortar	0.025	0.88	2800	896
Stucco	0.025	0.72	1856	840
Bitumen layer	0.004	0.43	1600	1000
Heavyweight concrete	0.15	1.95	2240	900
Concrete block	0.2	1.11	800	920
Gypsum board	0.015	0.16	640	1150
Expanded polystyrene EPS	0.05	0.03	40	1470

According to the household, the envelope of the case study building was constructed without insulation and the windows are single-glazed, both practices seemingly still common in residential building construction in Saudi Arabia. Figure 6-2 illustrates a typical envelope of a villa under construction in KSA, clearly showing the concrete blocks.

Figure 6-2: Typical envelope of a villa building under construction in KSA (Source: Khabaz, 2018)

The materials used in the construction of the selected building are detailed in Table 6-3 and cross sections of the inner and outer surfaces of the building envelope elements are shown in Figure 6-3.

Table 6-3: Details of the building elements in the case study construction

Building Element	No. of Layers	Description of layers	Thickness (mm)	U-Value (W/m²-K)
External walls	*3*	25mm stucco + 200mm concrete hollow block + 20mm cement plaster	*245*	*2.146*
Internal walls (Partitions)	*3*	20mm cement plaster + 200 concrete hollow block + 20mm cement plaster	*240*	*1.728*
Roof	*6*	25mm terrazzo + 25mm cement sand render + 50mm sand + 10mm Bitumen + 220mm cast concrete + 200mm air gap+ 15mm gypsum plasterboard	*545*	*2.123*
Internal floor (Ceiling)	*5*	12mm ceramic + 25mm cement sand render + 50mm sand + 220 cast concrete + 150mm air gap+ 15mm gypsum plaster	*322*	*2.047*
Ground floor	*4*	12mm ceramic + 25mm cement sand render + 50mm sand + 100mm cast concrete	*187*	*2.767*
Windows	*1*	6mm single pane blue glass	*6*	*5.778*
External doors	*3*	3mm steel + 40mm air gap + 3mm steel	*46*	*2.856*
Internal doors (Rooms)	*1*	40 mm woods	*40*	*2.381*
Internal doors (Toilets)	*3*	3mm aluminium + 25mm EPS + 3mm aluminium	*31*	*1.258*

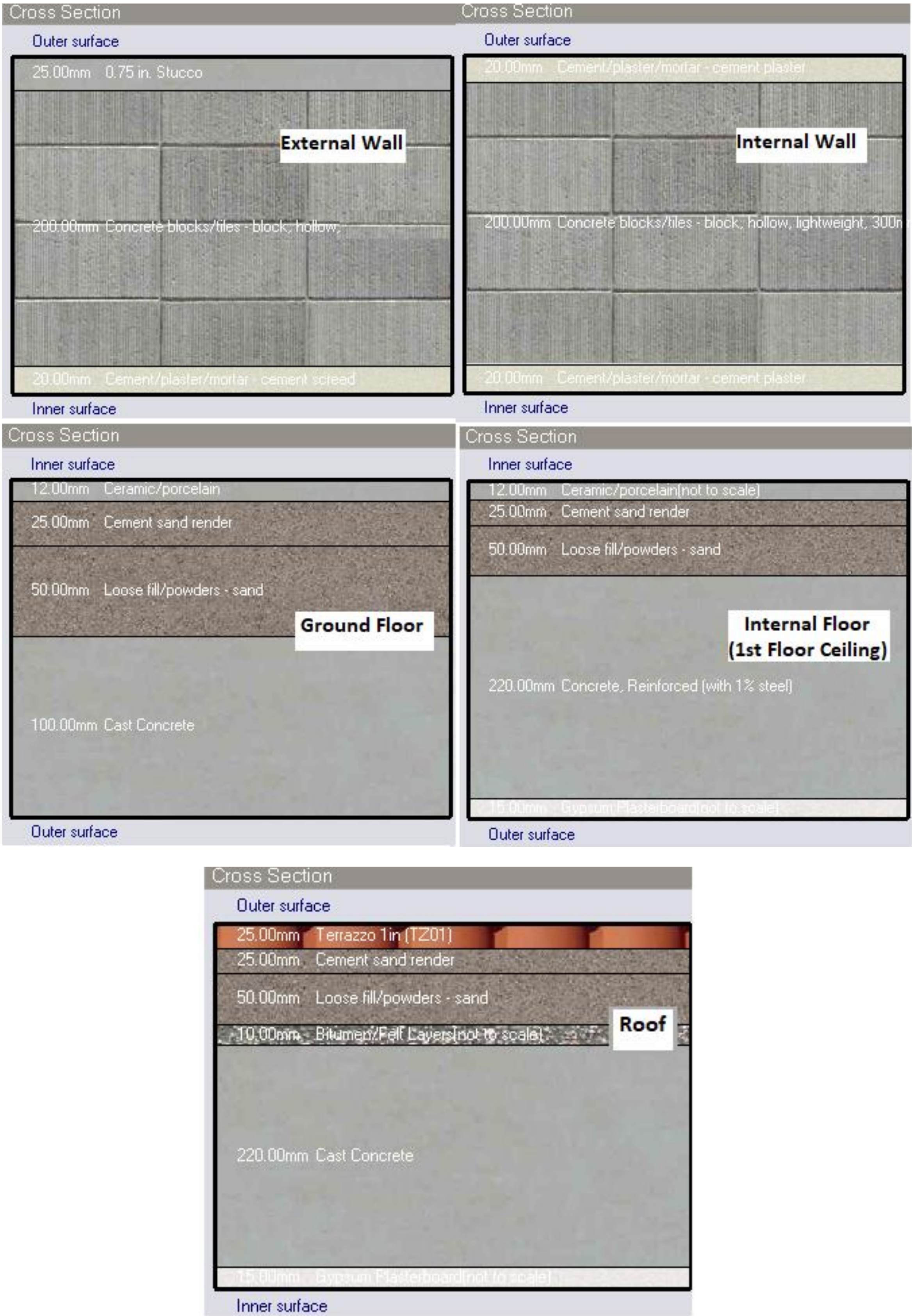


Figure 6-3: Cross sections of building envelope elements

6.2.3 Building Occupancy Profile

This household's occupancy profile echoes those found in the public survey analysis in Chapter 5. Of the six family members, only two go out to work or school (7:30 am to 2:30 pm), with the others staying at home. This reflects the fact that many wives in KSA do not work outside the home and a cultural preference amongst some people for females not to leave the house unless necessary. The householder of building indicated that the guest rooms and guest dining rooms on the ground floor were only occasionally occupied such while the bedrooms and kitchen on the upper floor were occupied almost continuously. As for family gathering, the family use the sitting room (on the upper floor) most of the time. An occupancy schedule for the building is provided in a Table 6-4 showing the periods when each of the rooms is in use. This information was obtained from the household occupancy profiling as informed by the householder himself. The data were collected in the site visit stage.

Most rooms in the house use window type air conditioning with the exception of the master bedroom where a split system is used. The householder indicated that the SASO efficiency rating of the AC is a 2-star (roughly equivalent to a coefficient of performance CoP=2.5). During the summer, the AC is operated all day and at night (i.e. more than 12 hours per day), according to the householder at a setpoint thermostat temperature of 20°C. He also reported that artificial lighting in used for most of the day and at night, although natural lighting is used occasionally.

Table 6-4: Occupancy schedule for the case study building

		Occupancy Schedule (Time of the day)							
	Zone	***00:01- 4:00***	***4:01- 7:00***	***7:01 - 10:00***	***10:01 - 12:00***	***12:01 - 15:00***	***15:01 - 18:00***	***18:01 - 21:00***	***21:01 - 00:00***
Ground Floor	Male Guest Room								
	Female Guest Room								
	Guest Dining Room								
	Common Lounge								
	Kitchen								
Upper Floor	Master Bedroom								
	Children's Rooms								
	Office								
	Sitting Room								
Occupancy Frequency			***Rare***		***Often***		***Repeated***		

6.2.4 Energy Consumption of the Case Study Building

In order to assess the household's energy consumption, copies of the monthly electricity bills for the year 2019 were gathered from the household and the Saudi Electricity Company. The monthly readings revealed an annual consumption level of 46,143 kWh. The cost per kWh of electricity is 0.18

Saudi Arabian Riyal (SAR), equivalent to 0.048 USD/kWh, giving a total annual cost of 8306 SAR (i.e. 2215 USD).

The monthly totals were used to plot the energy consumption pattern throughout the year. As Figure 6-4 demonstrates, the highest consumption rates occurred in the summer months, from Jun to Sep, with a particular focus on the two hottest months of the year, July and August.

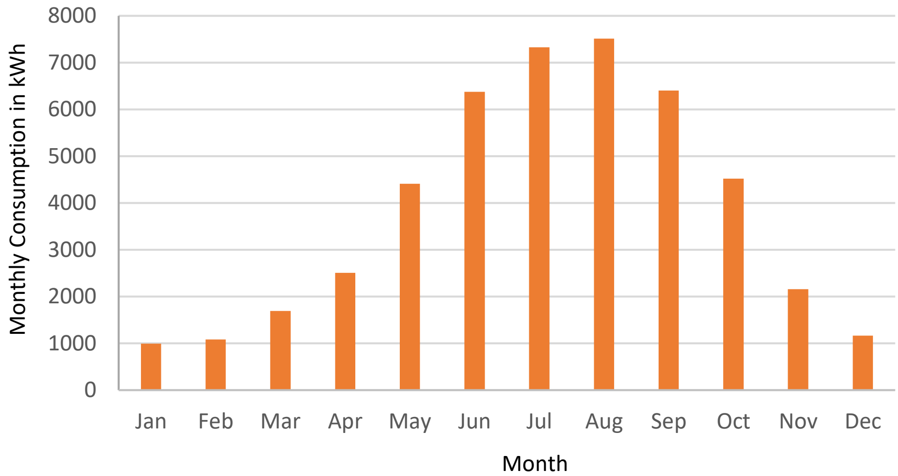


Figure 6-4: Electricity consumption pattern for 2019 in the case study villa

6.2.5 General Observations on the Dwelling and the Household

Several of the common building design problems identified in relation to indoor and outdoor spaces were observed in the case study villa. The lack of wall insulation and efficient gazing means artificial cooling is required to maintain thermal comfort in indoor spaces, especially in the summer months. In addition, the household finds it difficult to open their windows for ventilation or lighting purposes, often because the harsh outer climate and the fact that windows are covered with drapes to preserve privacy. From an energy efficiency perspective, households should harvest sunlight as a source of lighting; instead, the use of window coverings leads to the use of artificial light during the day and higher energy consumption. In addition, while tall walls are erected around the house for more privacy, there is minimal use of vegetation and shading devices, something which is widely observed in the Saudi housing sector.

Most of these observations accord with the public survey findings described in Chapter 5. However, with reference to vernacular building construction, the site visit indicated that some households appear to have copied the design of their neighbours' or friends' houses (known as Repeated Design Pattern), with little or no consideration for energy efficiency or climate responsive design.

6.3 Parameters for the Simulation

Riyadh is characterised by its hot dry weather. Based on Auliciems and Szokolay's (1997) study of the climatic design criteria that can influence a building's thermal performance, the following parameters for the simulation and analysis process were identified:

- External wall (thermal mass, insulation, and thickness)
- Internal ground floor (thermal mass, insulation, and thickness)
- Roof (thermal mass, pitch, structure, overhang length, covering)
- External window (size, type, glazing thickness and type)
- Window to wall ratio

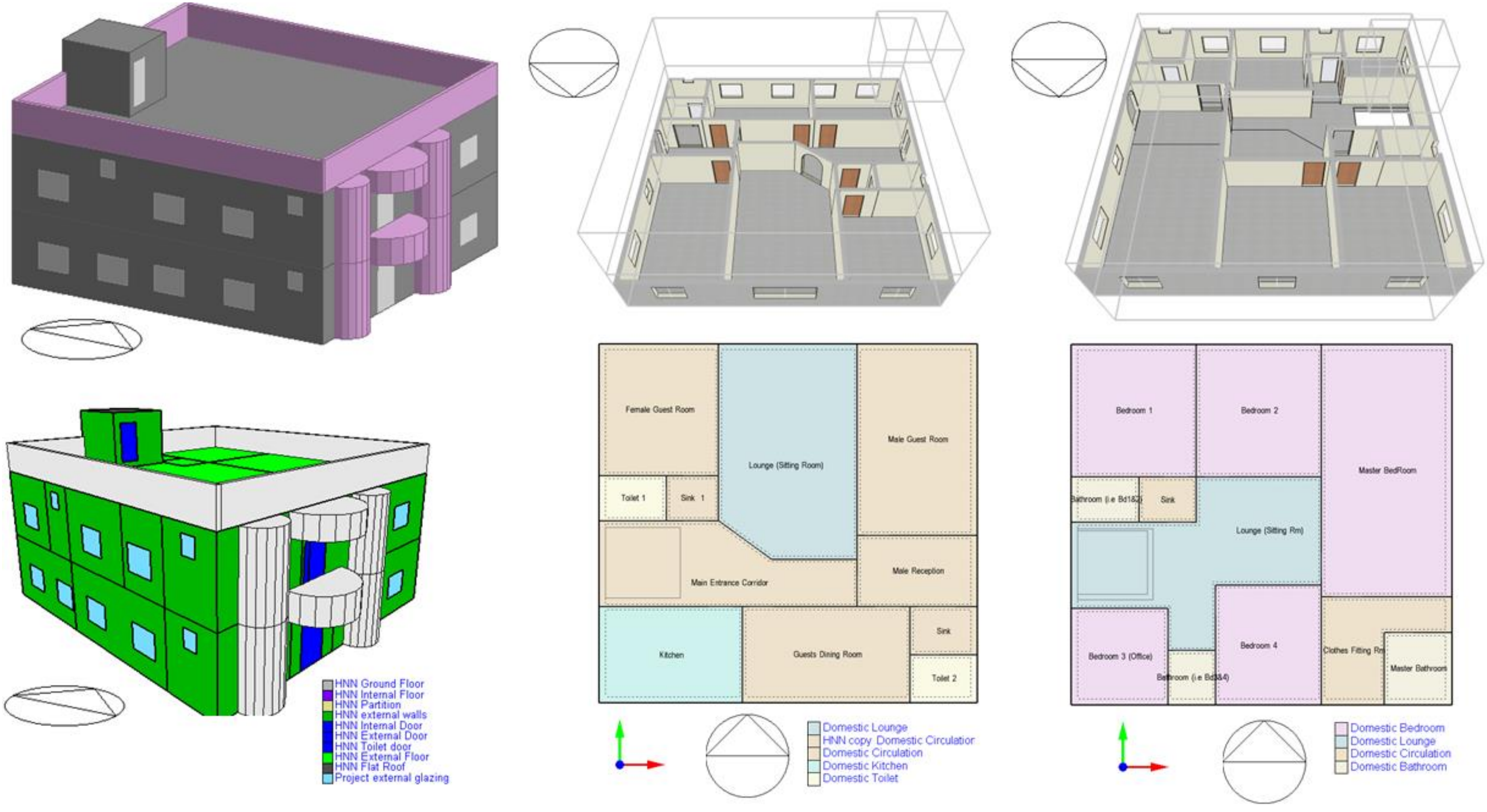
The input data from the representative case study house are given in Table 6-5. The details of the construction materials as well as the electricity bills were provided by the householder. Windows were assumed to be closed or rarely opened as indicated by the householder due to privacy and climatic reasons. Hence, the effect of opening windows was neglected. The 20°C cooling set point was given by the householder as the frequent base temperature. Cooling and lighting operation schedules were inserted into the DesignBuilder HVAC/lighting input tabs for each zone. Generally, air-conditions were operated continuously and artificial lighting is still being used even during daytime.

The parameters selected for the simulation values included the floor plan and physical geometry, the physical location and orientation, using longitude and latitude values, the building material parameters, and the hourly weather conditions for the local area.

Table 6-5: Summary of input data for simulation in DesignBuilder

Openings	HVAC	Lighting	DHW	Occupancy
Single Glazing windows (Blue 6mm) U-value = 5.778 (W/m^2-K) Position: Inside	Packaged DX AC with CoP= 2.5 *Split AC no fresh air (in specific zones) Cooling Setpoint temperature = 20 °C Electricity from grid	Surface mount LED Lighting Power density = 2.5 (W/m^2 – 100 lux) Radiant fraction = 0.72 Visible fraction= 0.18	Instantaneous hot water with a default CoP = 0.85 Electricity from grid	Density = 0.16 people/m^2 Metabolic activity = Light Manual Work Metabolic Factor = 0.9

The data were entered into DB in order to generate a base model. The plans and the axonometric description of the model are shown in Figure 6-5 whereas the individual dimensions for each zone were presented earlier in Figure 6-1. This setup was established to enable the comparison and validation of the simulation results, as described in the rest of this chapter.



Axonometric View **Plan View (Grd Floor)** **Plan View (1st Floor)**

Figure 6-5: The axonometric and plan view of the modelled building (DesignBuilder)

6.3.1 Site Data

The general site description of the base case simulation is shown in Table 6-6. DB includes an extensive library of weather files, covering almost all the regions of world, and the file RIYADH-SAU IWEC Data WMO#=404380 was selected to provide the most appropriate weather characteristics for the simulation.

Table 6-6: General site description of the simulation

	Value
Program Version and Build	EnergyPlus, Version 8.9.0-40101eaafd, YMD=2021.02.25 00:06
RunPeriod	UNTITLED (01-01:31-12)
Weather File	RIYADH - SAU IWEC Data WMO#=404380
Latitude [deg]	24.70
Longitude [deg]	46.80
Elevation [m]	612.00
Time Zone	3.00
North Axis Angle [deg]	0.00
Rotation for Appendix G [deg]	0.00
Hours Simulated [hrs]	8760.00

It is worth noticing that the pre-set 'summer' months for the Riyadh weather file simulation run from April to October; however, these were altered to run from June to September. In these months the maximum dry-bulb temperatures are highest (See Table 6-7), and the analysis of the electricity usage in the case study villa showed that AC use was significantly higher during this period. Given the impact of AC usage on building energy performance and the fact that Saudi summers are forecast to get even hotter, with a rise of between 2.0°C to 2.75°C expected by the year 2050 (Ragab and Prudhomme, 2000; Almazroui et al., 2012), it is critical that buildings can adapt to meet these future conditions.

Table 6-7: Dry-bulb temperatures for the summer months

	Maximum Dry Bulb [C]
SUMMER DESIGN DAY IN UNTITLED (01-01:31-12) JUN	41.00
SUMMER DESIGN DAY IN UNTITLED (01-01:31-12) JUL	41.10
SUMMER DESIGN DAY IN UNTITLED (01-01:31-12) AUG	40.90
SUMMER DESIGN DAY IN UNTITLED (01-01:31-12) SEP	39.90
SUMMER DESIGN DAY IN UNTITLED (01-01:31-12) OCT	35.10

6.4 Building Simulation Results (Base Case)

This section discusses the results of the simulation based on the previously defined parameters and the DB software, and examines data for the building envelope, the orientation, and the performance of the model in terms of the energy, thermal comfort, and daylighting. In the final stage, the real gathered values of the energy consumption for the case study building are compared to the simulated values to assess the accuracy of the model.

6.4.1 Building Envelope Data

Research has indicated that the window to wall ratio (WWR) has more impact on the building energy consumption than window U-value (Lee et al., 2012), and previous studies have recommended WWRs of 20% and 24% for adequate daylighting in buildings in Singapore and Thailand respectively (Tantasavasdi et al., 2001; Liping and Hien, 2007). However, the findings of this study indicate that the WWR for dwellings in Saudi Arabia is typically much lower than this; for example, the selected building's WWR is around 9%. This is very low by international standards and it significantly affected the daylight factor in the building; this is explored in more detail below (Bichiou and Krarti, 2011; Olofsson and Mahlia, 2012; Tantasavasdi et al., 2001; Liping and Hien, 2007).

The walls of the case study villa are mainly made of 200 mm hollow concrete blocks, and there is no adequate thermal insulation in the external walls. As discussed in Chapter 2, concrete masonry is considered a high thermal mass material with a high capacity to store and absorb heat gained from solar radiation. With longer sunlight hours and more intense heat during the summer months, uninsulated walls cannot prevent indirect solar gains and indoor thermal temperatures can quickly become uncomfortable unless mechanical cooling is used. Figure 6-6 illustrates the heat exposure of external surfaces in August (the hottest summer month).

- Early Daytime: East façade (main façade) will have a surface temperature of around 40°C
- Mid-Day to Early afternoon time: the roof will have a temperature between 40.1 - 42°C
- Late Afternoon times: West elevation will also experience surface temperatures up to 40.1°C

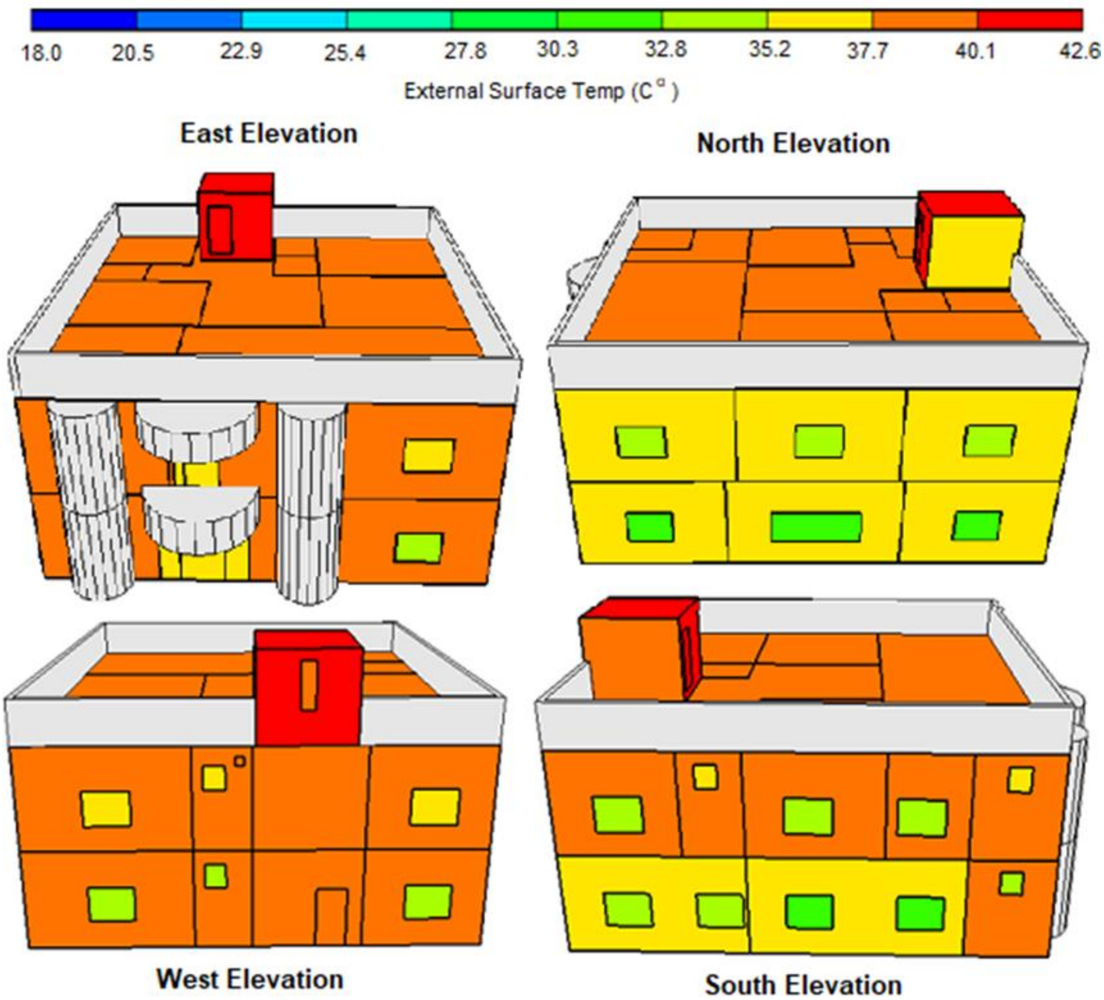


Figure 6-6: External surface heat exposure (Source: DesignBuilder Model)

6.4.2 Orientation Data

The existing villa is oriented toward the east and this orientation was also used for the modelling. Figure 6-7 shows the simulated sun paths over the building in the morning (at 8 am) and in the late afternoon (4 pm) on the 15th of August 2019.

As seen in Figure 6-8, the solar emittance, both at 8 am and 4 pm, seems to have only a minor effect on the building zones, possibly due to the small window sizes and the WWR of this building. DesignBuilder is a sophisticated software that has inbuilt worldwide data library. For this particular data, the solar emittance is simulated and calculated according to the input data of the site location (Riyadh), weather profile library, building orientation, and windows sizes. This is in line with previous studies suggesting that the orientation of a building has an insignificant influence on its energy performance, even in hot climate regions. For example, Alrashed et al. (2015) found that changing the orientation of buildings in Saudi Arabia would lead to less than 0.5% energy saving, and Ali (2018) found only a 0.02% saving in the annual energy demand only in the context of Libya. As a result of this insignificant effect, the parameter of orientation will not be considered in the improvement simulations.

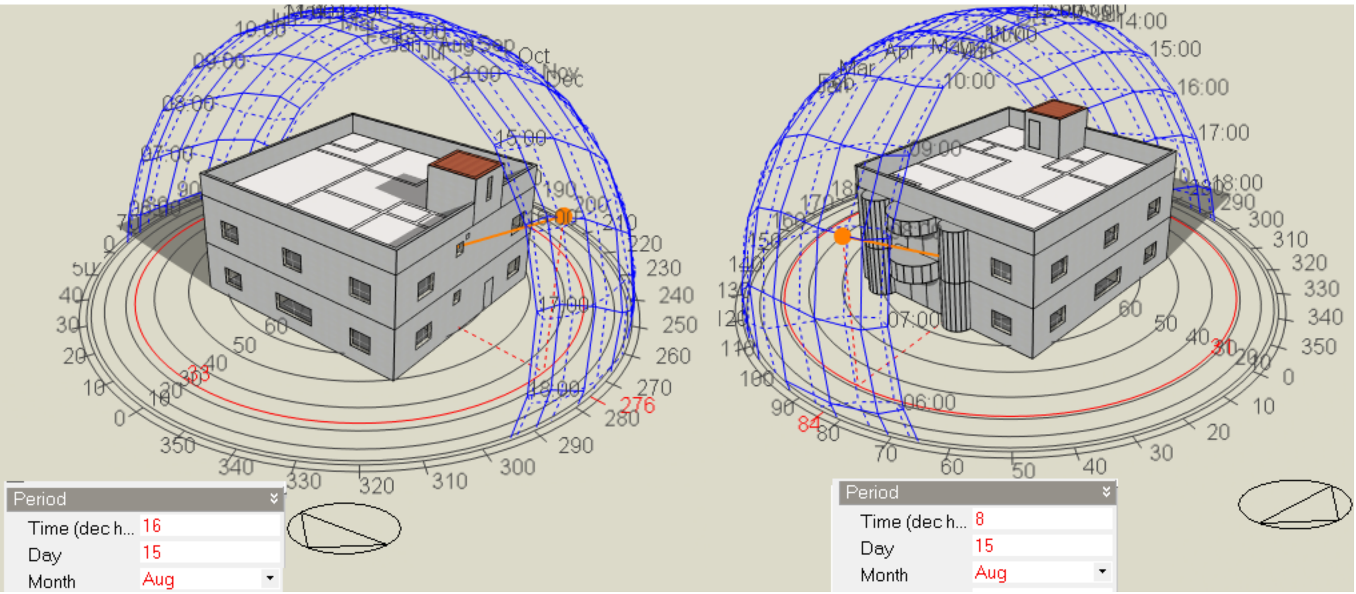


Figure 6-7: Diagram showing the simulated sun paths of the building

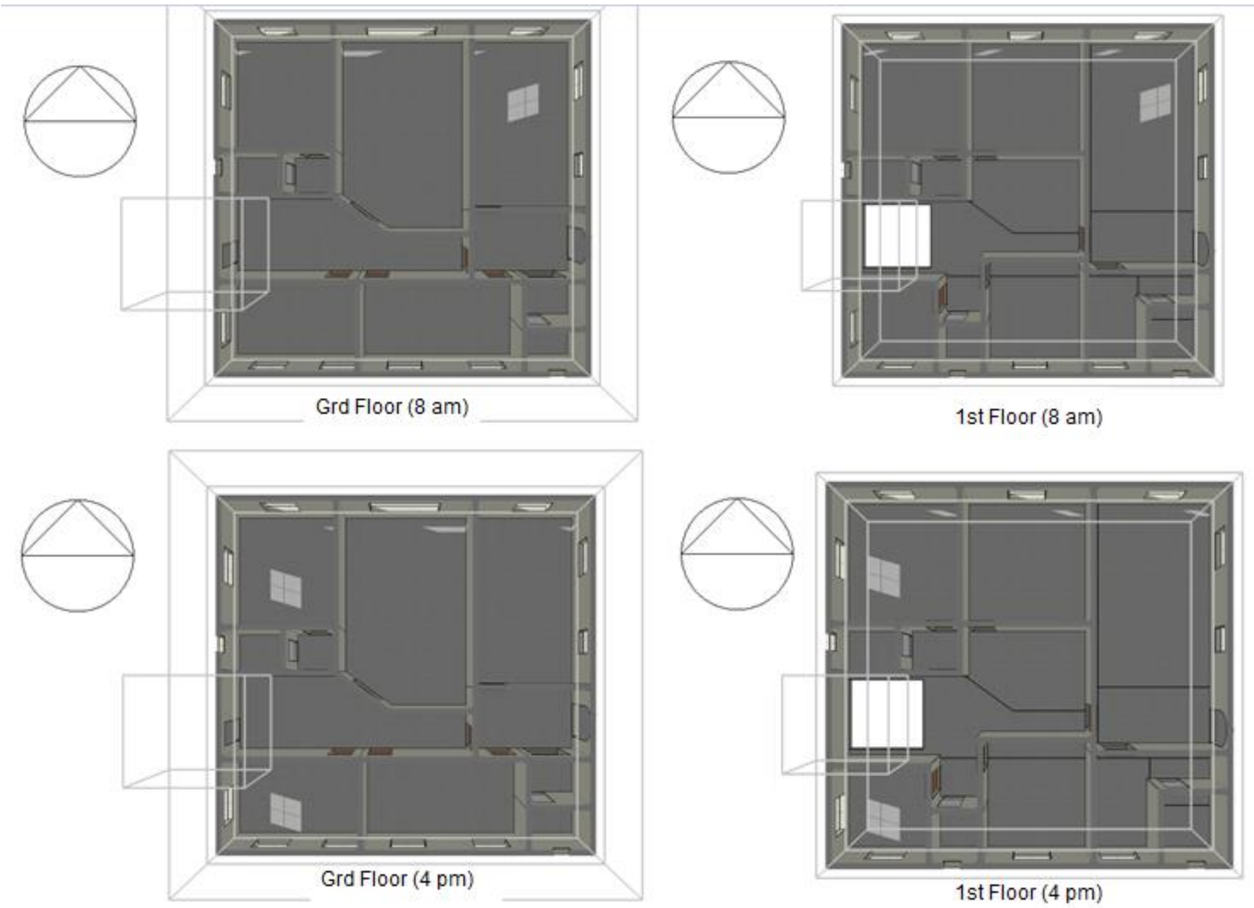


Figure 6-8: Solar emittance of both floors (East and West directions)

6.4.3 Energy Consumption

The annual energy consumption of the modelled base case was 47,389 kWh. A breakdown showing the energy consumption totals for cooling, lighting, heating, domestic hot water, and room electricity is given in Figure 6-9. As can be seen, the computer simulation was able to capture the significant increase in energy consumption from May to October – which is primarily due to the increased use of the AC during the hot summer period. The annual energy consumption can also be expressed as an energy use intensity (EUI) in kWh/m²/year. The EUI for the base case model is nearly 141 kWh/m²/year, with energy consumption for cooling alone at nearly 115 kWh/m² per year which by far exceeds the average annual energy for space cooling in residential buildings in European countries at nearly 22 kWh/m² per year (Kurnitski et al., 2018; Dittmann et al., 2017). This is due to the local harsh climatic conditions which require mechanical cooling to maintain occupants' comfort. As Figure 6-10 demonstrates, 82% of the total annual energy consumed was due to the cooling load, estimated at 38,836 kWh per annum.

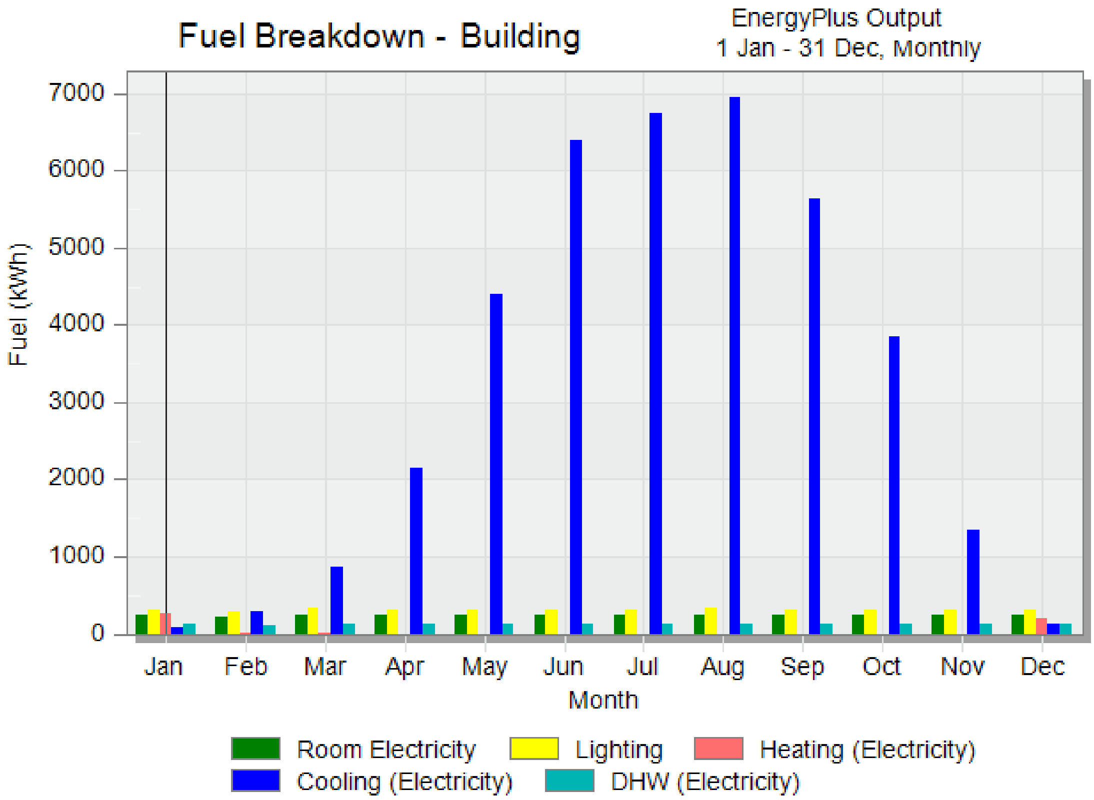


Figure 6-9: Breakdown of monthly energy consumption of base case simulation

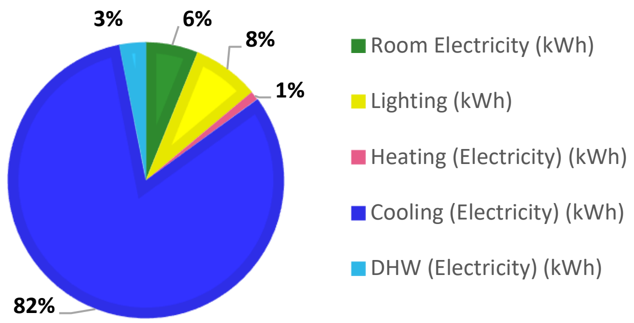


Figure 6-10: Annual energy consumption breakdown

The total CO_2 emissions for the whole year amounted to 28,718 kg. A breakdown showing the monthly CO_2 emissions for the building is displayed in Figure 6-11. As there are six occupants in the house, the CO_2 emissions per capita were about 4,786 kg (4.8 tonnes), which is almost double the average CO_2 emission per capita in EU member states (about 2.5 tonnes) (Kurnitski et al., 2018; Aldossary et al., 2014). It is clear that the emissions increased in summer due to the operation of cooling systems, so any reduction in the cooling load would lead to a reduction in CO_2 emissions.

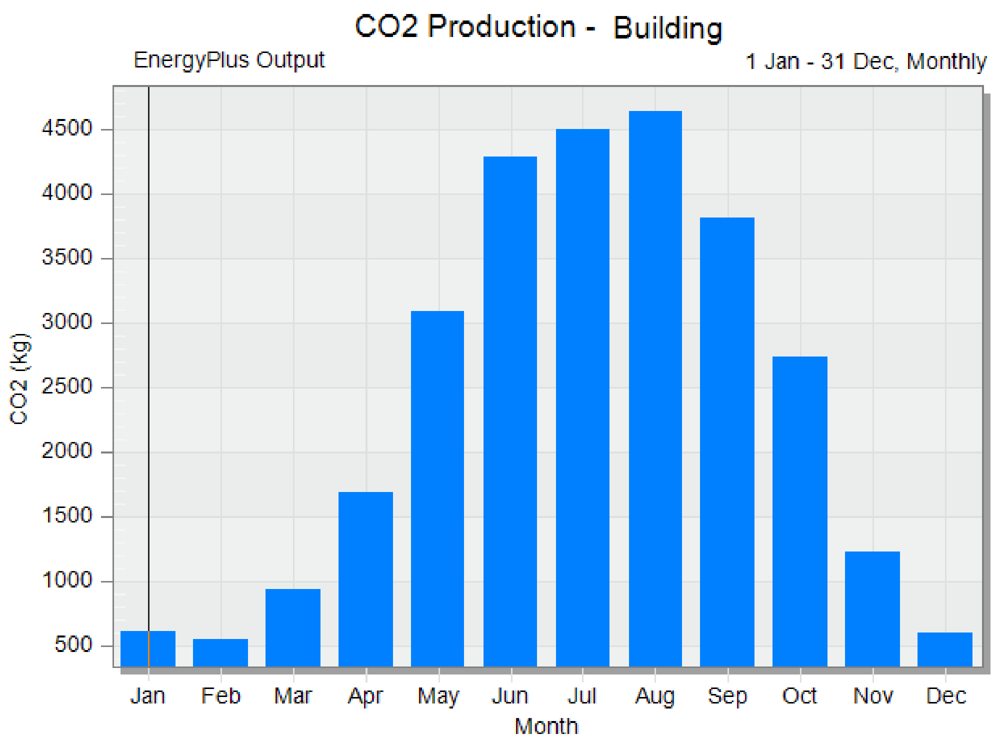


Figure 6-11 Monthly CO_2 emissions for the base case model

6.4.4 Thermal Comfort Performance

Figure 6-12 depicts the results of the simulation of the thermal comfort level of the base case house over the period of one year. The comfort level is measured by the levels of:

- outside dry-bulb temperature (i.e. site data)
- air temperature (i.e. the dry-bulb temperature of the internal space)
- radiant temperature (i.e. the average Mean Radiant Temperature (MRT) of the zone, calculated assuming that the person is in the centre of the zone, with no weighting for any particular surface)
- operative temperature (i.e. the mean of the internal air and radiant temperatures).

As the figure demonstrates, as the outside temperature begins to rise above 25°C at the end of March, the AC system achieves its aim of maintaining an acceptable level of indoor thermal comfort.

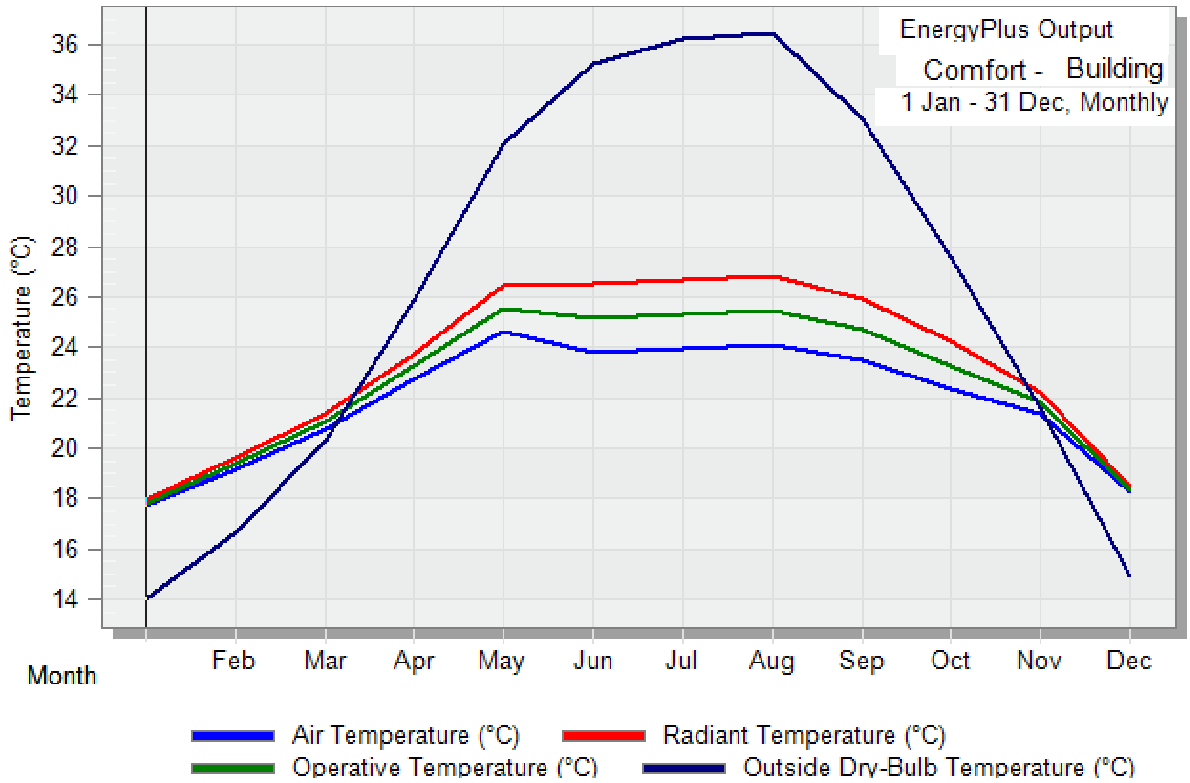


Figure 6-12: Simulation results for thermal comfort level in the base case building

Furthermore, the fabric and ventilation heat balance analysis of the base case model indicated that the walls were the main contributor to the heat gain in the building, followed by the roof. This is illustrated in Figure 6-13.

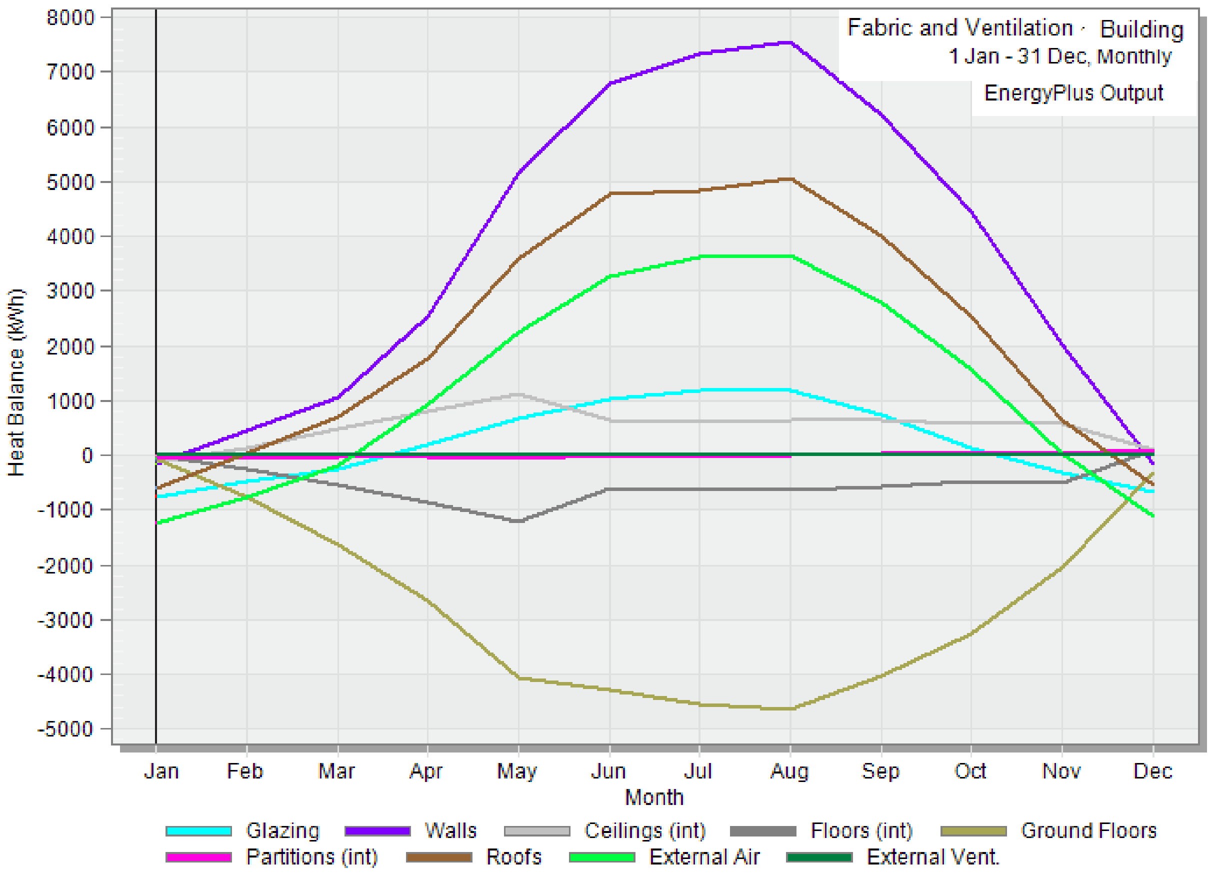


Figure 6-13: Fabric and ventilation heat flow in the base case building

6.4.4.1 Thermal Comfort Analysis

Occupant thermal comfort is difficult to analyse because 'comfort' is a state of mind or a personal feeling rather than a quantifiable metric (Beizaee and Firth, 2011). However, Fanger (1970) established a model to evaluate occupant comfort with reference to specific parameters and proposed a method by which the actual thermal sensation could be predicted by producing values for the 'Predicted Mean Vote' (PMV) and the 'Predicted Percentage of Dissatisfied' (PPD) (Kumar, 2014). The PPD index provides an estimate of how many occupants in a space would feel dissatisfied by the thermal conditions, and the PMV index is explained below.

The PMV equation is now widely used to predict the thermal sensation of occupants and It has been incorporated into international standards such as ISO-7730. Indeed, research indicates that it is probably the most broadly used thermal comfort index to measure indoor thermal environments (Humphreys and Nicol, 2002). The PMV equation uses four environmental parameters (air temperature, MRT, air velocity and relative humidity [RH]) and two personal variables (clothing insulation [Clo] and metabolic rate [MET]) as inputs to predict the thermal sensation of occupants on ASHRAE's 7 point thermal sensation scale. The PMV index is presented in Figure 6-14, with a PMV equal to zero representing thermal neutrality.

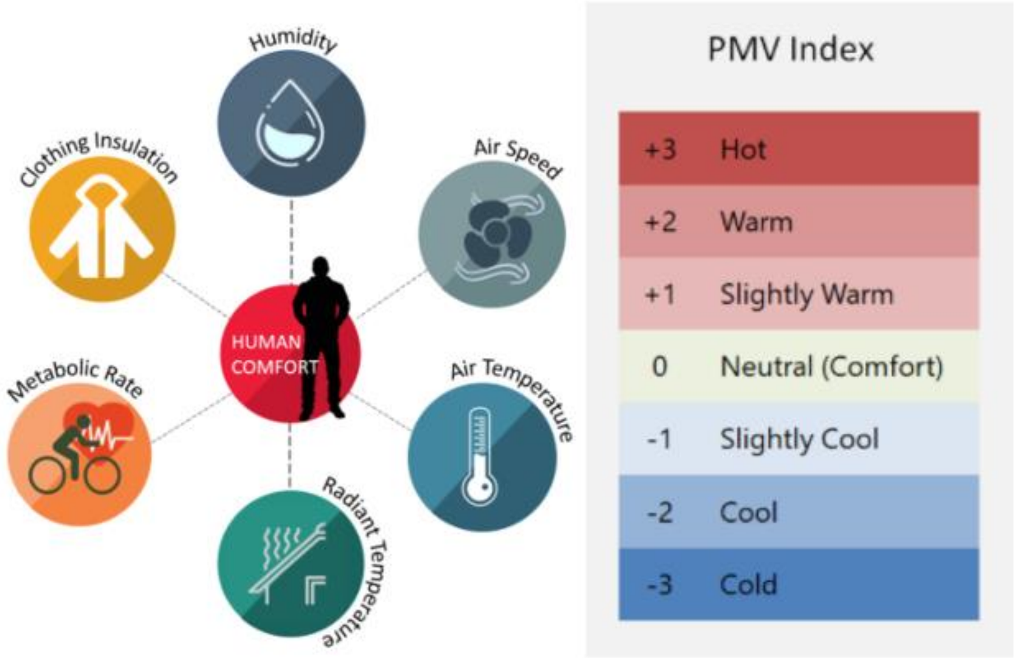


Figure 6-14: Thermal sensation scale (Source: Kumar, 2019)

The PMV model has been validated by numerous studies as an accurate predictor in air-conditioned buildings with HVAC systems, in any climatic conditions (Yau and Chew; 2014; Beizaee and Firth; 2011; Fanger; 2002). Comfort limits can in this case be expressed by the PMV and PPD indices.

Acceptable PMV and PPD Ranges:

- ASHRAE 55 standard states that the recommended thermal limit on the 7-point PMV scale is between -0.5 and 0.5 with a corresponding PPD falling below 10%.
- ISO 7730 expands on this limit, giving different indoor environments ranges. ISO defines the acceptable comfort limits range between -0.7 and +0.7 for old buildings, and between -0.5 and +0.5 for new buildings.
- All occupied areas in a space should be kept below 20% PPD in order to ensure thermal comfort according to the known standards (ASHRAE 55 and ISO 7730).

6.4.4.2 Base Case Thermal Comfort Analysis

EnergyPlus provides a sophisticated building thermal analysis tool, the DesignBuilder Thermal Comfort Calculator, which can be used to determine whether the environmental control strategy in place will be sufficient for the occupants to be thermally comfortable (DesignBuilder, 2021). For this tool to produce the proper output, the six parameters used in the PMV equation are inserted as follows:

1. Clothing value (Clo) – this can be calculated simply by using a Clo value of 1.0 for winter and 0.5 for summer, or by adding the Clo value of each individual garment. Table 6-8 provides recommended Clo-values for different items of clothing and typical outfits.

Table 6-8: Clo-values for different items of clothing and outfits

Clothing	Clo-Value
Naked	0.0
Briefs	0.06
T-shirt	0.09
Bra and panties	0.05
Long underwear	
upper	0.35
lower	0.35
Shirt	
White, short sleeve	0.14
heavy, long sleeve	0.29
Add 5% for tie or turtleneck	
Skirt	0.22-0.70
Trousers	0.26-0.32
Sweater	0.20-0.37
Socks	0.04-0.10
Light summer outfit	0.3
Working clothes	0.8
Typical indoor winter clothing combination	1.0
Heavy business suit	1.5

2. Air temperature (°C) - the average temperature of the air surrounding the occupant.
3. MRT (°C) - this is related to the amount of radiant heat transferred from a surface, and it depends on the material's ability to absorb or emit heat, or its emissivity.
4. Air speed (m/s) - DB has a default air velocity of 0.137 m/s used by EnergyPlus.
5. Relative humidity (%) - this is also provided by DB simulation according to the site data.
6. Activity metabolic rate (MET) - this can range from 0.7 to 4.4 Met for different activities, according to the ASHRAE standard for thermal environmental conditions for human occupancy. The metabolic rates for some typical tasks are presented in Table 6-9.

Table 6-9: The metabolic rates for typical tasks (Source: ASHRAE, 2013)

Activity		Metabolic Rate Per Person (Met)
Resting	sleeping	0.7
	reclining	0.8
	seated, quiet	1.0
	standing, relaxed	1.2
Office activities	reading, seated	1.0
	writing	1.0
	typing	1.1
	filing, seated	1.2
	packing/lifting	1.4
Misc. activities	cooking	1.6-2.0
	house cleaning	2.0-3.4
	seated, heavy limb movement	2.2
	walking on level surface	2.0
	dancing/social	2.4-4.4

The outcome of Thermal Comfort Calculator is reflected by Fanger's Comfort Model (shown in Figure 6-15). Discussion on how these values were obtained and what is an acceptable range of thermal comfort was provided earlier in Sections 6.4.4.1 and 6.4.4.2. If the PMV value is within the comfort region (-0.5 to +0.5), then the outputs and the line between the PPD axis and the curve are displayed in green, otherwise they are displayed in red, as is the case in Figure 6-15. This indicates that the comfort analysis in the building falls outside the recommended comfort limits, with a PMV value of -1.39 and a PDD of 45.2% which implies that the indoor condition is cool. This can be explained by the lack of thermal insulation and the continuous operation of air conditioning to reduce the level of discomfort caused by the hot weather in Riyadh. This is in line with Beizaee and Firth (2011) who found that hot climatic regions in the summer season have a trend towards -1 and -2 actual thermal sensation vote which suggests that the occupants are overcooled.

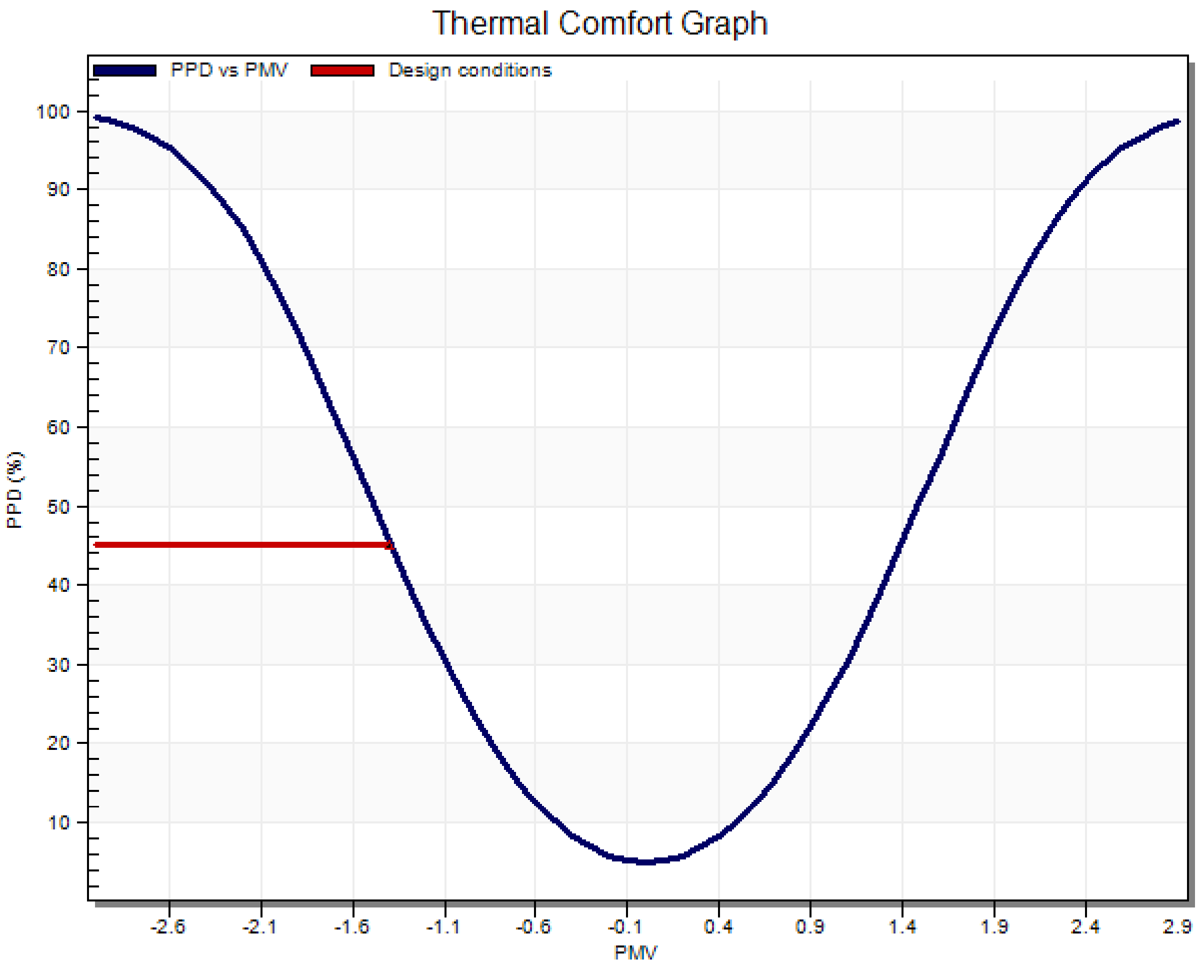


Figure 6-15: DesignBuilder thermal comfort graph for the base model

6.4.5 Daylighting Analysis

The position of a building in relation to its neighbours can affect the level of daylight it receives. However, the case study building is not sheltered on any side by other buildings, so daylighting analysis could evaluate the building performance in terms of energy. Therefore, the effect of shading of neighbouring buildings/structures was neglected as the actual case building has no surrounding structures. DB can generate high quality contour plots to illustrate daylight availability and glare within each zone, block, or slice through the whole building, and the daylighting simulation can provide insights into how reduced electric lighting use can lead to energy and carbon savings. It also provides reports on eligibility for LEED v4 BD+C (Options 1 and 2), BREEAM HEA 01, and Green Star IEQ4 daylighting credits. The aim of the daylighting credit is to encourage and recognise designs that provide appropriate levels of daylight for building users. This study performed two daylighting analyses, and these are described below.

6.4.5.1 BREEAM Health and Wellbeing Credit HEA 01

A pass requires that at least 80% of net lettable floor area in occupied spaces is adequately daylit on the working plane height 0.7 m above the floor under a uniform overcast sky. A zone is adequately daylit if both the following conditions are met:

- Average daylight factor is at least 2.0%.
- A uniformity ratio of at least 0.3 or a minimum point daylight factor of 0.8%.

The results of the building simulation failed to meet the above conditions (See Table 6-10).

Table 6-10: Summary of the results of the BREEAM credit test

Summary Results	
Total area (m2)	403.5
Total area meeting requirements (m2)	20.5
% area meeting requirements	5.1
BREEAM Health and Wellbeing Credit HEA 01 Status	FAIL

6.4.5.2 LEED NC 2.2 Credit EQ 8.1

A pass requires at least 75% of net lettable area in occupied spaces to be adequately daylit, having illuminance over the minimum threshold value. As with the previous analysis, the building again failed to meet the conditions (See Table 6-11).

Table 6-11: summary for LEED credit test

Summary Results	
Total area (m2)	403.5
Total area meeting requirements (m2)	47.8
% area meeting requirements	11.8
LEED NC 2.2 Credit EQ 8.1 Status	FAIL

Both performed daylighting analyses confirmed that the base case building lacks adequate light levels which may be attributed to reasons such as small window sizes and ineffective orientation.

6.5 Model Validation

Validation ensures that research is conducted in an objective and unbiased way (Kumar, 2014). The following sections describe the processes which were used to prove that the case study is close to reality and representative of the actual building.

6.5.1 Calculating the Energy Performance Gap

In order to assess the accuracy of the simulated consumption data, a comparison of the real-life energy consumption values and the DB simulated case was made. The results are shown in Figure 6-16. Differences found between the actual and the simulated consumption are referred to as the 'energy performance gap' (Brom et al., 2017). A number of possible reasons have been given to explain the difference between simulated and actual building performance (Ingle et al., 2014); however, most government institutions and researchers believe that the main cause is the behaviour of the building occupants (Brom et al., 2017). Occupant behaviour, the properties of the construction materials, household-appliances' age and usage, and simulation model oversimplification were all considered as possible explanations for the performance gap in this study. However, the reality is that there is no current method that allows for a 100% similarity in the measured and modelled energy consumption rates of buildings because of real-life complexity.

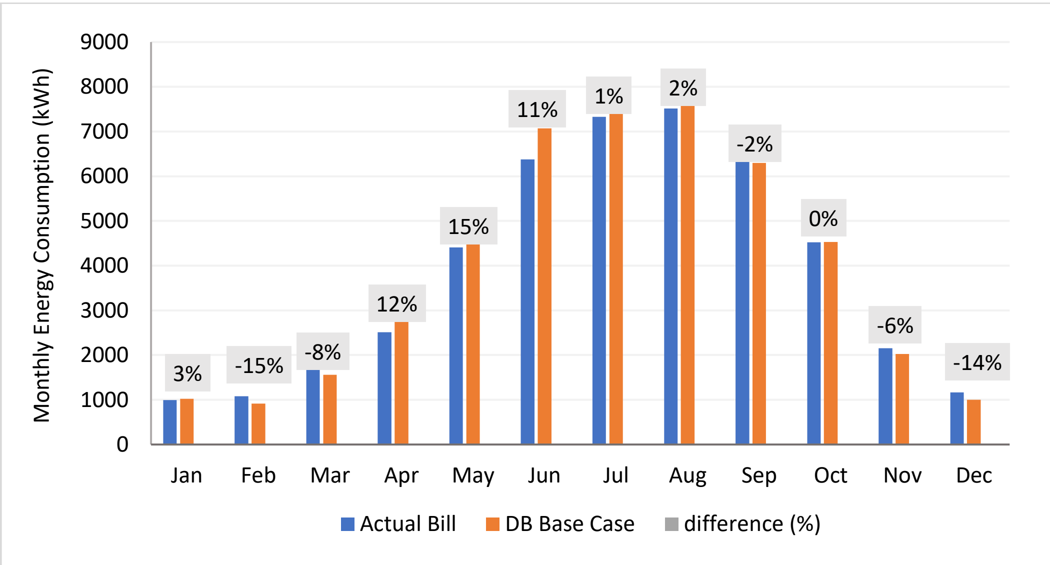


Figure 6-16: Comparison between actual and simulated monthly energy consumption

6.5.2 Calibrating the Model

Due to increased levels of automation, lower costs, and other factors, the whole-building approach of Building Energy Models (BEMs) is now more popular than the single-measure approach (Ruiz et al., 2017; Judkoff et al., 2008; Salvalai et al., 2010; Salvalai, 2012). Since the BEM's accuracy is a deciding factor in all applications, calibrated models are needed. The task of determining the accuracy of BEMs is critical since once the model has been validated through a calibration process, it can be used to test and implement various strategies for reducing energy consumption while preserving human comfort. Calibration is defined according to ASHRAE 14-2014 guidelines as the "process of reducing the uncertainty of a model by comparing the predicted output of the model under a specific set of conditions to the actual measured data for the same set of conditions" (ASHRAE, 2014). The three principal guidelines that clarify how to determine this "degree" of uncertainty are: FEMP (Schiller et al., 2000; Webster and Bradford, 2008; Webster et al., 2015; IPMVP Committee, 2002), ASHRAE Guideline 14, and IPVMP (EVO, 2012; and Reddy et al., 2006). The calibration criteria and model recommendations associated with each source are summarised in Table 6-12.

Table 6-12: Three main criteria to validate a calibrated model (Kumar, 2014)

Data Type	Index	FEMP Criteria	ASHRAE Guideline 14	IPMVP
Calibration Criteria				
Monthly criteria %	*NMBE*	*±5*	*±5*	*±20*
	CV (RMSE)	*15*	*15*	*-*
Hourly criteria %	*NMBE*	*±10*	*±10*	*±5*
	CV (RMSE)	*30*	*30*	*20*
Model Recommendation				
	R^2	-	*>0.75*	*>0.75*

The principal uncertainty indices used are:

- Normalized Mean Bias Error (*NMBE*) - this can be found by applying Equation 6-1
- Coefficient of Variation of the Root Mean Square Error (*CV(RMSE)*) - this measures the variability of the errors between the measured and simulated values (as in Equation 6-2), and
- coefficient of determination (R^2).

$$NMBE = \frac{1}{\bar{m}} \cdot \frac{\sum_{i=1}^{n}(m_i - s_i)}{n-p} \times 100\ (\%) \rightarrow \bar{m} = \frac{\sum_{i=1}^{n}(m_i)}{n} \quad Equation\ (6-1)$$

Where:
m_i refers to measured value
s_i refers to simulated value
n is the number of measured data points (in this study *n*=12 months)
($\tilde{m}$) is the mean of measured values
p is the number of adjustable model parameters, which is suggested to be zero, for calibration purposes.

$$CV\ (RMSE) = \frac{1}{\bar{m}}\sqrt{\frac{\sum_{i=1}^{n}(m_i - s_i)^2}{n-p}} \times 100\ (\%)\ \ Equation\ (6-2)$$

It is worth noting that a positive value means that the model under-predicts measured data, and a negative one means over-prediction. ASHRAE Guidelines subtract measured values (m_i) from simulated ones (s_i), while FEMP and IPMVP do the opposite. For this reason, the explanation of the under- or over-prediction is inverted. In Equation 6-2, the value of p is suggested to be one (Reddy et al., 2006; and Robertson et al., 2013). Table 6-13 shows the final calculations for validating the model using both equations.

Table 6-13: Validation of the model

Month	**Monthly Consumption (kWh)**		Difference (kWh) (m_i - s_i)	Difference %
	Measured (m_i)	*Simulated (s_i)*		
Jan	995	1024	-28.8	3%
Feb	1080	915	165.4	-15%
Mar	1689	1557	131.9	-8%
Apr	2509	2800	-290.9	12%
May	4410	5090	-679.6	15%
Jun	6374	7073	-698.9	11%
Jul	7329	7426	-96.9	1%
Aug	7510	7656	-145.2	2%
Sep	6403	6296	106.8	-2%
Oct	4522	4532	-10.0	0%
Nov	2156	2024	132.2	-6%
Dec	1165	998	167.0	-14%
Total	***46143***	***47389***		

Mean (Measured values $\tilde{m}$)	*2990.91*
(*NMBE*)	*-3.47%*
(*CV(RMSE)*)	*12.57%*

Coefficient of determination (R^2) indicates the proximity of simulated values to the regression line of the measured values. It is a statistical index that is widely used to calculate the uncertainty of a model. It is limited to a range of 0.00 to 1.00, with the upper limit indicating the perfect match of simulated and measured values and the lower limit indicating the opposite. Both the ASHRAE Handbook and the IPVMP suggest that it should never fall below 0.75. In this study, R^2 value was equal to 0.987 as shown in Figure 6-17.

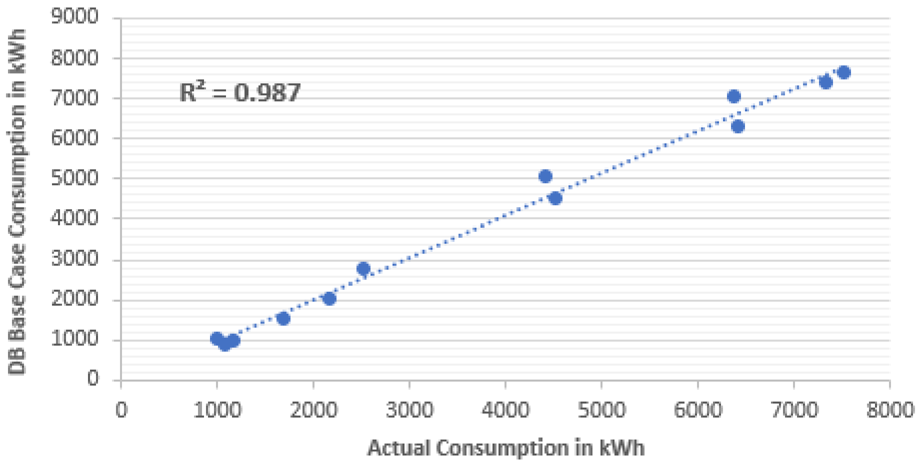


Figure 6-17: A plot of coefficient of determination between actual and simulated values

These results indicate that, according to the validation criteria set out in Table 6-12, this model has met these guidelines and proven to be valid as the predictions from the monthly simulation fit the data from the actual measurements.

6.6 Summary

This chapter has described the modelling of the representative case study building based on information provided by the householder and an observation visit. Drawing on real-life data about the building operation and the energy consumed in a typical year (2019), a comparison of the monthly energy consumption in the real building and the simulated model was conducted. This established that the model was reliable and within the limits of validity, and thus suitable for use as a base case model. Overall, the simulation results indicated poor thermal performance in the building: the EUI in *kWh/m^2* per year was about 141 and the subsequent CO_2 emissions exceeded standard values. The building also failed to meet the required limits for thermal comfort and daylighting. The next chapter describes the targeted improvement measures applied to the base case model to address the shortcomings identified above and the measures taken to assess their effectiveness and proposes a framework for low energy buildings development in Saudi Arabia.

Chapter Seven: Holistic Analysis of Building Improvement

7.1 Introduction

Without optimal design, appropriate materials, and efficient operation, it is difficult to reduce high energy demand in residential buildings. This chapter was derived from previous methods outcomes covered in literature review (Chapters 2 and 3), physical observation (Chapter 6), and professional consultation (Chapter 5). The simulation of the base case model in Chapter 6 showed a number of design weaknesses related to the architectural design and/or to the construction materials used in the building. This chapter identifies the improvement parameters and discusses the various improvements impacts made to the existing building based on the individual and combinations of measures. Next, a further analysis will be carried out to reach the final improved model. This will be followed by a cost-benefit analysis of the selected measures that exhibits environmental and economic benefits and building performance enhancement. The improved building model is then compared with the existing building, local regulations, and international standards. Finally, the chapter will conclude by proposing a framework to adopt for energy-efficient buildings development.

7.2 Areas Targeted for Improvement

Since most Saudi buildings rely heavily on mechanical cooling systems to ensure thermal comfort, a proper strategy for reducing overall energy consumption is required. The target areas identified in this study included: 1) improvement of thermal resistance in building envelopes (walls and roof); 2) application of advanced window systems (WWR, glazing type, and shading devices); 3) airtightness expressed by infiltration rate (i.e., air changes per hour ac/h); and 4) the use of efficient AC systems.

The building simulation parametric analysis tool enables researchers to see the effects of different parameters on the building's annual energy performance (in kWh). This process allows for comparison of different inputs for each individual parameter and parameters in combination in term of total annual energy consumption. For the purposes of this study, the simulation parameters (also called variables) were categorised into Design-related parameters and Operating-related parameters, as described in Table 7-1. These parameters were then analysed, individually, in combination, and as a whole set, in order to establish their impact on the total energy consumption of the base model.

Table 7-1: Parameters to consider in DB simulations

Parameters	
Design Related	External Wall Construction
	Flat Roof Construction
	WWR
	Glazing Type
	Local Shading
	Airtightness
Operating Related	Cooling Setpoint Temp
	AC CoP

These categories are discussed in more detail below, and the impacts and outcomes of each of the variables are described in the following sections through comprehensive parametric analysis.

7.2.1 Design-Related Parameters

The heat balance analysis of the base building fabric (described in Section 6.4.5) showed that the external walls and roof were the most significant sources of heat gain. As a result, these two envelope elements were the primary focus in relation to the building design. The floor design in Saudi Arabia consists mainly of ceramic, cement render, sand layer, and cast concrete. This has been almost the only current design. Also, the contribution to the heat gain analysis is insignificant compared to the other envelope elements such as walls and roof. As discussed in Chapters 2 and 6, this is a common problem in residential buildings in Saudi Arabia, as housing envelopes tend to have wall layers consisting of mortar, brick, and then mortar, and generally lack thermal resistance (Ghabra, 2017). Thermal resistance is essential for suppressing the rate of heat dissipation into the interior of the building, and the simulation showed that the R-value (thermal resistance) of the model fabric was low, i.e. high U-values were detected.

As discussed in Chapter 2, thermal insulation has been proven to reduce cooling energy demand and improve thermal comfort in buildings (Braulio-Gonzalo and Bovea, 2017; Boermans and Petersdorff, 2007; Al-Tamimi, 2021; Alaidroos and Krarti, 2015). However, the findings of the public survey and the literature review indicated that most residential buildings in KSA are erected without sufficient insulation (Lahn et al., 2013; Ghabra, 2017; Aldossary, 2015). This was also the case with the existing building case study, so the base case model was simulated without insulation. As a result, a key aim of the simulations described in this chapter was to explore the effects of insulation on the building in order to identify the most energy-efficient configurations. A number of wall structures were investigated, mainly cavity and insulated walls, along with a number of roofing systems and compositions in order to determine the most suitable types in this context. The parameters for the modelling and simulation of these wall and roof types are presented below.

Researchers have made a number of recommendations to improve the energy efficiency of windows. For example, Alwetaishi (2019) found that a smaller WWR (10%) may be optimal in hot and dry climates such as in Saudi Arabia. As a result, although the base building WWR falls within the recommended range, the WWR parameter was considered for further analysis. It was indicated in Chapter 6- sections 6.4.5.1 and 6.4.5.2 that the building fails to meet recommended adequate daylit. To improve this, it would require re-orient the building, windows resize and redesign. This is beyond the scope of this study as these are not retrofit solutions and would be possible only to new design/construction. In addition, as mentioned in Chapter 6 (Section 6.1.1), the existing building has a single pane glazing system, which can increase the demand for cooling, and this was used in the simulation of the base case. The more efficient system of double or triple glazing has been shown to decrease the amount of direct sunlight and heat, while still allowing enough daylight to enter the interior (Susilawati and Al-Surf, 2011). Glazing and shading can also help improve the comfort conditions by lowering the interior temperature (Al-Homoud, 2004; Aboulnaga et al., 2016), and external shading devices are more effective than any internal mechanism because the latter absorbs solar heat (Baldinelli, 2009). Hence, the improvement of the base building included the adoption of measures such as double-glazing and shading devices.

It is worth mentioning that air quality is a dependent variable. It depends on whether condition, envelope tightness, insulation, and even occupant user profile. It is a complex area to assess. However, this was considered in Chapter 5 in the Public and Experts' surveys. For example, the public were asked in the survey to assess their dwellings' performance in term of indoor air quality. Furthermore, while natural ventilation is considered an asset, air infiltration is not at all desirable. Due to the harsh climatic condition of Saudi Arabia, the option of ventilation is only applicable in the mountainous southern region of the country which represents only a small area of the country. On the other hand, the infiltration process involves the entry of unintentional air from outside, through cracks, openings, vents, and through the porosity of the fabric (DB Manual, 2021). Infiltration in residential buildings can have many negative consequences, including reduced thermal comfort, interference with the proper operation of mechanical ventilation systems, degraded indoor air quality, moisture damage to building envelope components, and increased energy consumption (Emmerich et al., 2007). The Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA) suggests that there is considerable infiltration impact on energy use in buildings in mild and hot climates (Kraus and Kubečkova, 2013). For these reasons, attention has been given to methods of improving airtightness, both in existing buildings and new construction. For example, "sealed air" technology, where air is sealed in the cavity of external windows, offers efficient thermal insulation as well as a simple and economical design (Chow and Li, 2013).

7.2.2 Operation-Related Parameters

According to the Housing Survey Data for 2018, villas in most Saudi provinces have at least seven AC units, compared to four in traditional houses and three in apartments, and an average of five units per household is required to keep the internal temperature at a comfortable level (GAS, 2018). Given the number of units required, people tend to buy low-priced AC systems, possibly to lower the capital cost of house appliances, without considering the long-term effects on utility costs, as these typically have a low efficiency performance (SEEC, 2018). In response to this, in 2019, the Saudi government launched the High Efficiency AC (HEAC) initiative, with the aim of incentivising local production of high efficiency AC systems, and encouraging Saudi households to buy more efficient systems (HEAC, 2021).

Despite the availability of the incentive scheme, the householder indicated that the AC systems used in the base case villa, a combination of window and split AC, only had 2-star efficiency labels according to the SASO efficiency rating. Due to the fact that all of the components are contained within a single unit, window air conditioners are inherently less efficient than split systems (Krarti and Howarth, 2020), but the findings of this study indicate that these systems are prevalent across all regions. In addition, due to the intense heat in Saudi Arabia, people tend to use the lowest cooling setpoint temperature (SPT) (i.e., 16-18 °C), regardless of the impact this has on the energy load (Krarti et al., 2017). As a result, cooling SPT and Coefficient of Performance (CoP), a measure of AC system efficiency, were selected as the operating parameters in order to explore their impacts on energy consumption. The findings of the public survey also indicated that the Saudi public lacks awareness of these two parameters, so they were also included in order to provide recommendations based on the results of the simulations.

The occupancy profile revealed that the AC was used both day and night during the summer (i.e., more than 12 hours/day) in the base case villa, with the SPT set to 20°C. The 20°C cooling set point was given by the householder as the frequent base temperature. This is in accordance with other studies that have also selected 20°C as the base line setpoint temperature for their simulation analysis (Alshahrani, 2018; and Alrashed, 2015). Given these justifications, the study adopted 20°C for the study. This was replicated in the base case model, and analysis was conducted to assess the effects of varying the SPT on energy consumption, initial costs, and annual utility costs. Simulations were also run to assess the impact of enhancing system efficiency (by raising the CoP) on the building's energy consumption and cooling load.

Lighting is also important when considering energy efficiency in buildings. However, the base case utilised light emitting diode (LED) fixtures, and this type of lighting is very efficient in term of energy consumption, consuming 40-50% less than other conventional systems, such as fluorescent lighting

(Byun et al., 2013; Pattison et al., 2018). Hence, no further improvement or analysis was made regarding lighting.

The following sections present the improvement analysis in terms of building energy performance, beginning with improvements to the reference case based on the individual design- and operation-related parameters before going on to assess the improvements possible with combined parameters.

7.3 Phase One: Improvements to the Reference Case Based on Individual Parameters

The first phase aimed to identify the improvements in building performance which could be achieved by varying the individual parameters. The next phase was to test the impact of selected variables in combination. The variables were parametrically analysed and categorised according to their individual effect on energy use.

7.3.1 External Wall Construction

External walls are the largest element in a building's envelope and form a very significant design aspect when considering efficient buildings. The base case building was erected without proper thermal insulation, so a number of commonly used wall insulation systems and materials were considered in order to enhance thermal performance. The architectural installation systems selected for simulation were External Insulation and Finish System (EIFS), Double Wall System (DWS), and Internal Insulation and Finish System (IIFS). Details of their characteristics and applications are provided in Chapter 2 (Section 2.4.6.4). Furthermore, 18 compositions of external walls, involving different insulation thicknesses and placement, were investigated. Some of these were selected because they are widely used for buildings in KSA, while others were included due to their potential to reduce the overall U-value of the walls. A description of each of these is presented in Table 7-2, along with their corresponding U-values. It should be noted that wall EW-6 is considered to be self-insulating as the blocks used are made of Autoclaved Aerated Concrete (AAC) which also provides thermal insulation. Despite its positive impact on wall heat gain (reduced by 75.3%) and energy consumption (reduced by 21.1%), it has to be adopted from the start of the envelope construction and should not be used as a retrofitting solution.

Four insulation products were also used in this analysis; extruded polystyrene (XPS), expanded polystyrene (EPS), polyurethane (PUR), and rock wool, with commonly used thicknesses of 50mm and 100mm. These are all approved by SASO (SASO, 2019). As the U-value column in Table 7-2 illustrates, the addition of thermal insulation to the external wall lowered the overall thermal transmittance (i.e., U-value) significantly, from 2.146 W/m²K (Base Case) to values as low as 0.219 (Type 4-C).

Table 7-2: External wall constructions for simulation

External Wall	No of Layers	Description	System of Installation	U-value (W/m²K)
Base Case	**3**	**25mm stucco+ 200mm concrete hollow block+ 20mm cement plaster**	**-**	***2.146***
Type 1-A	4	25mm stucco + 50 mm XPS (Extruded) + 200mm concrete hollow block + 20mm cement plaster	EIFS	*0.516*
Type 1-B	4	25mm stucco + 100 mm XPS (Extruded) + 200mm concrete hollow block + 20mm cement plaster	EIFS	*0.246*
Type 1-C	4	25mm stucco + 100 mm EPS (Standard) + 200mm concrete hollow block + 20mm cement plaster	EIFS	*0.337*
Type 2-A	5	25mm stucco + 150mm concrete hollow block + 50mm EPS (standard) + 100mm concrete hollow block + 20mm cement plaster	DWS	*0.507*
Type 2-B	5	25mm stucco + 150mm concrete hollow block + 100 mm EPS (standard) + 100mm concrete hollow block + 20mm cement plaster	DWS	*0.310*
Type 2-C	5	25mm stucco + 150mm concrete hollow block + 50 mm EPS (Standard) + 150mm concrete hollow block + 20mm cement plaster	DWS	*0.481*
Type 2-D	5	25mm stucco + 150mm concrete hollow block + 100mm EPS (standard) + 150mm concrete hollow block + 20mm cement plaster	DWS	*0.301*
Type 3-A	5	25mm stucco + 150mm concrete hollow block + 50mm XPS (Extruded) + 100mm concrete hollow block + 20mm cement plaster	DWS	*0.418*
Type 3-B	5	25mm stucco + 150mm concrete hollow block + 100mm XPS (Extruded) + 100mm concrete hollow block + 20mm cement plaster	DWS	*0.294*
Type 3-C	5	25mm stucco + 150mm concrete hollow block + 50 mm XPS (Extruded) + 150mm concrete hollow block + 20mm cement plaster	DWS	*0.401*
Type 3-D	5	25mm stucco + 150mm concrete hollow block + 100mm XPS (Extruded) + 150mm concrete hollow block + 20mm cement plaster	DWS	*0.240*
Type 4-A	5	25mm stucco + 150mm concrete hollow block + 50mm Rock Wool + 150mm concrete hollow block + 20mm cement plaster	DWS	*0.427*
Type 4-B	5	25mm stucco + 150mm concrete hollow block + 100mm Rock Wool + 100mm concrete hollow block + 20mm cement plaster	DWS	*0.266*
Type 4-C	5	25mm stucco + 150mm concrete hollow block + 100mm PUR polyurethane rigid board + 100mm concrete hollow block + 20mm cement plaster	DWS	*0.219*
Type 5-A	4	25mm stucco + 200mm concrete hollow block + 100mm XPS (Extruded) + 20mm plaster	IIFS	*0.252*
Type 5-B	4	25mm stucco + 200mm concrete hollow block + 100mm rock wool + 20mm plaster	IIFS	*0.273*
Type 5-C	4	25mm stucco + 200mm concrete hollow block + 100mm PUR polyurethane rigid board + 20mm plaster	IIFS	*0.232*
Type 6	3	25mm stucco + 250 mm AAC block + 20mm plaster	Self-insulated	*0.397*

DB runs the parametric analysis through many iterations to produce the final outcomes of each variable in terms of total annual energy consumption and the wall heat balance. The results of the analysis of the potential wall improvement strategies in respect of total annual energy consumption and wall heat balance are displayed in Table 7-3 and Figure 7-1.

Table 7-3: Effects of wall improvements on total energy consumption

Variable	Output		Percentage Reduction Effect on	
External wall construction	**Walls heat gain (kWh)**	**Total site energy consumption (kWh)**	***Wall heat gain***	***Energy consumption***
Base Case	43198.8	47389.5	*0.0%*	*0.0%*
EW 1-A	12852.9	38146.3	*70.2%*	*19.5%*
EW 1-B	7391.3	36161.5	*82.9%*	*23.7%*
EW 1-C	9098.6	36859.7	*78.9%*	*22.2%*
EW 2-A	13078.8	37882.0	*69.7%*	*20.1%*
EW 2-B	8825.5	36493.6	*79.6%*	*23.0%*
EW 2-C	12549.8	37451.9	*70.9%*	*21.0%*
EW 2-D	8618.4	36604.4	*80.0%*	*22.8%*
EW 3-A	11186.5	37372.0	*74.1%*	*21.1%*
EW 3-B	8160.2	36113.4	*81.1%*	*23.8%*
EW 3-C	10818.9	36990.9	*75.0%*	*21.9%*
EW 3-D	7260.3	35804.0	*83.2%*	*24.4%*
EW 4-A	11381.3	37138.9	*73.7%*	*21.6%*
EW 4-B	7842.1	36228.8	*81.8%*	*23.6%*
EW 4-C	6760.7	35947.7	*84.3%*	*24.1%*
EW 5-A	7483.1	36292.1	*82.7%*	*23.4%*
EW 5-B	7952.9	36415.7	*81.6%*	*23.2%*
EW 5-C	6828.9	36207.3	*84.2%*	*23.6%*
EW 6	10689.5	37384.9	*75.3%*	*21.1%*

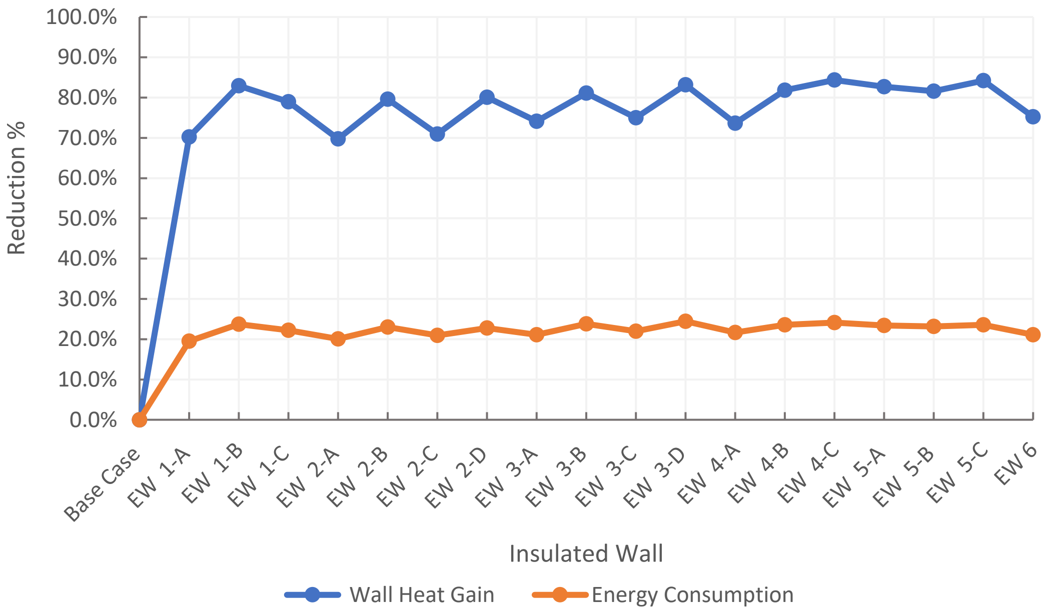


Figure 7-1: Annual energy reduction of the various insulation options

As these results demonstrate, the lower the U-value, the better the insulation, leading to greater energy saving. Also, increasing the thickness of the insulation reduces the wall thermal transmittance. Indeed, the analysis showed that the addition of insulation reduced overall energy consumption by up to 24.4% (EW 3-D).

According to the results reported above, four wall compositions achieved the highest reductions in both energy consumption and heat gain. Their properties are summarised in Table 7-4.

Table 7-4: Details of the best four wall structure options

Wall	***Insulation***	***System used***	***U-Value (W/m^2K)***	***Energy saving (%)***	***Heat gain reduction (%)***
EW 1-B	100mm XPS	EIFS	0.246	23.7	82.9
EW 3-D	100mm XPS	DWS	0.240	24.4	83.2
EW 4-C	100mm PUR	DWS	0.219	24.1	84.3
EW 5-C	100mm PUR	IIFS	0.232	23.6	84.2

It seems that the application of DWS performs slightly better than EIFS and IIFS. However, DWS may not be the best practice as the installation cost of this system can be high compared with the others and the effect of all three systems on wall heat gain and energy consumption can be very similar. As a result, a comprehensive cost benefit analysis is presented in later sections to determine which system and insulation material to use in terms of suitability and affordability.

Since the main focus of this study is on a model located in Zone 1, it was essential that the U-value of each proposed wall construction should comply with the Saudi Building Code (SBC602) requirements for walls in Zone 1, i.e. not exceeding 0.403 W/m^2K. Hence, five walls were excluded from further analysis, regardless of their impact on energy saving. These walls (Types 1A, 2A, 2C, 3A, and 4A) indicated that 50mm of added insulation may not be sufficient to achieve compliance with the SBC.

7.3.2 Roof Construction Scenarios

The base case building uses a flat roof structure with no thermal insulation, a common practice in the region. The U-value of the roof was estimated at 2.123 W/m^2K. The roof of residential buildings typically comprises seven layers: 25mm terrazzo (outer layer), 25mm cement sand render, 50mm sand, 10mm Bitumen, 220mm cast concrete, 200mm air gap, and lastly 15mm gypsum plaster (innermost layer). As a result, improvements to the flat roof included the insertion of a thermal insulation layer between roof layers and the employment of cool roof techniques, such as reflective coating and ceramic. In addition to the ceramic and reflective coated roofs, nine other roof related improvements were proposed, as shown in Table 7-5.

Table 7-5: The proposed improvements in the construction of the flat roof

Flat Roof Construction	Description of layers	U-Value (W/m^2K)
Base Case	25mm terrazzo + 25mm cement sand render + 50mm sand + 10mm Bitumen + 220mm cast concrete + 200mm air gap + 15mm gypsum plaster	**2.123**
Ceramic roof	10 mm ceramic tile + 25mm cement sand render+ 50mm sand+ 5mm Bitumen+ 220mm cast concrete+200mm air gap+ 15mm gypsum plaster	**2.09**
Reflective coated roof	5mm reflective coating + 25mm terrazzo + 25mm cement sand render + 50mm sand + 5mm Bitumen + 220mm cast concrete + 200mm air gap + 15mm gypsum plaster	**2.08**
R 1	40mm polyurethane Spray + 25mm terrazzo + 25mm cement sand render + 50mm sand + 10mm Bitumen + 50 mm XPS (Extruded) + 220mm cast concrete +200mm air gap + 20mm gypsum plaster	0.303
R 2	25mm terrazzo + 25mm cement sand render + 50mm sand + 10mm Bitumen + 100 mm glass fibre board + 220mm cast concrete + 200mm air gap + 20mm gypsum plaster	0.289
R 3	40mm Polyurethane Spray + 25mm terrazzo + 25mm cement sand render + 50mm sand + 10mm Bitumen + 220mm cast concrete + 200mm air gap + 20mm gypsum plaster	0.612
R 4	25mm terrazzo + 25mm cement sand render + 50mm sand + 10mm Bitumen + 100mm XPS (Extruded) + 220mm cast concrete + 200mm air gap + 20mm gypsum plaster	0.239
R 5	25mm terrazzo + 25mm cement sand render + 50mm sand + 10mm Bitumen + 220mm cast concrete + 200 mm Polyurethane Foam + 20mm gypsum plaster	0.131
R 6	25mm terrazzo + 25mm cement sand render + 50mm sand + 10mm Bitumen + 220mm cast concrete + 100 mm XPS (Extruded) +100 mm air gap+ 20mm gypsum plaster	0.239
R 7	25mm terrazzo + 25mm cement sand render + 50mm sand + 10mm Bitumen + 220mm cast concrete + 50mm rock wool + 150 mm air gap + 20mm gypsum plaster	0.455
R 8	25mm terrazzo + 25mm cement sand render + 50mm sand + 10mm Bitumen + 50mm rock wool + 220mm cast concrete + 150mm air gap + 50mm Polyurethane Foam + 20mm gypsum plaster	0.251
R 9	40mm Polyurethane Spray + 25mm terrazzo + 25mm cement sand render + 50mm sand + 10mm Bitumen + 220mm cast concrete + 100mm air gap +100mm Polyurethane Foam+ 20mm gypsum plaster	0.201

The results of the simulations are illustrated in Figure 7-2. These show that the proposed roof improvements reduced the roof heat gain by between 20% to 90%. The addition of thermal insulation resulted in the highest reductions as the overall thermal transmittance of the structure was lowered. This was mainly due to the positive effect of the thermal insulation materials on heat gain through the roof, which subsequently reduced the cooling load. The energy savings achieved by adopting the cool roof measures (ceramic or reflective coating) were much lower than the other nine suggested improvements that range from 13.8% to 18.4%. The highest reductions in both annual energy consumption and roof heat gain were achieved by adopting Roof 5, Roof 9, and Roof 4, respectively.

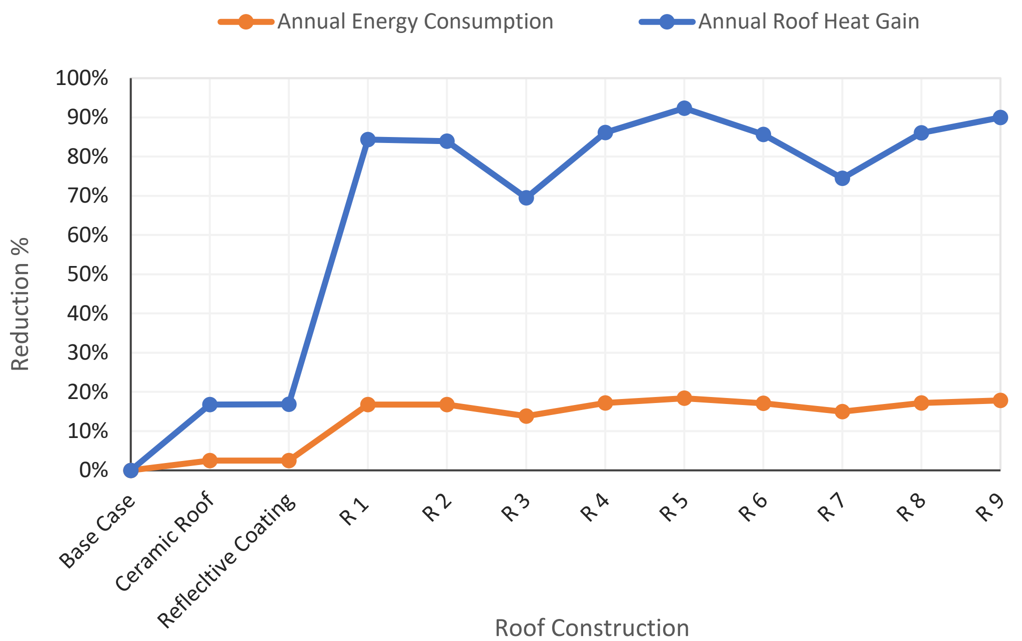


Figure 7-2: Impact of various roof scenarios on the building's energy consumption

Amongst roof insulation products, the findings indicate that PUR and XPS are considered to be the most efficient. According to the SBC, the roof U-value should not exceed 0.272 W/m²K for low rise residential buildings in Zone 1. Therefore, four proposed roof insulation structures were eliminated from further analysis, despite the savings they achieved, since their overall assembly U-values were larger than the recommended maximum specified by the SBC.

7.3.3 Window to Wall Ratio (WWR)

Since the amount of sunlight admitted is highly influenced by the design features of the window systems, the design variables of window systems were included in the energy performance analysis. The WWR of the reference building was nearly 10%, so seven different WWRs (ranging from 10%- 40% in 5% increments) were simulated to assess the relative heat gain (external windows solar gain) and subsequent energy performance. The results are shown in Table 7-6. These reveal that for each 5% increase in WWR, solar gains increased by almost 50% and energy consumption by nearly 3%. Therefore, increasing the WWR negatively affects energy consumption and actually increases costs. As a result, the base case WWR was considered to be the best performance scenario, especially as it also complies with the prescriptive criteria of the SBC602 that limits WWRs to a maximum of 25%.

Table 7-6: Effect of changing WWR on energy use

WWR	***Total Annual Energy Consumption***		***Solar Gains External Windows***	
%	***in (kWh)***	***% of increase***	***in (kWh)***	***% of increase***
10	47389.5	0.00%	13182.4	0.00%
15	48950.4	3.30%	19204.4	45.70%
20	50265.8	6.10%	25996.9	97.20%
25	51563.0	8.80%	32832.0	149.10%
30	52849.2	11.50%	39692.9	201.10%
35	54112.0	14.20%	46570.6	253.30%
40	55367.2	16.80%	53594.0	306.60%

7.3.4 Glazing Type

Another important design variable is the glazing type. For the reference building, a single blue 6mm glazing was used, with a thermal transmittance of 5.78 W/m²K and SHGC of 0.62. 14 different types of glazing were selected to be individually analysed to evaluate their performance in terms of solar heat gain and energy use in the building. Both single and double glazing types were included, filled with either argon gas or air, and of 6mm or 3mm thickness. Triple glazed windows were not considered as they are still not commonly used in Saudi Arabia due to the high costs of supply and installation. The results are shown in Table 7-7. As the data demonstrates, the most effective glazing option in terms of reducing energy consumption and solar gain, is the double reflective glazing in the following combinations: Dbl Ref- 6mm/13mm Air, and Dbl Ref- Clr 6mm/13mm Arg. This suggests that the wider the gap between the panes, the better, and that argon gas acts as a better filling than air.

Figure 7-3 depicts the DB parametric analysis results for total energy consumption (kWh) and for Solar Gains External Windows (kWh). Again, double reflective glazing systems proved most effective, reducing the total annual energy use by 4.5% and the solar gain by 71.2%. The proposed glazing type Dbl Ref- 6mm/13mm (with either air or argon) is in compliance with the recommended thermal properties for windows according to the SBC602, which stand at 2.668 W/m²K for the U-value and 0.25 for SHGC.

Table 7-7: Effects of adopting different glazing types (Negative sign indicates reduction, i.e. saving)

Glazing type	U-value *W/m²K*	SHGC	Impact on Annual Energy Consumption	Impact on Solar Gain
Sgl Blue 6mm	**5.778**	**0.62**	**0.00%**	**0.00%**
Sgl LoE (e2=.2) Clr 6mm	3.779	0.72	0.20%	53.37%
Sgl Ref-A-H Tint 6mm	4.851	0.304	-2.31%	-75.06%
Dbl Clr 3mm/13mm Air	2.716	0.764	-0.36%	48.29%
Dbl Clr 3mm/13mm Arg	2.556	0.764	-0.41%	48.29%
Dbl Clr 6mm/13mm Arg	2.511	0.704	-0.84%	24.40%
Dbl Blue 6mm/6mm Air	3.094	0.503	-2.05%	-27.13%
Dbl Blue 6mm/13mm Air	2.665	0.497	-2.32%	-27.13%
Dbl Blue 6mm/13mm Arg	2.511	0.494	-2.41%	-27.13%
Dbl Ref- Clr 6mm/6mm Air	2.906	0.248	-4.02%	-71.25%
Dbl Ref- 6mm/13mm Air	**2.412**	**0.234**	**-4.41%**	**-71.25%**
Dbl Ref- Clr 6mm/13mm Arg	**2.233**	**0.228**	**-4.55%**	**-71.25%**
Dbl LoE (e2=.1) Clr 6mm/13mm Air	1.761	0.568	-2.46%	-3.57%
Dbl LoE (e2=.1) Clr 6mm/13mm Arg	1.493	0.568	-2.62%	-3.57%

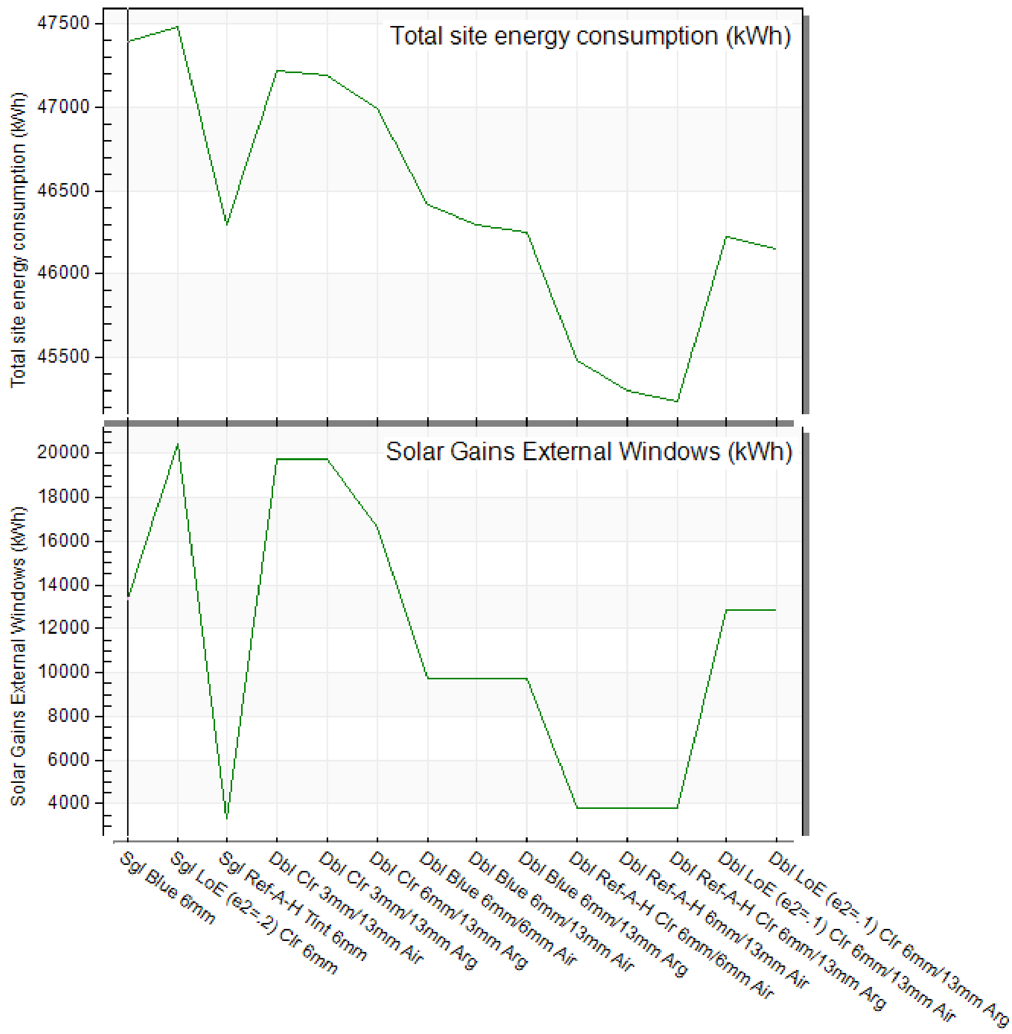


Figure 7-3: Parametric analysis results for glazing types

7.3.5 Local Shading

The fifth design-related parameter considered in this study was the local shading. The reference building was erected with no external shading devices. However, to admit sunlight effectively, it is imperative to use external shading devices, so the impact on the solar transmittance and energy performance of overhangs, sidefins, and louvres were investigated. These are illustrated in Figure 7-4. Two different projection lengths (0.2m and 0.5m) of overhangs, overhangs with sidefins, and louvres were considered.

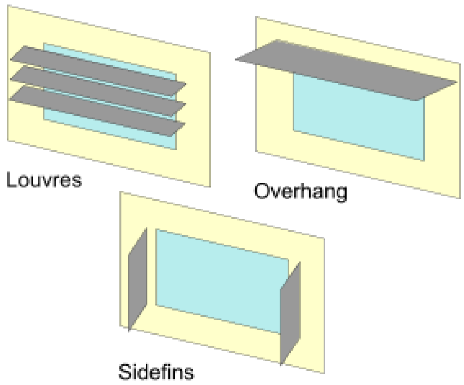


Figure 7-4: Shading devices

Figures 7-5 and 7-6 illustrate the impact of various configurations of shading devices on annual energy consumption and heat gain by solar transmittance, respectively. As can be seen, both energy consumption and heat gain were reduced as the projection length of the shading devices was increased. However, the highest reduction was achieved with the employment of overhangs with fins at 0.5m projection length, which generated a 2.18% reduction in energy costs resulting from a 38.7% decrease in the solar transmittance heat gain. It may be argued that 0.5m projection shading devices are not an ideal solution due to cost and aesthetic reasons when compared with lower projections. In this case, when considering devices of 0.2m projection, louvres could be considered as a replacement since they reduced the heat gain by solar transmittance by approximately 21% (See Figure 7-6).

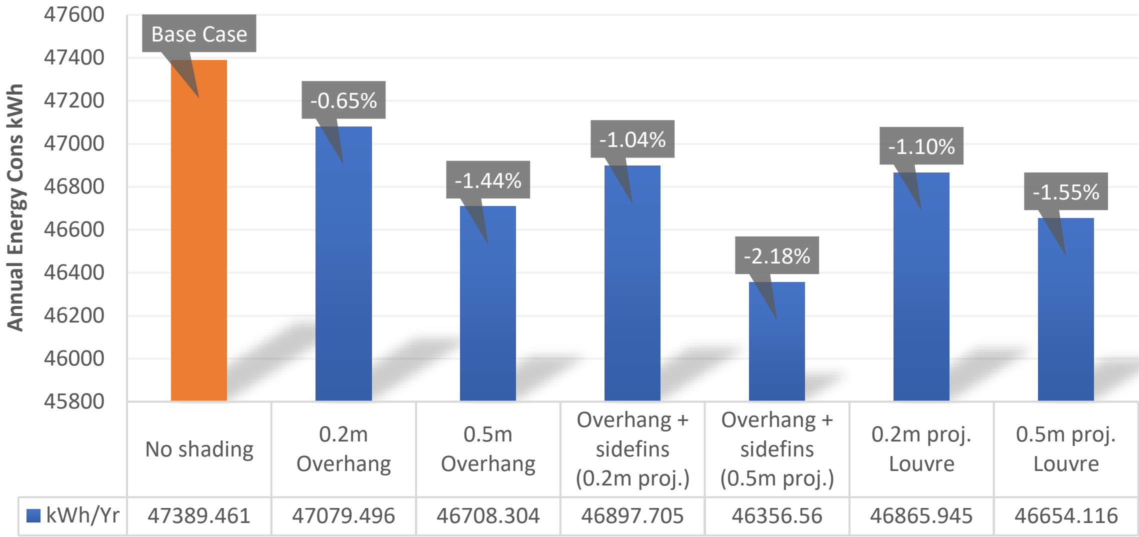


Figure 7-5: Effects of applying local shading devices on the annual energy consumption

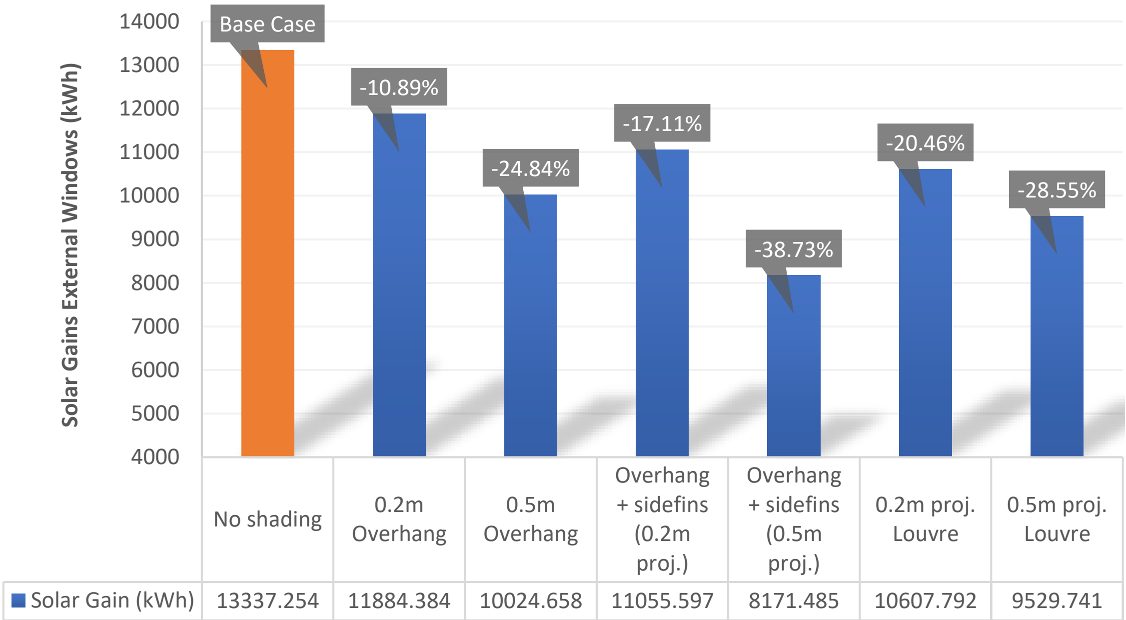


Figure 7-6: Effects of applying local shading devices on heat gain by solar transmittance

7.3.6 Airtightness

The building fabric should be reasonably airtight to maintain good indoor air quality and minimise energy use. This can be achieved through the proper sealing of building gaps, holes, and cracks, if found. Some potential sources of air leakage are window frames, pipes, and lighting fittings.

In this context, it is important to note that the SBC602 does not specify an infiltration rate for a building as a whole structure or for its envelope; instead, it specifies maximum limits for fenestration, sliding doors, and swinging doors, at 1.5 L/s/m², 1.5 L/s/m², and 2.5 L/s/m², respectively (SBC, 2021).

However, DesignBuilder express the infiltration rate in ac/h. Therefore, the following formula given in ASHRAE Standard 90.1 will be used:

$$L/s/m^2 = \frac{ac/h \times height\ (m)}{3.6} \qquad \text{Equation } (7-1)$$

Using equation 7-1, a building of 7 m height and a model default value of 1ac/h would yield an infiltration rate of nearly 2 L/s/m² which falls within the SBC limits. Therefore, the base case infiltration rate will be 1.0 ac/h, which is assumed to be constant throughout the simulation. Previous studies have also assumed the same value (Aldossary, 2015; Alshahrani, 2018).

To investigate the effect of airtightness on energy consumption, six infiltration rates were analysed. As can be seen in Figure 7-7, the results demonstrate that the higher the infiltration rate (ac/h), the more energy is consumed. Table 7-8 expresses the percentage of change in the total energy consumed in kWh, clearly showing that the highest reduction (11.74%) occurs at an infiltration rate of 0.25 ac/h. It is also apparent that for each 0.25 ac/h change, energy consumption increases by almost ±4%.

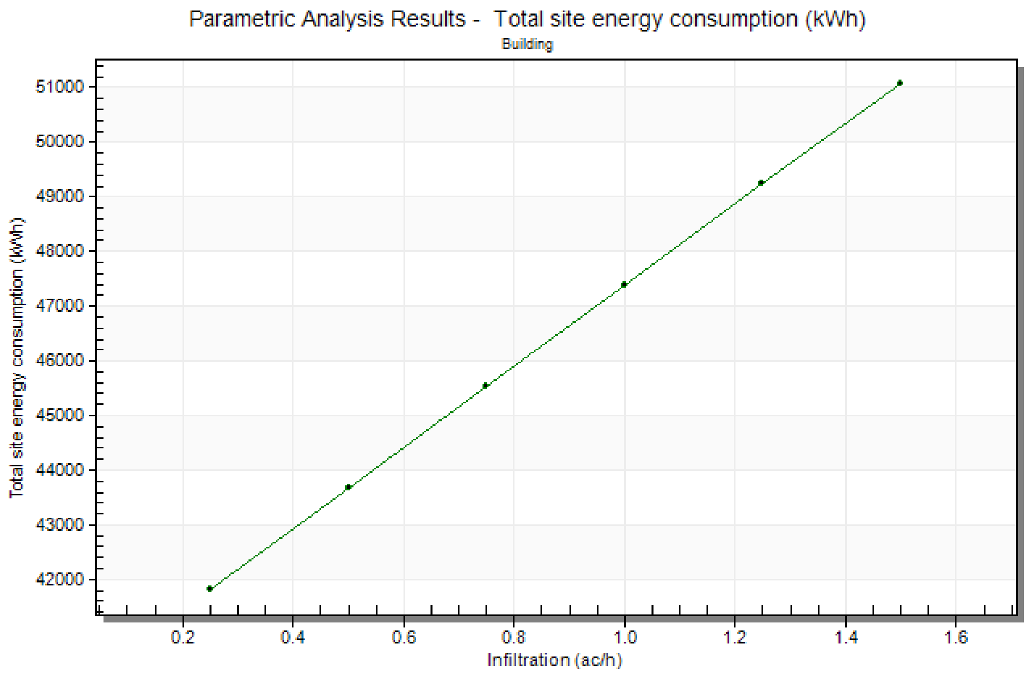


Figure 7-7: Effect of airtightness (ac/h) on total energy consumption

Table 7-8: Percentage of change in the total energy consumed due to airtightness parameter

Infiltration rate (ac/h)	***Change in energy use (%)***
0.25	*-11.74%*
0.5	*-7.82%*
0.75	*-3.90%*
1	***Base Case***
1.25	*3.89%*
1.5	*7.76%*

7.3.7 Cooling Setpoint Temperature (SPT)

The second category of parameters that were considered in the improvement of the building energy performance were the operating parameters. The first variable investigated in this category was the internal cooling setpoint temperature (SPT), which directly impacts energy consumption for air conditioning and subsequently affects the total annual energy consumption. The SEEC recommends that the SPT should be set to between 23 and 25°C (SEEC, 2018); however, the SBC suggests an indoor SPT of 21.9°C (summer) and 23.9°C (winter) (SBC, 2019). As a result, this study performed an analysis of a range of SPTs (from 18 - 25 °C) to evaluate their impact on cooling load and total energy use. The reference temperature was set at 20°C, as reported by the householder of the case study building, and cooling was assumed to be available all year around, as was the case in the reference building. The effects of altering the SPT are displayed in Figure 7-8.

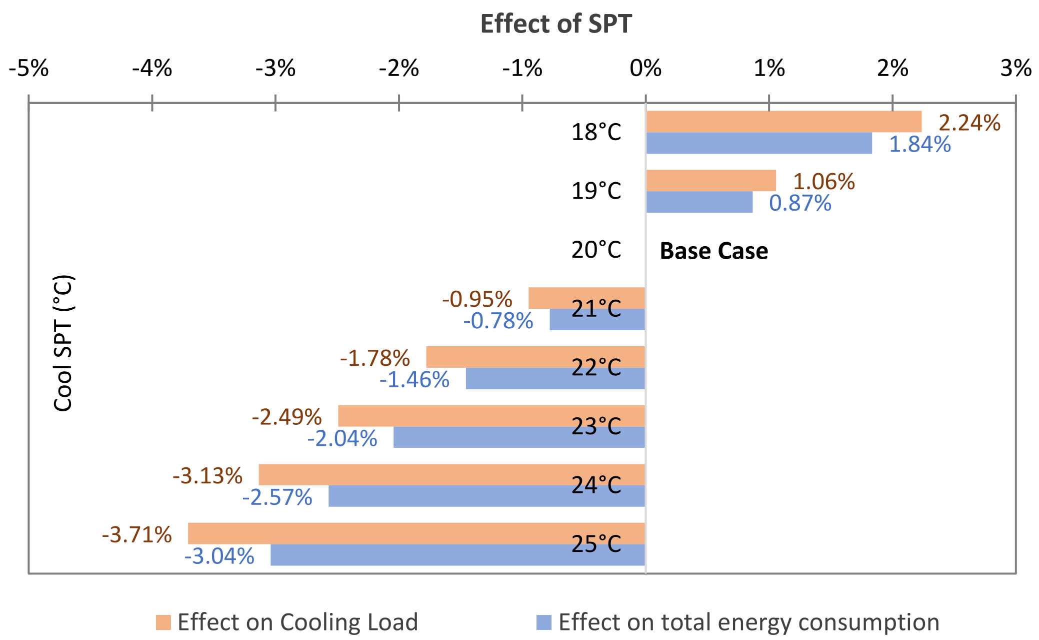


Figure 7-8: Effects of varying cooling SPT on energy consumption

The results of the simulation of the base case building revealed that the cooling load was responsible for 82% of its total annual energy consumption (kWh), with an STP of 20°C. As was expected, Figure 7-8 demonstrates that the higher the SPT, the greater the reduction in energy use. For instance, a 3.7% saving in cooling load was obtained with an SPT of 25 °C, while setting the internal cooling to 18° C led to an increase in annual energy consumption of around 2%.

7.3.8 AC Energy Performance (CoP and EER)

The second operating parameter was the heating and cooling efficiency of the AC systems. Both 'Coefficient of Performance (CoP)' and 'Energy Efficiency Ratio (EER)' are used to describe the ratio of heating or cooling provided by a unit relative to the amount of electrical input required to generate it: the higher the CoP or EER, the more energy efficient the equipment. Many studies preferred to use the EER metric for cooling systems performance rather than CoP (Hijazi and Howieson 2018; Kharseh et al., 2015; Al-Homoud and Krarti, 2021). As mentioned above, the base case householder reported that both AC systems in operation were relatively inefficient, with just 2-star labels according to SASO's energy efficiency rating (shown in Table 7-9). SASO has updated the energy performance standards for AC systems since the villa was built, and now only units conforming to a 3-star rating or higher can be manufactured and sold in Saudi Arabia (Krarti et al., 2017).

Table 7-9: Label for minimum energy performance standard for air conditioners (Source: Krarti et al.,2017)

Star Rating	Air conditioners EER
1	<7.5
2	7.5-8.5
3	8.5-9.0
4	9.0-9.5
5	9.5-10.0
6	10.0-11.5
7	11.5-12.4
7.5	12.4-13.4
8.0	13.4-14.5
8.5	14.5-15.6
9.0	15.6-16.8
9.5	16.8-18.1
10	>18.1

The DB parametric tool only considers CoP as a variable rather than EER. However, for the purposes of this study, theoretical EER was derived from a given CoP by the following universal formula, as recommended by HVAC experts from the Air-Conditioning, Heating, and Refrigeration Institute - AHRI:

$$EER = 3.41 \times CoP \qquad \text{Equation (7-2)}$$

Based on Table 7-9 and the conversion formula, the CoP was set to 2.5. Figure 7-9 depicts the results, clearly demonstrating the significant effect CoP plays in the energy performance of cooling systems. For example, employing a cooling system with CoP=4 (i.e EER=13.6) reduced the cooling energy by 18.8% resulting in energy savings of 15.4%.

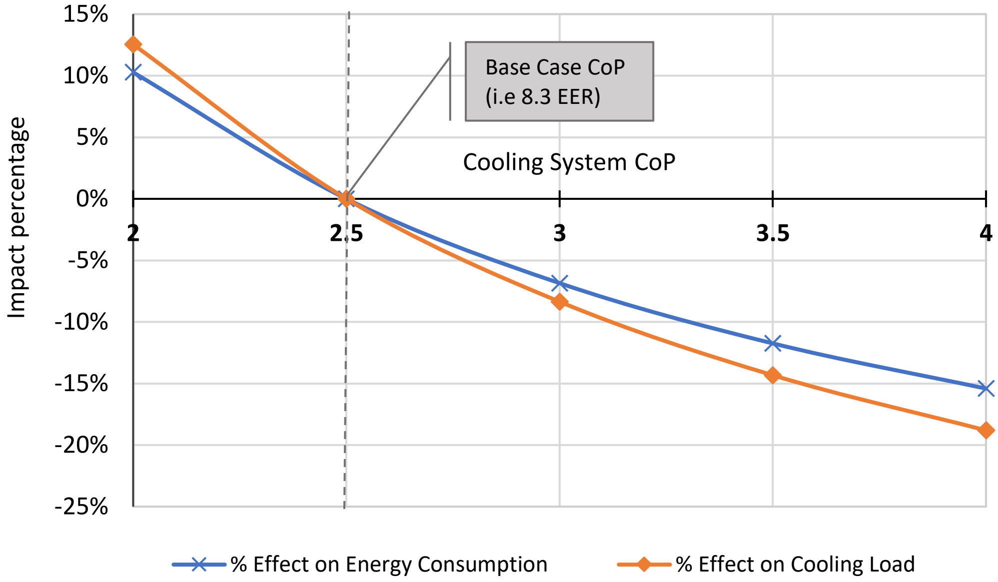


Figure 7-9: Effect of CoP on energy consumption and cooling load

The SEEP and SBC602 Minimum Energy Performance Standard (MEPS) for AC systems specify that the minimum EER should not be less than 11.8 (i.e. CoP≥3.46) (AlFaraidy and Azzam, 2019; Krarti and Howarth, 2020). However, it is important to note that selecting a system with a very high EER (or CoP) is likely to incur more capital costs.

7.4 Phase Two: Improvements Based on Best Combined Variables

The simulation results reported above demonstrated the significant improvements in building performance which could be achieved based on the individual parameters. The next step was to test the impact of selected variables in combination. In order to achieve this, the variables were first categorised according to their individual effect on energy use and then given a code (from EM1- EM16) for ease of reference. Table 7-10 summarises the variables which were considered and then analysed in light of SBC requirements.

Different versions of the existing building were then created by applying various combinations of the individual parameters in order to achieve the highest possible energy savings, and five simulations were performed using the calibrated model. A description of the first four simulations is provided in the following sections, and the final simulation is described in Section 7.6.

Table 7-10: The variables considered for further improvement case analysis

		Variable	U-value W/m²K	Description	Total Energy Cons. Change	Heat Gain Change	*CODE*
Improvement Parameters	***External Wall Construction***	EW 1-B (EIFS)	0.246	25mm stucco + 100 mm XPS (Extruded) + 200mm concrete hollow block + 20mm cement plaster	-23.7%	-82.9%	*EM1*
		EW 3-D (DWS)	0.240	25mm stucco + 150mm concrete hollow block + 100mm XPS (Extruded) + 150mm concrete hollow block + 20mm cement plaster	-24.4%	-83.2%	*EM2*
		EW 4-C (DWS)	0.219	25mm stucco + 150mm concrete hollow block + 100mm PUR polyurethane rigid board + 100mm concrete hollow block + 20mm cement plaster	-24.1%	-84.3%	*EM3*
	Roof Construction	R 4	0.239	25mm terrazzo + 25mm cement sand render + 50mm sand + 10mm Bitumen + 100mm XPS (Extruded) + 220mm cast concrete + 200mm air gap + 20mm gypsum plaster	-17.2%	-86.1%	*EM4*
		R 5	0.131	25mm terrazzo + 25mm cement sand render + 50mm sand + 10mm Bitumen + 220mm cast concrete + 200 mm Polyurethane Foam + 20mm gypsum plaster	-18.4%	-92.3%	*EM5*
		R 9	0.201	40mm Polyurethane Spray + 25mm terrazzo + 25mm cement sand render + 50mm sand + 10mm Bitumen + 220mm cast concrete + 100mm air gap + 100mm Polyurethane Foam + 20mm gypsum plaster	-17.9%	-90.0%	*EM6*
	WWR	No change in WWR (due to negative effect on annual energy consumption when increasing WWR)					
	Glazing Type	**Glazing Type**	**SHGC**	**U-value W/m²K**	**Total Energy Cons. Change**	**Solar Heat Gain Change**	
		Dbl Ref-6mm/13mm Air	0.234	2.412	-4.41%	-71.25%	*EM7*
		Dbl Ref Clr 6mm/13mm Arg	0.228	2.233	-4.55%	-71.25%	*EM8*
	Shading Device	**Local Shading Device (External)**			**Total Energy Cons. Change**	**Solar Heat Gain Change**	
		Overhang + Sidefins (0.5m projection)			-2.18%	-38.7%	*EM9*
		Louvres (0.2m projection)			-1.1%	-20.5%	*EM10*
	Cool SP	**Cooling Setpoint Temperature °C**		**Cooling Cons. Change**	**Total Energy Cons. Change**		
		24		-3.1%	-2.6%		*EM11*
		25		-3.7%	-3.0%		*EM12*
	CoP	**AC Coefficient of Performance**		**Cooling Cons. Change**	**Total Energy Cons. Change**		
		3.5		-14.3%	-11.7%		*EM13*
		4		-18.8%	-15.4%		*EM14*
	Airtightness	**Infiltration Rate (ac/h)**		**Total Energy Cons. Change**			
		0.5		-7.8%			*EM15*
		0.25		-11.7%			*EM16*

7.4.1 Simulation 1 (Combination of All Highest-Effect Parameters)

This simulation considers the overall effect of combining only those variables which contribute to the highest reduction in energy consumption. These were identified as EM2, EM5, EM8, EM9, EM12, EM14, and EM16 (as coded in Table 7-10). Figure 7-10 provides a comparison of the monthly energy consumption between the base case and Simulation 1, highlighting the energy savings for each month.

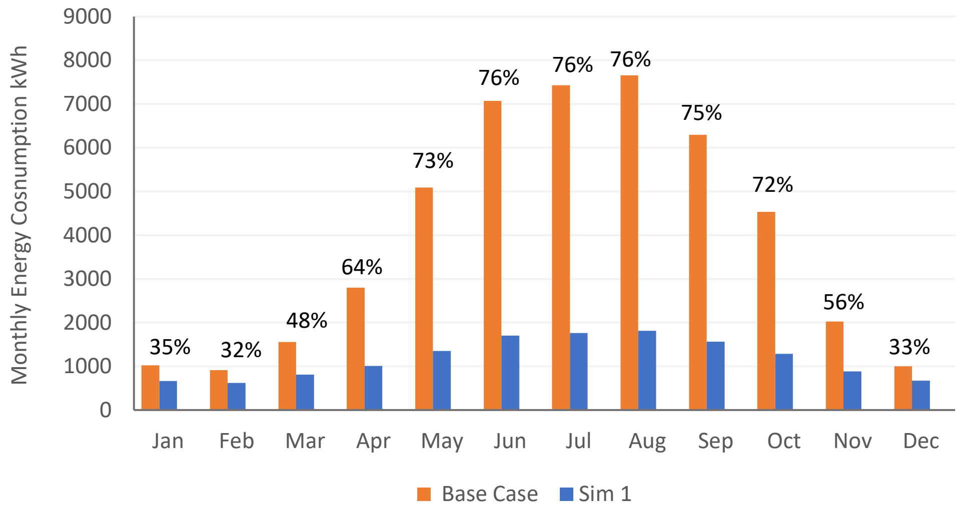


Figure 7-10: Comparison of monthly energy consumption in the base case and Simulation 1

The peak demand and the annual energy consumption for this simulation were 4.75 kW and 14141.3 kWh, respectively, compared to 19.6 kW and 47,389.5 kWh in the base case. Thus, peak demand and total energy consumption were reduced by 75.8% and 70.2%, respectively. The monthly energy savings ranged from 33% to 76%. The highest monthly savings occurred in the summer months (May to Oct), with an average reduction of 75% in total consumed energy. This is particularly significant, given the need for heavy cooling to overcome the hot outer temperatures in Saudi Arabia. Indeed, cooling savings alone contributed to 97.6% of the total reduction achieved in this simulation. According to the heat balance analysis for this simulation, heat gains for walls and roof were improved by 79.2% and 90.4%, respectively, indicating the importance of adding thermal insulation to the building envelope.

7.4.2 Simulation 2 (Combination of All Lowest-Effect Parameters)

Having considered the variables with the greatest effect on energy reduction, this simulation was run to analyse the overall effect on energy use of those variables which exhibited the lowest saving impacts. The variables considered in this model were EM1, EM4, EM7, EM10, EM11, EM13, and EM15. A comparison of the monthly energy demand in this simulation and the base model is depicted in Figure 7-11, showing the reduction achieved each month. It is important to note that, even when adopting only the least effective measures, significant reductions in peak demand (68.9%) and overall energy consumption levels (63.5%) were achieved.

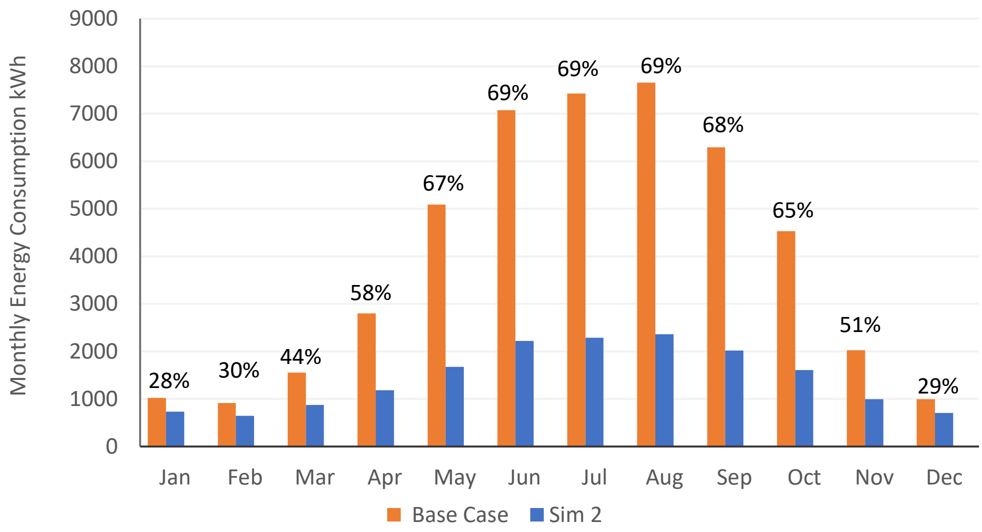


Figure 7-11: Comparison of monthly energy consumption in base case and Simulation 2

In Simulation 2, the monthly energy consumption was reduced by a minimum of 28% (in Jan) and a maximum of 69% in high summer (Jun - Aug). Again, cooling load reduction constitutes by far the largest share of the total saving achieved (98%). According to the heat balance analysis for this simulation, heat gains for walls and roof were improved by 80.8% and 82.8%, respectively.

7.4.3 Simulation 3 (Only Operating Parameters)

This improvement only considered the effect of the two operating parameters, cooling STP and CoP (EM12 and EM14). This was done in order to quantify the effect of occupants' behaviour related to these variables on total energy consumption. As Figure 7-12 demonstrates, there is a clear correlation between CoP and cooling SPT; however, peak demand in this case only reduced by 4 KW when compared with the base case. The adoption of only these two measures contributed to an annual energy saving of 18.5%, which was entirely attributed to the savings in the cooling load, reflecting the importance of occupants' behaviour in relation to operational energy consumption.

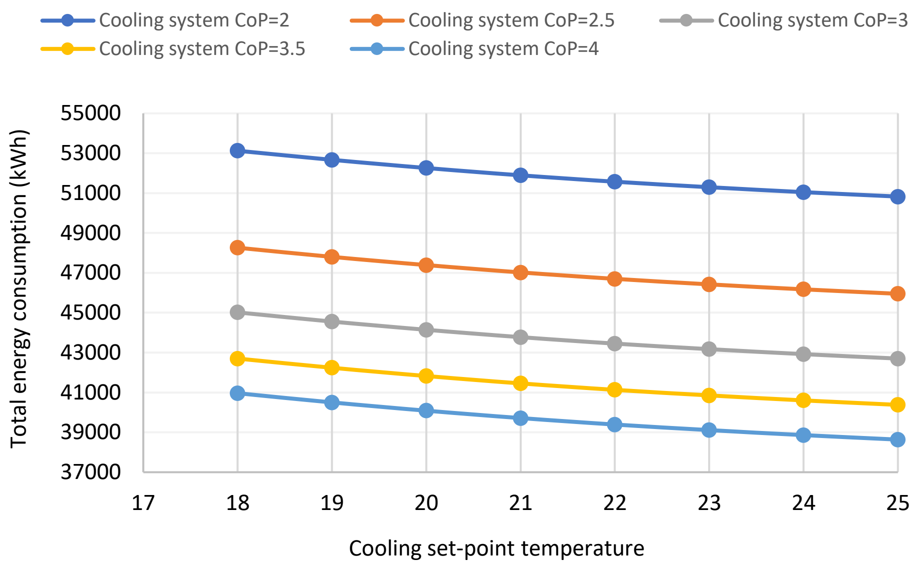


Figure 7-12: The effects CoP and cooling SPT on total energy use

It is important to note that, while the highest monthly energy savings (20%) occurred in the summer months (May - Oct), with a CoP of 4 and a cooling SPT of 25°C, it is more appropriate for the purposes of this study to consider an internal cooling SPT that ensures better thermal comfort of occupants.

7.4.4 Simulation 4 (Only Design Parameters)

Simulation 4 explored the effect of the design-related parameters (as presented in Table 7-1) in order to quantify their overall effect on total energy consumption. The measures applied in this simulation were EM2, EM5, EM8, EM9 and EM16, representing improvement to the external walls, roof, glazing, shading, and infiltration, respectively. The combination of these measures led to a 71.1% reduction in peak demand and an annual total energy consumption of 15,945.6 kWh, resulting in energy savings of 66.4%. As in Simulations 1 and 2, cooling energy saving was the main source of overall savings (97%). Moreover, the heat balance analysis for this simulation revealed that heat gains for walls and roof were improved by 79.1% and 90.3%, respectively. As can be seen in Figure 7-13, the highest energy demand reductions occurred in the summer months, with an average of 71%.

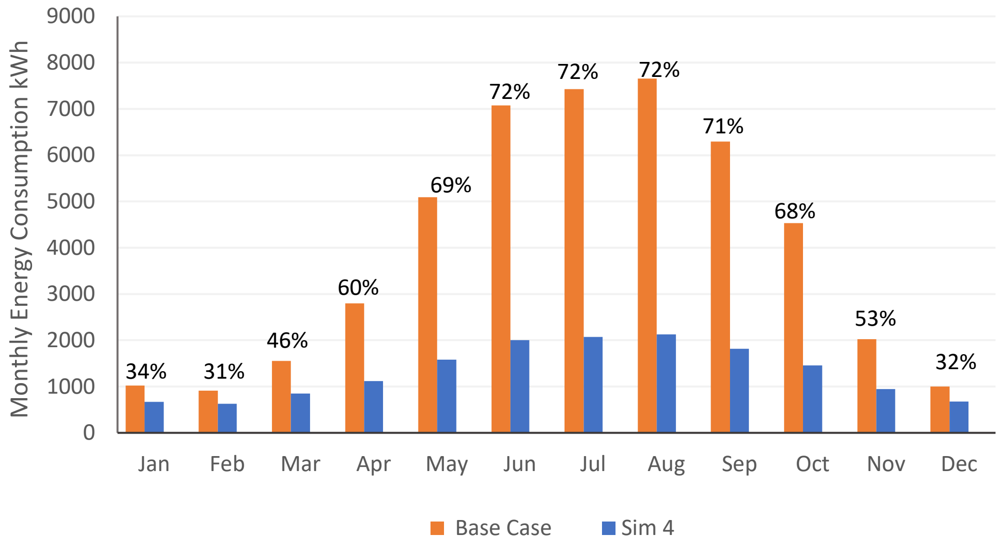


Figure 7-13: Comparison of monthly energy consumption in base case and Simulation 4

Further comparison between the simulations run in terms of peak demand, energy consumption, heat gains, and carbon emissions are provided below in Section 7.8.

7.5 Discussion of the Impact of the Simulation Parameters

A detailed parametric analysis of a prototypical model can be used to determine the effects of many designs and operating measures on total annual energy consumption. This section discusses the environmental and economic impact of the individual parameters whereas the impact of these parameters in combination is discussed in Section 7.6.4, as part of the overall cost-benefit analysis.

Figure 7-14 depicts the total energy saving associated with each individual parameter. As can be seen, the impact on energy consumption of wall insulation, roof insulation, CoP of the cooling systems, and reducing air infiltration were significant, with maximum energy savings of 24.4%, 18.4%, 15.4%, and 11.7%, respectively. However, the individual effects of measures such as double-glazed windows, shading devices, and internal cooling STP on the energy consumption of the building were not as significant.

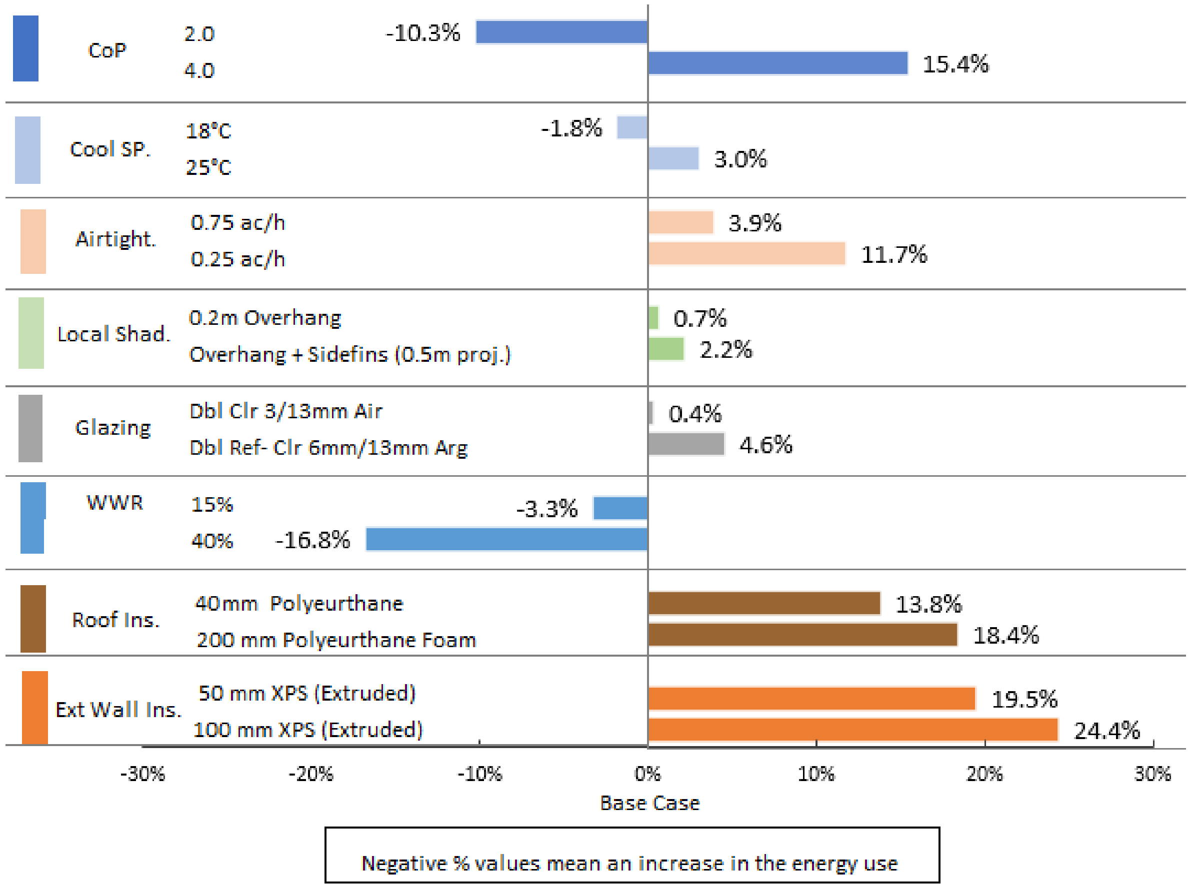


Figure 7-14: Impact of individual parameters on energy savings

7.5.1 Impact of Applying Insulation

As was expected, the simulation results indicate that applying insulation to the envelope elements (roof and walls) would have the highest impact on the building. This is mainly due to the positive effect of thermal insulation materials on heat gain through the envelope elements, which subsequently reduces the cooling required to maintain occupants' thermal comfort. The combined addition of thermal insulation to the building's walls and roof was found to achieve a 33% to 45% reduction in total energy consumption. This is consistent with previous literature, which suggested energy reductions of 15% to 35% could be achieved with the application of exterior wall and roof thermal insulation (Al-Sanea and Zedan, 2011; Al-Sanea, 2002; and Alaidroos and Krarti, 2014). However, adding insulation to the external walls may be the biggest contributor to this impact. As Esmaeil et al. (2019) noted, this may be attributed to the fact that more than 50% of a dwelling's enveloping areas are walls and improving their U-value causes heat gain through walls to significantly drop; indeed, this study suggests that reductions of up to 84% are possible. This is in line with previous studies (Radhi, 2009; Utama and Gheewala, 2009) which found that insulating only the walls could improve energy performance by 25% to 40%, depending on the type of wall system and the thickness of the insulation.

7.5.2 Impact of Energy-Efficient AC Systems

The measure with the second highest impact on the overall energy performance is the use of an energy-efficient AC system, an operating measure which can result in a reduction in the annual energy consumption of almost 16%. This is particularly significant given that window type AC systems, and window type combined with split systems are most commonly used in dwellings in KSA, and older window systems often have a CoP not exceeding 2.5, so are considered inefficient with respect to energy consumption (SEEC, 2018). The impact of CoP on efficiency was also endorsed by AlFaraidy and Azzam (2019) who indicated that the minimum EER of a cooling system should not be less than 11 (i.e. CoP≥3.2). The other operating measure considered in this analysis was the cooling SPT, and the results indicated that raising the cooling temperature from 20°C to 25°C reduced energy consumption by 3%. However, previous literature reported higher rate of savings in the context of hot climates, with an average reduction of 13% in domestic energy consumption area when raising the thermostat temperature by just 2°C (Kharseh et al., 2015; and Al-Mumin et al., 2003). This difference might be attributed both to technical advances in the intervening years and behavioural plasticity.

7.5.3 Impact of Enhancing Airtightness

Furthermore, the results also demonstrated the value of designing and constructing the building fabric to be reasonably airtight as energy consumption fell by almost 4% for each 0.25 ac/h reduction in infiltration. For the purpose of this study, the reference building was assumed to have an infiltration rate of 1.0 ac/h, and reducing this to 0.25 ac/h (i.e. reduced by 75%) led to a 12% reduction in the total consumed energy. This also accords with earlier observations by Krarti et al. (2017), who found that around 3.5% savings for each 25% infiltration reduction. These findings provides some support to the growing number of studies indicating that infiltration can have a considerable impact on energy use in buildings in both mild and hot climates (Emmerich et al., 2007; Kraus and Kubečkova, 2013).

7.5.4 Impact of Adding Glazing and Shading

The analysis also studied the impacts of alternative energy conservation methods such as glazing and shading. The incorporation of double-glazed windows was found to reduce overall annual energy consumption by up to 5%. There is a significant volume of published research confirming the importance of incorporating multiple layers of glazing to improve building performance; however, some studies (Forughian and Aiini, 2017; Assem and Al-Mumin, 2010) have demonstrated higher energy savings than this one when using double-glazed windows in a similar climate condition, depending on factors such as the type of glass being used and window sizes. Shading devices exhibited a maximum energy saving of 2.2% and nearly 29% reduction in solar gain.

7.5.5 Impact of Adjusting WWR

In respect of window sizes, the findings indicated that increasing the WWR negatively affects energy consumption and leads to no saving. The simulation results showed that an increase of only 5% in the modelled building's WWR could increase total energy consumption by 3%. This is in line with previous literature (Krarti et al, 2017; Alwetaishi, 2019) which found that a smaller WWR (i.e. 10%) was optimal in hot and dry climates, as opposed to 20% in temperate climates. Another finding (Alghoul et al., 2017) confirmed that a high WWR ratio could reduce heating loads but would also increase cooling loads in hot and humid climate conditions, with increases of up to 32% when adopting a WWR of 40%.

7.6 Final Improvement Parameters

The parametric simulations detailed above were intended to assess the overall impact of the suggested energy-efficiency strategies on building energy performance. However, some of these strategies may incur high costs and require the reconstruction of an envelope element if applied after the initial stage of building construction, as is the case with DWS. Therefore, this final simulation aimed to combine the best-in-class strategies with respect to the current base case building and to minimise the retrofitting costs as much as possible. As a result, the following parameters were applied in consideration of the Saudi building context: wall improvement, roof improvement, high efficiency cooling systems (i.e. higher EER or CoP), efficient windows, external shading, higher cooling SPT, and low infiltration rate. In addition to these design and operating parameters, two varieties of rooftop solar system were also utilised in the improvement modelling. It is worth mentioning that glazing type and shading improvements were insignificant compared to AC systems improvements. The internal temperature was set at 24°C due to the potential saving in cooling load and total energy when compared to any lower SPT. This temperature is also in line with the recommendations of SEEC, SBC, and the expert panel.

To ensure that the improved model is cost-effective, a cost-benefit analysis was performed to include three measures: insulating the building envelope (walls and roof), enhancing the cooling CoP, and incorporating a PV system. As established earlier in Section 7.5, the parametric analysis indicated that applying insulation to the envelope elements (roof and walls) had the highest impact on the building performance, with insulating the walls being the biggest contributor. The second highest impact on the overall energy performance came from the use of an energy-efficient air conditioning system. As cooling loads alone constituted about 82% of the base building's energy consumption, these two parameters significantly reduced overall energy consumption by virtue of reducing the cooling loads. In addition to these two measures, and based on the expert consultation and previous literature, the integration of solar systems on the building's roof was also considered in the cost-benefit analysis.

The following sections discuss the main considerations for the cost-benefit analysis in respect of each of these three measures.

7.6.1 Thermal Insulation

The simulation results in the previous sections showed that two insulation materials achieved the highest energy savings: Polystyrene (XPS) and Polyurethane (PUR). These were selected for this study based on their thermal performance and their availability in the Saudi market. Insulation application costs, including material and labour, were generated based on 2018 average market prices, according to a previous study conducted by AlFaraidy and Azzam (2019). However, an additional cost of 10% was added due to recent reform of the Value Added Tax (VAT) in Saudi Arabia in 2020, from 5% to 15%. The cost and properties of the selected insulation materials are listed in Table 7-11.

Table 7-11: Physical and thermal properties of selected insulation materials

	XPS Application		**PUR Application**	
	Roof	***Wall***	***Roof***	***Wall***
Cost *($/m³)*	*122*	*113*	*129*	*117*
Thermal conductivity K *(W/mK)*	*0.031*		*0.024*	
Specific heat *(J/kg)*	*1280*		*1590*	
Density *(kg/m³)*	*32-35*	*28*	*32-35*	*28*

The improvement solutions for the base case building's roof and walls mainly involved the addition of insulation material to the structure. Two particular solutions were selected, as they are most suitable for retrofitting, and cross sections of the wall and roof layers used are shown in Figure 7-15. As the purpose of this analysis was to find the optimum position and thickness for the application of insulation, three positions were proposed (on the roof only, on the walls only, and on both roof and walls), and the insulation thicknesses ranged from 0 to 140 mm. It should be noted that PUR insulation material was not used for this specific architectural wall insulation system (i.e. EIFS), but it can be applied in the case of DWS (See to Section 2.4.6.4 - Table 2-2).

Figure 7-15: Cross section of EIFS wall layers (Left) and roof layers (Right)

7.6.1.1 Impact of Insulation Position

The base building was erected without insulation and its EUI was 141 kWh/m²/Yr. Figure 7-16 illustrates the effect on energy consumption of adding thermal insulation of differing thicknesses in the selected positions. Overall, it is clear that energy consumption (kWh/m²/Yr) decreased as the thickness of the insulation increases, and that insulating both the walls and roof yielded the biggest reduction. Figure 7-17 shows the effect on energy conservation when these strategies are applied.

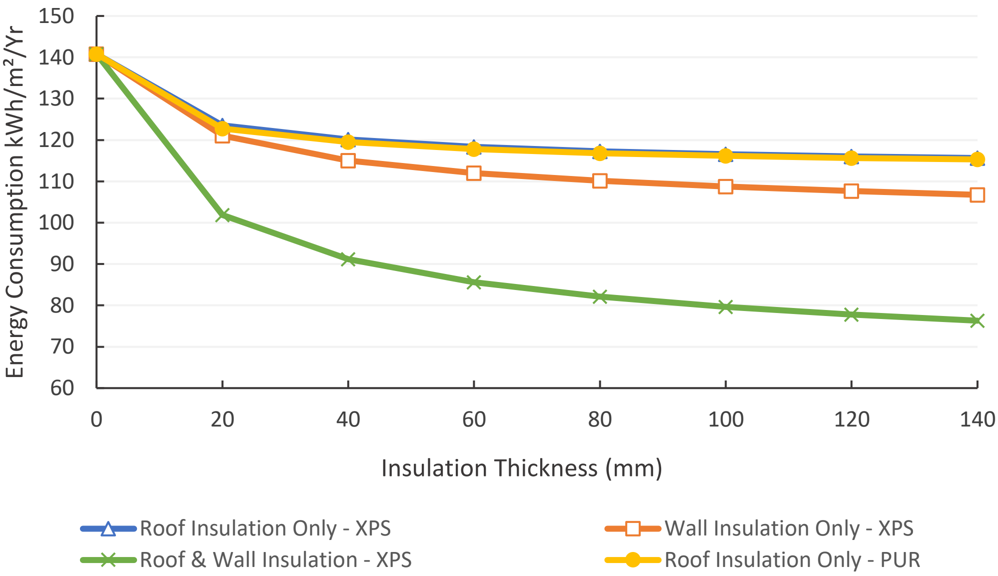


Figure 7-16: Effect of insulation thickness on energy consumption

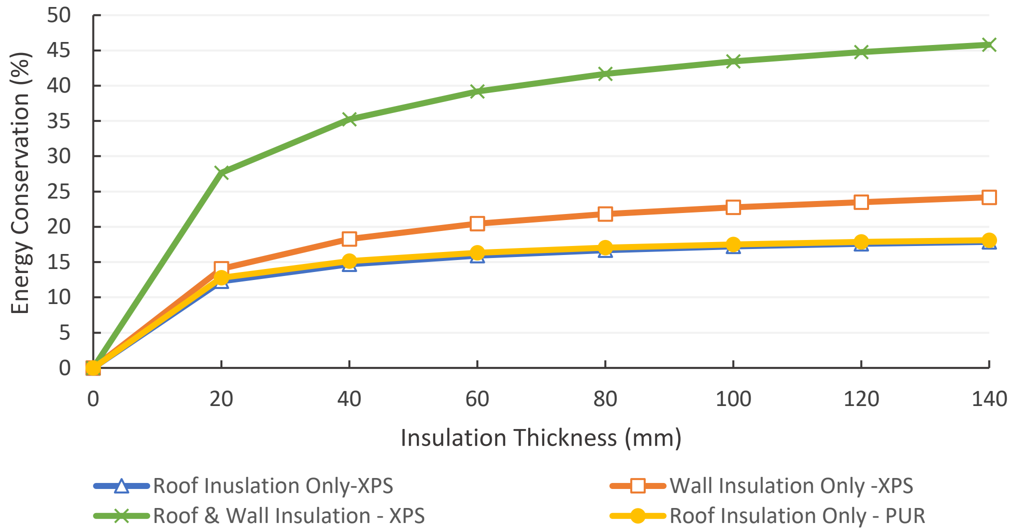


Figure 7-17: Effect of insulation thickness on energy conservation (savings)

Adding thermal insulation to the entire building envelope (roof and walls) at 140mm thickness seems to be the best solution, as it led to a reduction in energy consumption of up to 46% when using XPS material for both structures. Insulating only the walls is considered as the second-best scenario; in addition to its lower cost compared to insulating the entire envelope, a maximum reduction in energy consumption of approximately 25% was achieved at 140mm thickness. This is in line with the findings of the envelope fabric heat balance analysis of the base model presented in Chapter 6 (Section 6.4.5), which showed that the external walls were the main contributor to heat gain in the building, followed by the roof. This can be attributed to the fact that the external walls cover a larger area and directly affect every room, whereas the roof affects only the rooms on the top floor. The figures indicate that both materials (XPS and PUR) had similar trends and effects on energy consumption and conservation.

7.6.1.2 Optimum Thickness of Insulation

As the results above showed as the insulation thickness increases, the energy consumption reductions become evident. This in turn leads to reduced energy costs and reduced CO_2 emission. However, insulation cost increase linearly with insulation thickness. Hence, a nonlinear relationship exists between total cost and insulation thickness. The total cost decreases with increasing insulation thickness until it reaches the optimum insulation thickness, where the total cost is at its minimum (Altamimi, 2020). This condition will then continue to have an upward trend. For the purpose of costs and savings calculation, it was assumed that the lifetime of thermal insulation materials is 30 years (Al-Sanea et al. , 2016; Daouas et al., 2010; Al-Sanea and Zedan, 2011; Krarti et al., 2020).

In order to estimate the environmental impact and the cost savings of the three strategies at their optimum insulation thicknesses over the lifetime of the insulation material, i.e. 30 years, the following formula was used. Cost estimates used were those provided in Table 7-11.

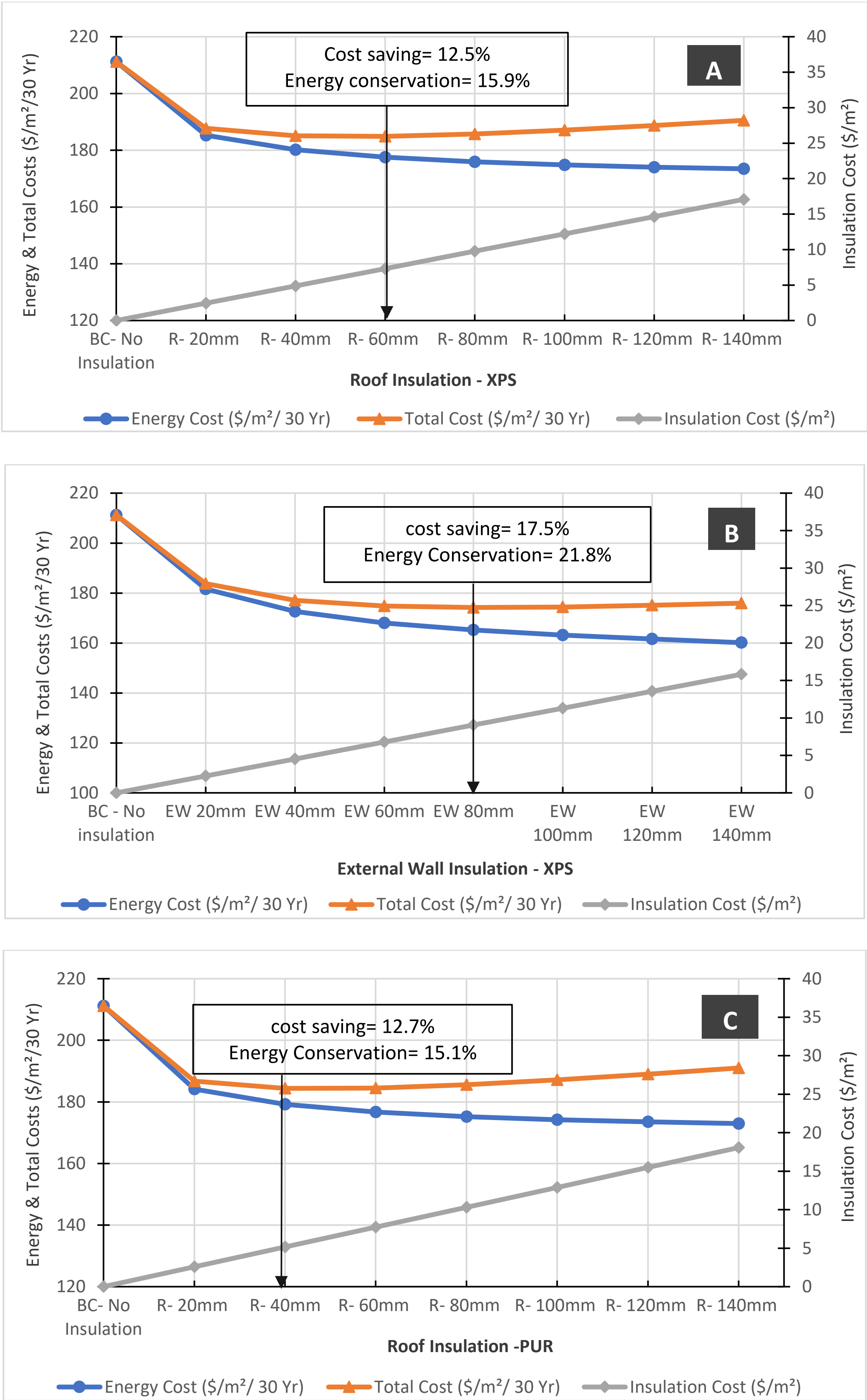
$$\text{Cost Saving } (\%) = \frac{\text{Total Cost at Optimum Thickness } - \text{ total Cost at No Insulation}}{\text{Total Cost at No Insulation}} * 100 \qquad \text{Eq}.7-3$$

Table 7-12 provides the data used in identifying the optimum thickness and cost saving for roof insulation using an XPS material. The same process was carried out for each insulation position.

Table 7-12: Optimum thickness identification for roof insulation using XPS material

Insulation	**Thick.** (*m*)	**Total Energy Consumption** (*kWh/Yr*)	**CO_2** (*kg*)	**EUI** (*kWh/m²/Yr*)	**Energy Cost** (*$/m²/ 30 Yr*)	**Insulation Cost** (*$*)	**Total Cost** (*$/m²/ 30 Yr*)	**Cost saving** (*%*)
BC- 0 mm	0	47389.5	28718.0	140.8	211.2	0.0	211.2	0.0%
R- 20 mm	0.02	41566.8	25189.5	123.5	185.3	2.4	187.7	11.1%
R- 40 mm	0.04	40432.4	24502.0	120.1	180.2	4.9	185.1	12.4%
R- 60 mm	0.06	39843.0	24144.8	118.4	177.6	7.3	184.9	12.5%
R- 80 mm	0.08	39480.3	23925.1	117.3	176.0	9.8	185.7	12.1%
R-100 mm	0.1	39233.3	23775.3	116.6	174.9	12.2	187.1	11.4%
R-120 mm	0.12	39056.5	23668.2	116.0	174.1	14.6	188.7	10.7%
R-140 mm	0.14	38922.9	23587.3	115.6	173.5	17.1	190.5	9.8%

Figures 7-18 A-C demonstrate the environmental and financial effects of applying different thicknesses of XPS and PUR insulation in two of the proposed positions: on the roof only and on the walls only. For these two positions, there were only seven thicknesses options, ranging from 20 mm to 140 mm (at 20 mm increments). As for the insulation of both envelope elements (roof and walls), the analysis to find the optimum thickness is provided in Appendix C as this yielded 64 thickness combinations.



Figures 7-18 (A-C): Effect of different insulation positions using XPS and PUR materials

The results show that the optimum thermal insulation thickness using XPS material was 60 mm for insulating the roof only (Figure 7-18 A), 80mm walls only (Figure 7-18 B), and, for both roof and walls, a combination of 60mm (for roof) and 100mm (for walls) (Appendix C). These led to reductions in annual energy consumption of 15.9%, 21.8%, and 41.8%, respectively. Moreover, applying the optimum thickness on the roof and walls had the highest total cost savings of 33%. Applying it on the wall only had the second highest total cost savings of 17.5%, while application on the roof had the lowest total savings at approximately 12.5%.

Similar analysis was also conducted for the application of PUR insulation material. However, as mentioned above, PUR is not usually used for external insulation application in the type of wall insulation system (i.e. EIFS) examined here, so it was considered only for insulating the roof. Figure 7-18C shows that applying PUR at the optimum thicknesses of 40mm to the roof only led to energy savings of 15.1% and cost savings of 12.7%. The analysis of insulating the whole envelope (using PUR for the roof and XPS for the walls) indicated that the optimum thicknesses for this application were 60 mm of PUR (for the roof) and 100 mm of XPS (for the walls), as this resulted in total energy savings of 42.5%. Further details are provided in Appendix C.

The previous thermal simulation described in Section 7.3.1 used initial thicknesses of 50 mm and 100 mm for the walls and roof, as these are most commonly used in KSA; however, the 50 mm thickness did not comply with the SBC602 requirements for wall insulation. In light of this, it is important to note that the optimum thicknesses for wall insulation identified here are all greater than 50 mm.

In summary, the findings indicate that proper insulation material installed at its optimum thickness could not only reduce heat transfer through the building envelope but also achieve economic and environmental advantages. According to results, both insulation materials have to some extent the same economic and environmental impacts. Environmentally, insulating the entire envelope proved to be the best practice due to the significant energy and carbon reductions exhibited. Economically, over a 30-year period, insulating the entire envelope also had the highest cost saving of 33% and the highest life cycle savings of 89 USD/m², compared to the other insulation alternatives. In general, this analysis indicates that applying insulation to both the roof and walls of a residential building is the best solution considering the hot arid climate of KSA because it provided the highest percentage of annual conserved energy, the highest cost savings, and the highest life cycle savings.

7.6.2 Cooling System Efficiency

Given the fact that cooling loads are responsible for about 70% of the total energy consumption in residential buildings in KSA, improving the efficiency of cooling systems is of major significance. This was confirmed by the parametric analysis results presented in Section 7.3.8 which indicated that significant energy savings could be achieved by upgrading the current stock of window and split AC systems to a higher CoP/EER. The Saudi government has recognised this and now subsidises the purchase of highly-efficient machines through the HEAC scheme by offering a discount of 900 SAR (240 USD) per unit to eligible residents for up to six units per household.

The average costs of the most common AC systems in the Saudi market are presented in Table 7-13, both with and without the HEAC incentive. To meet the MEPS for AC systems, the minimum EER should not be less than 11.8, (i.e. CoP≥3.46) (AlFaraidy and Azzam, 2019). It should be noted that, from a practical and economic point of view, a 2.0 tonne AC system may be too large for a typical room and is better suited to larger spaces, such as guest rooms and open sitting areas. Therefore, it will not be considered in later analysis.

Table 7-13: Average market costs per AC unit (Tabulated by author. Source: Krarti and Howarth, 2020)

AC Unit Type	Average Cost per Unit in USD	
	without incentive	*with incentive*
1.5 tonnes AC (18,000 Btu) - MEPS (EER>=11.8)	627	NA
1.5 tonnes AC (18,000 Btu) - HEAC (EER>=13)	748	508
2.0 tonnes AC (24,000 Btu) - MEPS (EER>=11.8)	780	NA
2.0 tonnes AC (24,000 Btu) - HEAC (EER>=13)	921	681

These costs will be used later for the cost-benefit analysis for the optimised building model, alongside the costs associated with the other significant measures. In fact, improvements to AC energy efficiency have been the subject of detailed cost-benefit analyses in several countries, including Malaysia (Kwong et al., 2017), Indonesia (McNeil et al., 2019), China (Karali et al., 2020), Mexico (Rosas-Flores et al., 2011), and Europe as a whole (Grignon-Masse et al., 2011). However, to the best of the researcher's knowledge, no comprehensive studies have examined the impact of energy efficiency improvements to AC stock in the context of Saudi Arabia.

7.6.3 Solar Panels Integration

This section explores the possibility of integrating solar panels into the building envelope, specifically the roof. The type of PV system selected for this study is the monocrystalline silicon module as it is widely used in the residential sector and is the most efficient type available in the Saudi market (Alshahrani, 2018). Monocrystalline panels use higher-grade silicon, making them the most efficient in terms of output and space (Vieira et al., 2016). According to the manufacturer's datasheet, each solar panel contains 60 PV cells forming a typical module size of 1.6 m², has a nominal power rating (i.e. capacity) of 300 Wp and a module efficiency of 18.3%. This means that, in ideal conditions, it can convert up to 18.3% of the sunlight which strikes it into electrical energy. For simplification, an ideal production condition for the roof PV arrays assumes the average solar radiation of 2470 kWh/m² from an annual average of 3245 sunshine hours, an average 8.9 sunshine hour per day (Pazheri, 2014; Zell et al., 2015; Rehman et al., 2007). These rooftop panels are to be configured at optimum orientation angles for Riyadh, as recommended by Al Garni et al. (2019) (see Section 2.4.2.2). These optimal angles are -20° and 24° toward south for azimuth angle and tilt angle, respectively.

A key value in respect of solar panels is their Performance ratio (PR). Specifically, PR is the ratio of the actual energy output of a PV system to the theoretical standard test condition output. It defines the quality of a PV module performance independently of the orientation or inclination of the panel. It includes all potential losses, such as losses from inverter, temperature, cables, and weak radiation due to dust or shading. This study adopted a PR of 0.78 for the system for Saudi Arabia, as proposed by Imam and Al-Turki (2020). Despite Riyadh's high solar potential, the system's PR is slightly lower than the 0.82 recorded in Dublin, Ireland (Pazheri et al., 2011). However, the PR has a strong temperature dependence, which implies that it will be lower in hot climates than cold ones. (Reich et al., 2012). To estimate the annual solar energy output of a PV system, as reported in Swain (2017), the following global formula was utilised:

$$E = A \times r \times H \times PR \qquad\qquad Equation\ (7-4)$$

Where E =Energy (kWh)
A =Total solar panel Area (m^2)
r =solar panel yield ($\%$)
H = Annual average solar radiation on tilted panels
PR = Performance ratio, coefficient for losses (range between 0.5 and 0.9, default value = 0.75)

Furthermore, two options of on-site (i.e. rooftop) solar systems were considered. The first option consisted of ten panels in total, configured in five modules per string and two parallel strings, with a total system size of 16m², with an inverter being used. As the gross roof area of the base case building is 237m², this option constituted about 7% of the gross roof area. The second option was of a similar configuration, but a larger application of the panels, with a total system size of 32m² and covering 13.5% of the total roof space. With each of these systems configured at the optimal angles for Riyadh, the energy outputs (in kWh) were 5641 and 11282, respectively.

The cost considered for PV panels covers the costs of each complete individual panel, installation, invertor, and grid connections. These were based on the average obtained from recent local studies and current market quotes. As discussed in Chapter 3 (Section 3.6.4), the grid connection cost for a solar system of a capacity not exceeding 50 kW is nearly 147 USD while the financial return paid to residential customers for surplus energy generated, or exported, by the system is 0.019 USD/kWh (ECRA, 2019). According to Imam and Al-Turki (2020), the average technology and installation costs, based on estimated quotations from the Saudi market, were 200 USD for each module, plus an average inverter cost of 650 USD for the whole system. It is expected that a PV panel can have up to 25 years life span (Tsang et al., 2016; Vieira et al., 2016; Imam and Al-Turki, 2020). These costs are required to perform the cost-benefit analysis.

The PV module characteristics obtained from the manufacturer's datasheet and the optimum configurations were inserted into the simulation software in order to evaluate the overall energy performance of the optimised model. The following section compares the effects of incorporating combinations of measures and discusses the impact of employing the best-in-class EEMs on the overall building performance, both economically and environmentally.

7.6.4 Cost Benefit Analysis of Combined Improvement Parameters

This section assesses the improved model parameters to ensure that their implementation is cost effective. The parameters included in the improvement simulation are shown in Table 7-14. Three parameters were considered in the cost-benefit analysis due to their considerable impact (as established in previous sections). These parameters were applied with consideration of the Saudi context and local building codes.

Table 7-14: Parameters considered for building improvement simulations

Parameters		Description
Design Related	*Ext. Wall Construction*	100 mm XPS Insulation (U-value = 0.246 W/m²K)
	Flat Roof Construction	Two options considered: (60 mm PUR Insulation, U-value = 0.263 W/m²K) and (60 mm XPS insulation, U-value=0.27 W/m²K)
	Glazing Type	Double Ref Clear (6mm/13mm Arg) (U-value= 2.233 W/m²K, SHGC= 0.228)
	Local Shading	Louvres (0.2m projection)
	Airtightness	0.5 ac/h
Operating Related	*Cooling Setpoint Temp*	24 °C (to meet SEEC and SBC specifications)
	AC efficiency	Two options considered: (EER=11.8, to comply with MEPS) and (EER=13 HEAC initiative)
On-site Renewable Energy	*Rooftop Solar Panels*	Two options considered: (10 PV modules, i.e. system size of 16m²) and (20 PV modules, i.e. system size of 32m²)

In order to evaluate each combination's economic and environmental impacts, eight simulations of different combinations of the measures shown in Table 7-14 were carried out. For the purposes of measuring financial profitability, the payback period for each combination was calculated by dividing the initial investment costs by the annual savings. Payback period refers to the time required for an investment to recoup its costs in terms of profits or net cash flow and is widely used for assessing cost effectiveness for energy efficiency improvements in buildings (Terry and Palmer, 2019; Imam and Al-Turki, 2020). The simple payback method is also thought to be well understood, including by households (Accent, 2016). Table 7-15 summarises the results of each combination in terms of peak electricity demand, energy performance, carbon emissions, heat gains, and payback periods.

Table 7-15: Cost-benefit analysis for all the combinations considered in the improved model

Base Case Data								
Electricity Peak Demand (*kW*)	19.6							
Total Annual Energy Consumption (*kWh*)	47389							
Total EUI (*kWh/m²/Year*)	140.8							
Annual CO_2 Emission (*kg*)	28718							
Cooling Load (*kWh*)	38836							
Cooling EUI (*kWh/m²/Year*)	115.4							
Roof Heat Gain (*kWh*)	26804.6							
Walls Heat Gain (*kWh*)	43198.8							
Improvement parameter	**Combination Considered**							
	Option 1	***Option 2***	***Option 3***	***Option 4***	***Option 5***	***Option 6***	***Option 7***	***Option 8***
Efficient AC System	EER=11.8	EER=11.8	EER=13	EER=13	EER=11.8	EER=11.8	EER=13	EER=13
Rooftop PV System	16 m² size	16 m² size	32 m² size	32 m² size	32 m² size	32 m² size	16 m² size	16 m² size
Roof Insulation	60mm XPS	60mm PUR	60mm XPS	60mm PUR	60mm XPS	60mm PUR	60mm XPS	60mm PUR
Wall Insulation	100mm XPS							
Efficient Window Glazing	Double Ref Clear 6mm/13mm Arg (U-value= 2.233 W/m²K, SHGC= 0.228)							
External Shading Device	Louvres (0.2m projection)							
Lower Infiltration Rate	0.5 ac/h							
Cooling Setpoint Temperature	24 °C							
Benefit	***Option 1***	***Option 2***	***Option 3***	***Option 4***	***Option 5***	***Option 6***	***Option 7***	***Option 8***
Electricity Peak Demand (*kW*)	5.34	5.33	5.14	5.13	5.33	5.31	5.16	5.14
Total Annual Energy Consumption (*kWh*)	15592.2	15553.4	15085.3	15050.4	15534.9	15497.9	15140.9	15104.3
Total EUI (*kWh/m²/Year*)	46.3	46.2	44.8	44.7	46.2	46.0	45.0	44.9
Annual Energy Generated (*kWh*)	5430.4	5430.4	10781.2	10781.2	10781.2	10781.2	5430.4	5430.4
Annual CO_2 Emissions (*kg*)	6158.1	6134.6	2608.3	2587.1	2880.7	2858.3	5884.6	5862.4
Cooling Load (*kWh*)	7824.6	7786.3	7316.7	7282.3	7766.3	7729.8	7373.3	7337.2
Cooling EUI (*kWh/m²/Year*)	23.2	23.1	21.7	21.6	23.1	23.0	21.9	21.8
Roof Heat Gain (*kWh*)	4846.1	4726.1	4635.9	4521.2	4635.9	4521.2	4846.1	4726.3

Walls Heat Gain (*kWh*)	8835.8	8841.3	8850.4	8855.8	8850.4	8855.8	8835.8	8841.6
Peak Demand Reduction (*%*)	72.8%	72.8%	73.8%	73.8%	72.8%	72.9%	73.7%	73.8%
Energy Consumption Reduction (*%*)	67.1%	67.2%	68.2%	68.2%	67.2%	67.3%	68.0%	68.1%
CO_2 Emissions Reduction (*%*)	78.6%	78.6%	90.9%	91.0%	90.0%	90.0%	79.5%	79.6%
Reduction In Cooling Load (*%*)	79.9%	80.0%	81.2%	81.2%	80.0%	80.1%	81.0%	81.1%
Reduction In Roof Heat Gain (*%*)	81.9%	82.4%	82.7%	83.1%	82.7%	83.1%	81.9%	82.4%
Reduction In Walls Heat Gain (*%*)	79.5%	79.5%	79.5%	79.5%	79.5%	79.5%	79.5%	79.5%
Conserved Energy (*kWh/Year*)	31796.8	31835.6	32303.7	32338.6	31854.1	31891.1	32248.1	32284.7
Return From Conserved Energy (*USD/Year*)	1589.8	1591.8	1615.2	1616.9	1592.7	1594.6	1612.4	1614.2
Return From Generated Energy (*USD/Year*)	103.2	103.2	204.8	204.8	204.8	204.8	103.2	103.2
Total Savings (*USD*) (Conserved And Generated)	1693.0	1695.0	1820.0	1821.8	1797.5	1799.4	1715.6	1717.4
Cost	***Option 1***	***Option 2***	***Option 3***	***Option 4***	***Option 5***	***Option 6***	***Option 7***	***Option 8***
Costs of AC upgrading (*USD*) (Given in Table 7-13, i.e., Average number of 5 ACs)	3135	3135	2540	2540	3135	3135	2540	2540
Costs of PV systems (*USD*) (Costs of each complete individual panel, installation, invertor, and grid connection)	2797	2797	4797	4797	4797	4797	2797	2797
Costs of insulation (*USD*) (Insulations for Walls and roof costs as specified in Table 7-11)	6608.4	6710.8	6608.4	6710.8	6608.4	6710.8	6608.4	6710.8
Total costs (*USD*) (AC upgrade, PV panels, and envelope insulation)	12540.4	12642.8	13945.4	14047.8	14540.4	14642.8	11945.4	12047.8
Payback Period (Years)	**7.4**	**7.5**	**7.7**	**7.7**	**8.1**	**8.1**	**7.0**	**7.0**
Total costs for Base Case (*USD*) (Energy and application costs)	71083.5							
Total costs for improved Case (*USD*) (Energy and application costs)	35928.7	35972.9	36573.3	36623.4	37842.7	37889.6	34656.7	34704.2
Cost Savings (%) for 30 years use-period	49.5%	49.4%	48.5%	48.5%	46.8%	46.7%	51.2%	51.2%

7.6.4.1 Reductions in Total Energy Consumption and Peak Demand

The results from Table 7-15 indicate that applying any of the suggested combinations of improvement parameters would reduce the total energy consumption of the base case building by 67.1% to 68.2%, and the peak demand by 72.8% to 73.8%. In term of improving the energy performance, it seems that all eight combinations would, on average, lead to 67.7% savings in annual energy consumption and 73.3% in electricity peak demand. Both integrated solar systems appear to have perform similarly in terms of energy saving, despite the noticeable difference in their capacities for electricity generation. As demonstrated earlier, most of the energy saving is attributed to the reduction in cooling loads, as this was reduced by 80.6% on average.

7.6.4.2 Total Cost Savings Over the Building-Use Period

Total cost savings analysis for a building-use period of 30 years indicated significant savings. These were calculated by the difference ratio between the total costs in the base case building and the improved model. The total costs are those required for the annual energy use in addition to any costs related to energy-efficiency applications. Theoretically, incorporating these measures into the building would lead to total operational cost savings of up to 51% for a building-use period of 30 years. In turn, this conserved energy would lead to average energy savings cost of 1,603 USD. However, the reduction in the amount of carbon emissions varies amongst these combination options, mainly depending on the size of the solar system incorporated. Combinations including the larger solar systems size (i.e. 32 m²) made a larger contribution to reducing carbon emissions, bringing them down by an average of 90.5 %, while incorporating the 16 m² solar system reduced them by 79.1%, on average. To be specific, the base case CO_2 emissions were estimated at 28,718 kg; however, after adopting solar system options of 16m² and 32m², they were reduced to 6,010 kg and 2,734 kg, respectively. Undoubtedly, the larger solar system would generate more energy and lead to higher financial return, with the 32 m² solar systems yielding an annual return of nearly 205 USD compared to 103 USD for the 16 m² systems. The total savings cost consists of the cost of conserved energy and the return of generated energy. For all options, the total savings in USD range from 1,695 to 1,822.

7.6.4.3 Cost-Effectiveness of Applying the Selected Measures

Since there was only one option to improve the external walls (adding 100 mm of XPS material), there was only one result, a 79.5% reduction in wall heat gain compared to the base case scenario. The roof improvement, on the other hand, applied a thickness of 60 mm of each of the two materials considered, XPS and PUR. As discussed in Section 7.6.1.1, these tend to have a similar effect on roof heat gains. The average roof heat gain was 4,682 kWh compared to 26,805 kWh in the base case building, a reduction of 82.5%. These significant reductions in heat gain in the envelope elements reflect the impact of adding thermal insulation to the walls and roof and the subsequent reduction in cooling demands. To find the payback period, it was necessary to calculate all the investments cost for incorporating PV panels, applying thermal insulation, and for upgrading the AC systems. As a typical Saudi household would require, on average, five AC units to maintain thermal comfort, this analysis upgraded five systems to comply with local standards, i.e. MEPS (EER=11.8) or HEAC (EER= 13). The findings proved that when the existing AC units were replaced with more efficient models (i.e., EER ≥13), significant reductions in electrical peak demand, annual electricity consumption, and carbon emissions were obtained. Thus, annual energy savings increased as the EER rating increased. Although systems with higher EER ratings usually cost more, the effect of the HEAC consumer subsidy meant that upgrading the AC systems to the HEAC standard would involve lower replacement costs than meeting the MEPS requirements, despite the higher EER. The subsidy also means that purchasing a more efficient unit may have a simple payback period for the consumer which is slightly shorter than those associated with less efficient AC options. Therefore, the options with the highest total costs were those with the larger solar system and the slightly less efficient AC system (EER=11.8), since there was no government discount offered for upgrading ACs to this efficiency ratio. Overall, the total costs for all options ranged from 11,945 to 14,643 USD for AC upgrade, PV panels, and insulation.

Economically, all combinations offered a range of payback periods from 7.0 to 8.1 years. Despite this relatively insignificant difference in payback periods, options 7 and 8, which incorporate an AC system of EER=13 and a 16 m² solar system, may be preferred due to their overall energy savings (68%), lower capital costs, and the shortest payback period (7 years).

7.7 Improved Case Model

The parameters for the final building improvement simulation (Option 8 in Table 7-15) are presented in Table 7-16.

Table 7-16: Parameters considered for final building improvement simulation

Parameters		Description	
		Base Case	***Improved Case***
Design Related	*Ext. Wall Construction*	No Insulation (U-value = 2.15 W/m²K)	100 mm XPS (Extruded) Insulation (U-value = 0.246 W/m²K)
	Flat Roof Construction	No Insulation (U-value = 2.123 W/m²K)	60 mm PUR Insulation U-value = 0.263 W/m²K
	Glazing Type	6mm single glass (U-value= 5.78 W/m²K, SHGC= 0.62)	Double Ref Clear 6mm/13mm Arg U-value= 2.233 W/m²K, SHGC= 0.228
	WWR	9%	9%
	Local Shading	No external shading	Louvres (0.2m projection)
	Airtightness	Infiltration 1 ac/h	0.5 ac/h
Operation Related	*Cooling Setpoint Temp*	20 °C	24 °C
	AC CoP	2.5	4 (i.e., EER=13)
On-site Renewable Energy	*Rooftop Solar Panels*	Not Applicable	PV arrays of 16m² size

7.7.1 Annual Reduction in Energy Consumption and Operating Costs

Generally, this simulation follows the same trends as the base case, with peak energy consumption in July-August (the hottest months in KSA). Hence, the effect of the improvements was most marked during this period, with an average reduction of 74% during the summer (May-Oct), as illustrated in Figure 7-19. The annual conserved energy was nearly 32,285 kWh with reference to the base case energy consumption. Give that the current cost of 1 kWh of electricity is 0.18 Saudi Riyal (equivalent to 0.048 USD) (SEC, 2021), this led to a reduction of around 1,614 USD in operational energy costs.

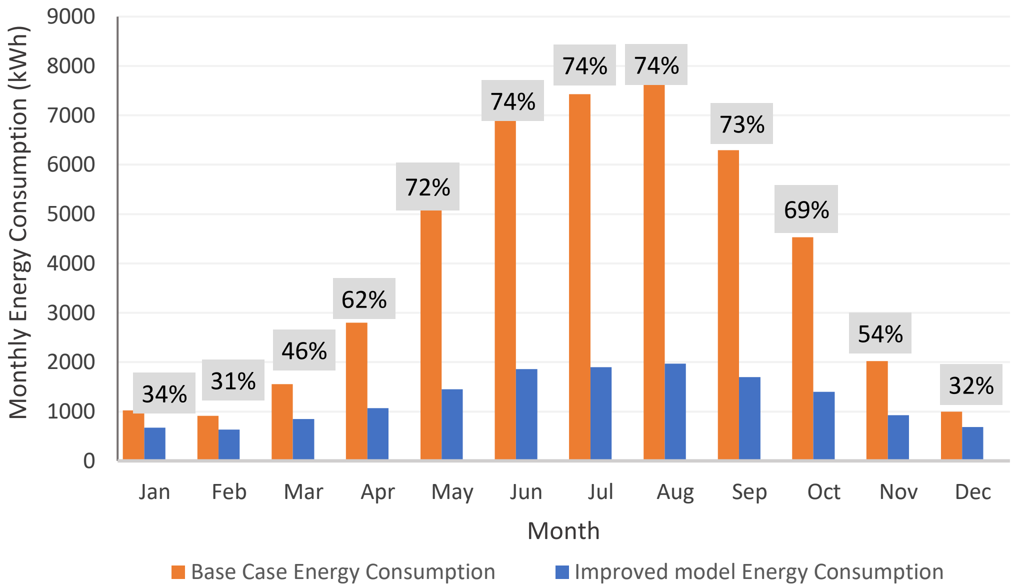


Figure 7-19: Comparison of monthly energy consumption between base case and improved case

7.7.2 Annual Reduction in Carbon Emissions

Similarly, Figure 7-20 indicates that the carbon emissions followed the same pattern, with average reductions of 81% during the summer months. Annually, the improved model would save nearly 23 tonnes of CO_2 emissions, representing an 80% reduction in comparison with the base case building.

According to the United States Environmental Protection Agency (EPA, 2021), the environmental impact of reducing GHG emissions can be expressed in terms of the annual number of cars not used. When the annual amount of CO_2 avoided in the improved model was divided by the typical passenger vehicle emissions (about 4.6 metric tonnes per year), the improvements were shown to have removed emissions equivalent to almost five vehicles from the environment.

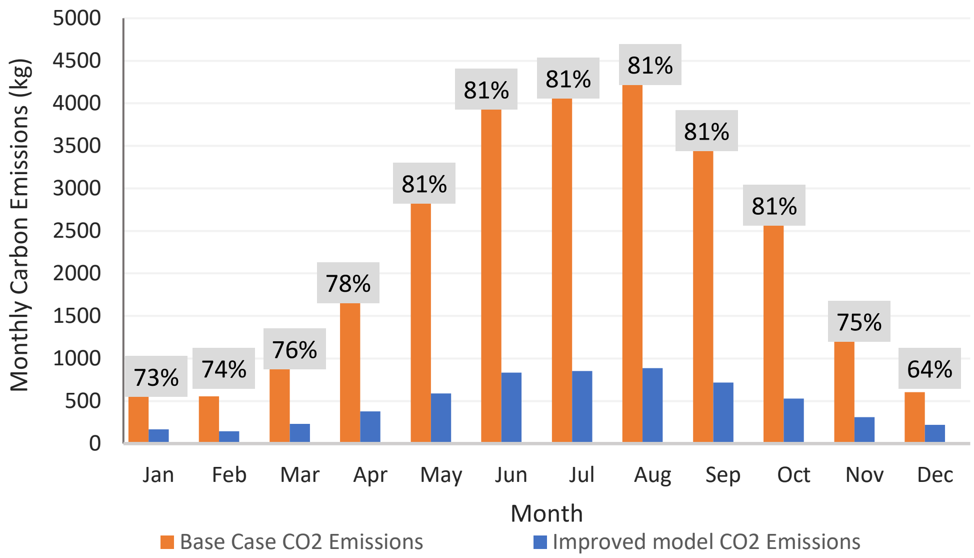


Figure 7-20: Comparison of monthly carbon emissions between base case and improved case

7.7.3 Cumulative Savings with All Measures Implemented

Figure 7-21 shows the cumulative energy saving when applying each of the improvement strategies to the existing building model (i.e. top to bottom). As the figure demonstrates, energy consumption in the existing building could be reduced by just over 68% if all the measures described in Table 7-16 were implemented.

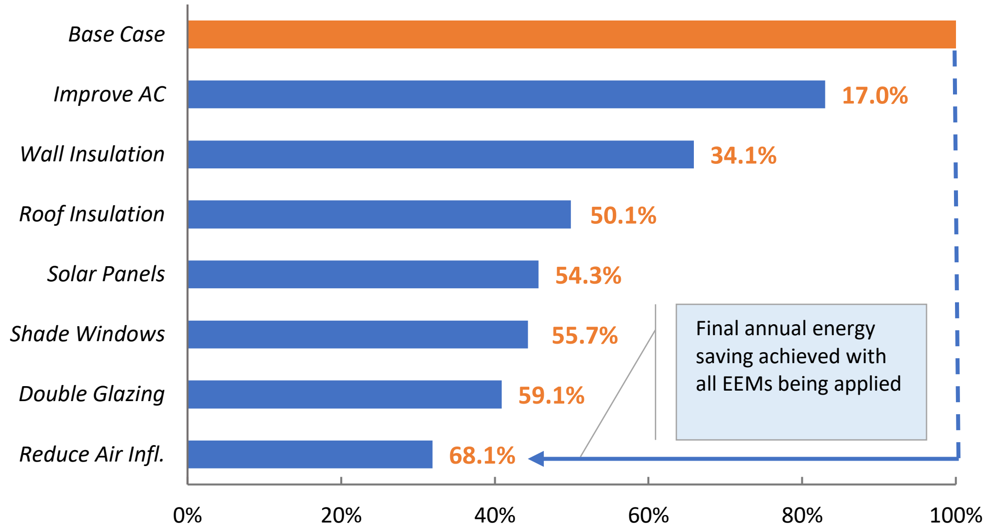


Figure 7-21: Cumulative energy saving when applying the final improvement strategies

7.7.4 Annual Reduction in Cooling Load

The comparison between the base case building and the improved version (presented in Table 7-17) demonstrates that reductions in the cooling load constituted the main source of energy savings. The base building, although recently built, was erected with no proper insulation, single glazed windows, no shading, and inefficient cooling systems. As a result, its EUI was 141 kWh/m²/year and total energy consumption for space cooling alone was nearly 115 kWh/m²/year. Applying the proposed efficiency measures significantly reduced the total energy load from 141 to 45 kWh/m²/year, mainly due to the considerable reduction in the cooling loads. The cooling EUI was reduced from 115 to 22 kWh/m²/year, which falls within the range of the recommended European Standard for space cooling of 20-30 kWh/m² per year (Carmody et al., 2009). Furthermore, the findings indicated that integrating PV arrays of a total size of 16m² (i.e. occupying only 7% of the roof area) could generate additional energy (up to 36% of the total energy consumed) which could be used in the form of electricity within the home or exported to the distribution grid, both providing a financial benefit to the householder.

Table 7-17: Comparison of energy consumption between the base case and improved case

Annual Energy Breakdown (Electricity)	**Base Case**	**Improved Case**
Room Electricity (*kWh/m²/Year*)	8.6	8.3
Lighting (*kWh/m²/Year*)	11.0	10.7
Heating (*kWh/m²/Year*)	1.4	0.1
Cooling (*kWh/m²/Year*)	115.4	21.8
DHW (*kWh/m²/Year*)	4.3	4.0
Total Consumed Energy *kWh/m²/Year*	140.80	44.9
Total Generated Energy (*kWh/m²/Year)*	-	16.1
Energy Generated to Energy Consumed (*%)*	-	36%

7.7.5 Potential Impact on Residential Housing Stock in Saudi Arabia

As mentioned earlier, the 2018 statistics indicated that the Saudi building sector consumes nearly 75% of the country's electricity production, with residential buildings accounting for about half of this (Abd-ur-Rehman et al, 2018; SEEC, 2018; Hijazi and Howieson, 2018; KAPSARC, 2020; ECRA, 2018). In the same year, the total electricity consumption for the residential sector was around 109 TWh (SAMA, 2019). As both recent national statistics (GAS, 2019) and the findings of the public survey showed that villa-type dwellings constitute about 32% of the total residential stock in KSA, applying the proposed measures suitable for retrofitting to existing villas could achieve substantial energy savings across the country. Indeed, the simulation results presented in this chapter indicate that savings of up to 68% can be achieved. However, the application of such measures is not proposed solely for retrofitting a specific dwelling type but rather for the domestic sector in general, as far as possible. While the scope of this study was limited to an existing building, much more widespread reductions in energy consumption could be obtained by the modification of similar properties during the design or construction stage. These measures would have a significant impact on Saudi Arabia's domestic sector, especially with the rising demand for housing to meet population growth.

7.7.6 Thermal Comfort Analysis of Improved Case Model

The thermal analysis of the base case reported in Chapter 6 (Section 6.4.5.2) revealed that the building failed to meet the requisite thermal comfort criteria (Acceptable PMV and PPD Ranges). A similar approach was adopted to assess the thermal performance of the improved case using the Thermal Comfort Calculator tool. The outcome of this analysis is reflected by the Fanger Comfort Model shown in Figure 7-22. If the PMV value is within the comfort region (-0.5 to +0.5) then the outputs and the line between the PPD axis and the curve will be displayed in green. As the graph illustrates, the improved building falls within the comfort limits, with a PMV value of -0.44 and a PDD of 8.96%, which indicates that the occupants would feel satisfied by the indoor thermal conditions. Discussion on how these values were obtained and what is considered to be an acceptable range of thermal comfort has been provided earlier in Sections 6.4.4.1 and 6.4.4.2.

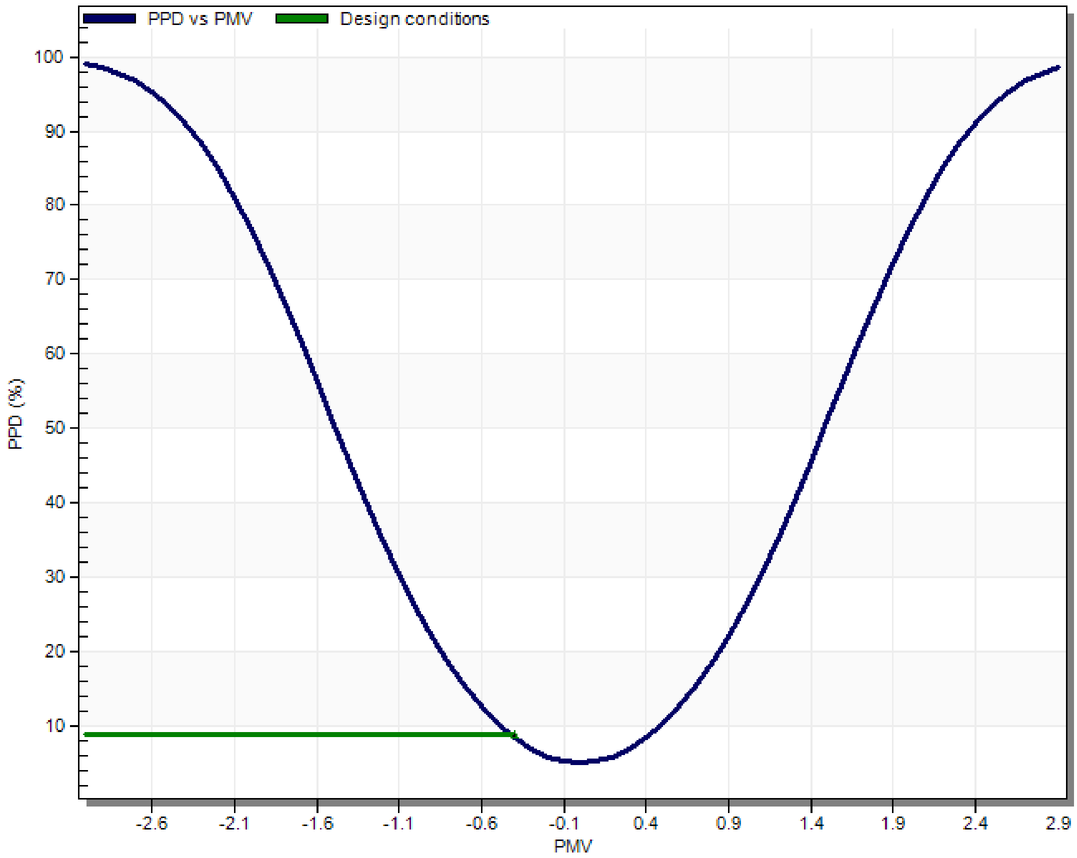


Figure 7-22: Thermal comfort graph for the improved case

7.8 Comparison Between All the Simulations

This study ran five simulations to establish the effect of the different variables on building energy performance (with Simulations 1-4 testing combined parameters and Simulation 5 being the improved model). The reductions achieved in each simulation in respect of peak demand, total energy consumed, and heat gain through the building envelope (walls and roof) compared to the base case are shown in Table 7-18.

Table 7-18: Reductions achieved in each simulation compared to the base case model

% Reduction	Simulation				
	Sim 1 - most effective	*Sim 2 - least effective*	*Sim 3 - operation-related*	*Sim 4 - design-related*	*Sim 5 - improved case*
Peak Demand	*75.8%*	*68.9%*	*20.5%*	*71.1%*	*73.8%*
Total Energy	*70.2%*	*63.5%*	*18.5%*	*66.4%*	*68.1%*
Wall Heat Gain	*79.2%*	*80.8%*	*1.7%*	*79.1%*	*79.5%*
Roof Heat Gain	*90.4%*	*82.8%*	*0.3%*	*90.3%*	*82.4%*

It is no surprise that Simulation 1 resulted in the highest savings since it applied all the most effective measures, yielding a reduction in total energy demand of 70.2%. However, the outcomes for

Simulation 1 (highest effect) and Simulation 5 (improved case) are not significantly different. Generally, the measures that were most effective in reducing annual energy consumption were also most effective in lowering peak electricity demand.

Figure 7-23 summarises the annual energy consumption for each simulation, showing the reduction by comparison with the base case, and the total amount of carbon emissions.

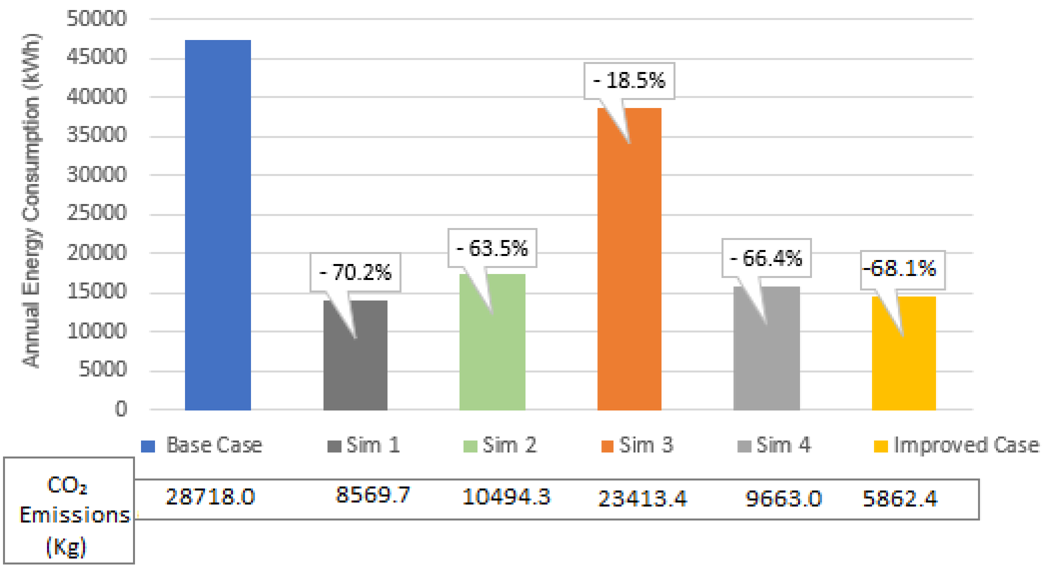


Figure 7-23: Comparison of all simulations' total energy consumption and carbon emissions

As the figure demonstrates, applying the parameters in Simulation 5 (the final improved model) reduced total energy use by 68.1%. Simulation 3 (operating parameters only) was created and run separately to reflect the importance of occupants' behaviour on building energy performance, and an annual energy saving of 18.5% was achieved. However, it may be difficult to develop a baseline to determine how much influence is normal due to societal variations (Esmaeil et al., 2019). Furthermore, while applying the design-related parameters only (Simulation 4) led to a 66.4% reduction in energy used, the impacts could not be studied separately from certain other parameters, including the building's characteristics, technological applications, and climate conditions. In addition, the carbon emissions were reduced by 70.2% (Sim. 1), 63.5% (Sim 2.), 18.5% (Sim. 3), 66.4% (Sim. 5), and 79.6% (Sim. 5).

Generally, all the simulations tended to follow the same trend as the base case, with the largest reductions in peak energy consumption occurring in the summer months (May-Oct), as shown in Figure 7-24. As the cooling load of the base case building was responsible for 82% of the total energy consumption, the savings in the cooling load were highly significant, accounting for at least 97% of total energy savings obtained in all five simulations.

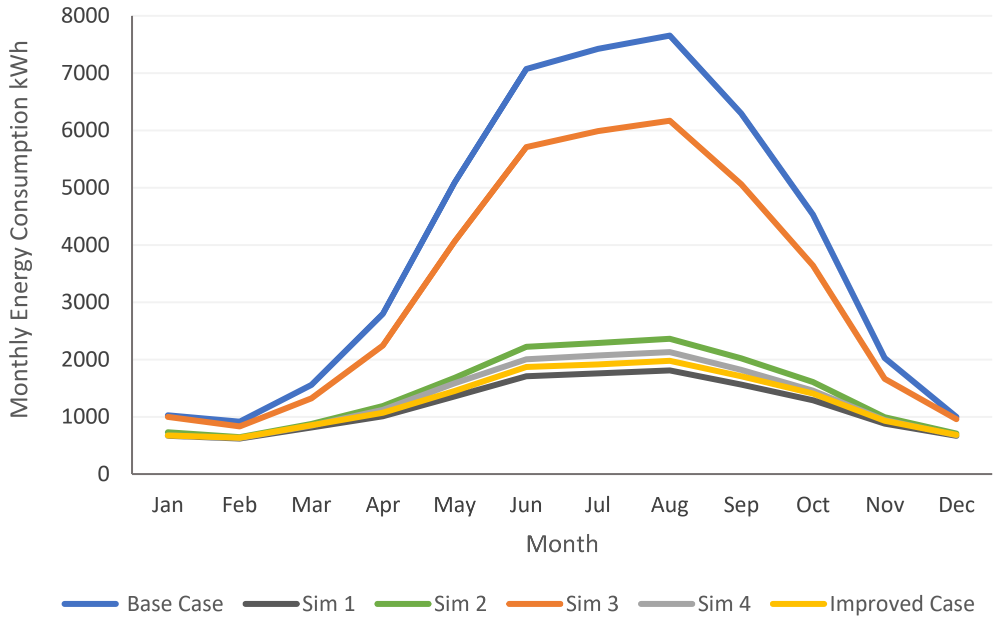


Figure 7-24: Monthly energy consumption for base case and all improvement simulations

As can be seen in Figure 7-24, Simulations 1, 2, 4, and 5 produced significant energy saving. Although adopting any combination of the measures applied in these four simulations would be energy efficient, adopting the measures found in the improved case may be recommended due to their cost effectiveness. In addition, it should be noted that the wall insulation system applied in Simulations 1 and 4 was DWS whereas EIFS was used in Simulations 2 and 5. From an economic point of view, EIFS might be the only insulation option for retrofitting the external walls of an existing building, as DWS applications may require the construction of another wall to create a cavity for the insulation material, whereas, in EIFS, the insulation materials are installed on the external wall surface and clad by mechanical means without the need for an additional wall. According to AlFaraidy and Azzam (2019), the latter practice has been proven efficient and meets the minimum SBC requirements in terms of continuous insulation for the building envelope and elimination of thermal bridges. Hence, for the purposes of this study, EIFS is considered to be the most appropriate and cost-effective method of architectural installation of thermal insulation.

7.9 Benchmarking the Improved Model

7.9.1 Comparative Analysis: Local Residential Buildings Regulations

As discussed in Chapter 3, the Saudi Vision 2030 aims to control the high energy load demand in several ways, including by making all buildings more efficient. The Saudi Building Code (SBC) has been developed in an attempt to meet local climate conditions and is being introduced in phases, although the expert panel findings suggest it is not yet widely implemented or enforced by the Saudi government. The main goal of the SBC is to decrease cooling loads by promoting optimum thermal insulation, and regulations for its application in low-rise buildings are set out in SBC602. In the past, the SEC has also initiated a set of minimum requirements for thermal insulation to achieve efficiency in both new and existing buildings. Table 7-19 compares the requirements for thermal performance in both SBC602 and the SEC codes in respect of the thermal characteristics of building envelope elements (i.e., U-values of walls, roofs, and windows) expressed in W/m²K with the characteristics of both the base and the improved case. As the SBC requirements vary according to the location of the building, climatic zones are also included.

Table 7-19: Requirements for thermal performance in SBC-602 and SEC

Specification	**Climatic Zone**	**U-values (W/m².K)**			
		Wall	*Roof*	*Window*	*Door*
SBC602	Z1	0.403	0.272	2.668	2.839
	Z2	0.454	0.34	2.668	2.839
	Z3	0.511	0.397	2.668	2.839
SEC	All Zones in SA	1.75	0.6	2.9	5
Base Case	Z1- Riyadh	2.15	2.123	5.78	2.38
Improved Case	Z1- Riyadh	0.246	0.263	2.233	2.38

This section considers the parameters stated in Table 7-19 and attempts to evaluate the impact of applying these requirements across Zone 1, a vast area and the most significant zone in Saudi Arabia (AlFaraidy and Azzam, 2019). In order to draw meaningful conclusions, the model residential building will be studied in the following four scenarios:

- Not insulated (existing and relatively old buildings i.e., Base Case).
- It complies with the SEC construction specifications.
- It fulfils the SBC602 thermal insulation requirements.
- The thermal parameters used in the improved case model are applied.

For the purposes of this study, an SPT of 20°C was selected to be applied in all scenarios to facilitate comparison. The outputs of the four scenarios studied are summarised in Table 7-20.

Table 7-20: Monthly energy consumption and consumption reductions for each scenario

	Base Case	**SEC**		**SBC602**		**Improved Case**	
Month	*Energy Cons. (kWh)*	*Energy Cons. (kWh)*	*Reduction (%)*	*Energy Cons. (kWh)*	*Reduction (%)*	*Energy Cons. (kWh)*	*Reduction (%)*
Jan	1023.8	946.0	7.6%	823.9	19.5%	815.5	20.3%
Feb	914.6	857.4	6.2%	744.5	18.6%	668.9	26.9%
Mar	1557.1	1351.8	13.2%	1103.2	29.2%	956.1	38.6%
Apr	2799.9	2309.3	17.5%	1741.5	37.8%	1534.2	45.2%
May	5089.6	3951.9	22.4%	2710.4	46.7%	2402.5	52.8%
Jun	7072.9	5417.9	23.4%	3642.6	48.5%	3256.0	54.0%
Jul	7425.9	5698.8	23.3%	3804.6	48.8%	3379.8	54.5%
Aug	7655.6	5868.3	23.3%	3907.8	49.0%	3484.7	54.5%
Sep	6296.2	4878.6	22.5%	3299.9	47.6%	2929.3	53.5%
Oct	4532.1	3599.8	20.6%	2513.4	44.5%	2202.1	51.4%
Nov	2023.8	1760.2	13.0%	1359.7	32.8%	1177.0	41.8%
Dec	998.0	928.2	7.0%	806.1	19.2%	767.6	23.1%
Total Annual (kWh)	**47,389.5**	**37,568.1**		**26,457.6**		**23,573.7**	
CO_2 Emissions (kg)	**28,718**	**22,766.3**		**16,033.3**		**14,286**	
Savings (kWh)		**9821.4**		**20931.9**		**23815.8**	
Savings (%)		**20.7%**		**44.2%**		**50.3%**	
EUI (kWh/m²/Yr)	**140.8**	**111.6**		**78.6**		**70.0**	

As was expected, the highest monthly energy savings for the SEC, SBC602, and improved case scenarios occurred in August, at 23.3%, 49%, and 54.5%, respectively. Comparison of these values reveals that the annual energy consumption when applying the minimum SEC requirements is still relatively high when compared with the SBC602 and improved case scenarios. An annual energy reduction of 44.2% was observed when applying SBC602 and 50.3% with the improved case insulation.

A comparison of the total monthly electrical energy consumption at 20°C is displayed in Figure 7-25. The results reveal that the amount of energy consumed in the four summer months (Jun - Sep) constitutes nearly 60% of the annual energy consumption of the building. This reflects the dependence on cooling systems to maintain thermal comfort in these hot months. The findings corroborate those of Alaidroos and Krarti (2015) who suggested that reducing summer cooling loads presents a much greater challenge, and, in order to achieve physiological thermal comfort in hot regions, building design and construction methods must be adapted to address the extreme summer conditions.

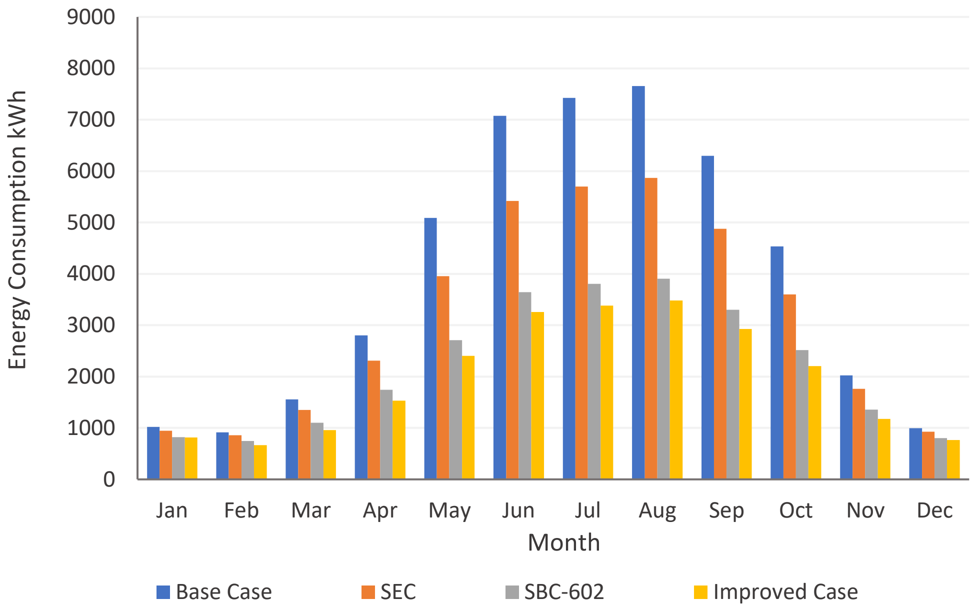


Figure 7-25: Comparison of the total monthly electrical energy consumption at 20°C cooling SPT

As this analysis was primarily concerned with the effects of insulating the envelope elements, Table 7-21 presents the impact of wall and roof insulation on heat gain and the overall impact on annual energy consumption.

Table 7-21: Comparison of thermal and energy performance of the four scenarios

Envelope Element	**Heat Balance**						
	Base Case (kWh)	***SEC (kWh)***	***Reduced by (%)***	***SBC-602 (kWh)***	***Reduced by (%)***	***Improved Case (kWh)***	***Reduced by (%)***
Wall	*43198.82*	*39484.83*	*8.6%*	*11999.3*	*72.2%*	*8680.7*	*79.9%*
Roof	*26804.57*	*9228.69*	*65.6%*	*4837.7*	*82.0%*	*4830.4*	*82.0%*
Energy Performance	**Energy Consumption**						
	Base Case (kWh)	***SEC (kWh)***	***Saving (%)***	***SBC-602 (kWh)***	***Saving (%)***	***Improved Case (kWh)***	***Saving (%)***
Cooling Energy (kWh)	*38836*	*29096.2*	*25.1%*	*18294.6*	*52.9%*	*15577.1*	*59.9%*
Total Energy (kWh)	*47389.5*	*37568.1*	*20.7%*	*26457.6*	*44.2%*	*23573.7*	*50.3%*
EUI (kWh/m²/Yr)	140.8	111.6		78.6		70.0	
Total Energy Cost ($)	2275	1803		1270		1132	
Total Energy Saving ($)		471		1005		1143	

As can be seen, applying the SEC thermal requirement did not significantly reduce heat gain through the walls (8.6%) when compared with the SBC and improved case scenarios, which contributed in reductions of 72.2% and 80%, respectively. This can be explained by the fact that the SEC wall U-value requirement is considered to be higher than the recommended value. In the case of roof insulation, on the other hand, the SEC requirements contributed to a reduction of 65.6% in roof heat gain, with an 82% reduction achieved in the SBC602 and improved case scenarios. Furthermore, the results in

Table 7-21 reveal that the highest energy saving was achieved in the improved case scenario, corresponding to a 60% drop in cooling load demand and a subsequent drop of 50% in total energy consumption. The total annual savings (in USD) when applying the SEC, SBC602, and improved case improvements were 471, 1005, and 1143, respectively. Thus, it can be concluded that the improved case scenario achieved the highest savings, both thermally and operationally.

7.9.2 Comparative Analysis: International Residential Low Energy Standards

Many European countries have set national standards for low energy consumption based on local climate and local demand. According to Aldossary (2015), there were no energy consumption standards for sustainable houses in the GCC countries, or the wider Middle East, at the time, and, regrettably, to the best of the researcher's knowledge, this is still the case. Therefore, a number of international standards for low energy consumption were used to compare the findings and energy patterns identified in this study. Figure 7-26 compares the annual energy consumption per unit area of the existing base case and the improved version with other reference standards.

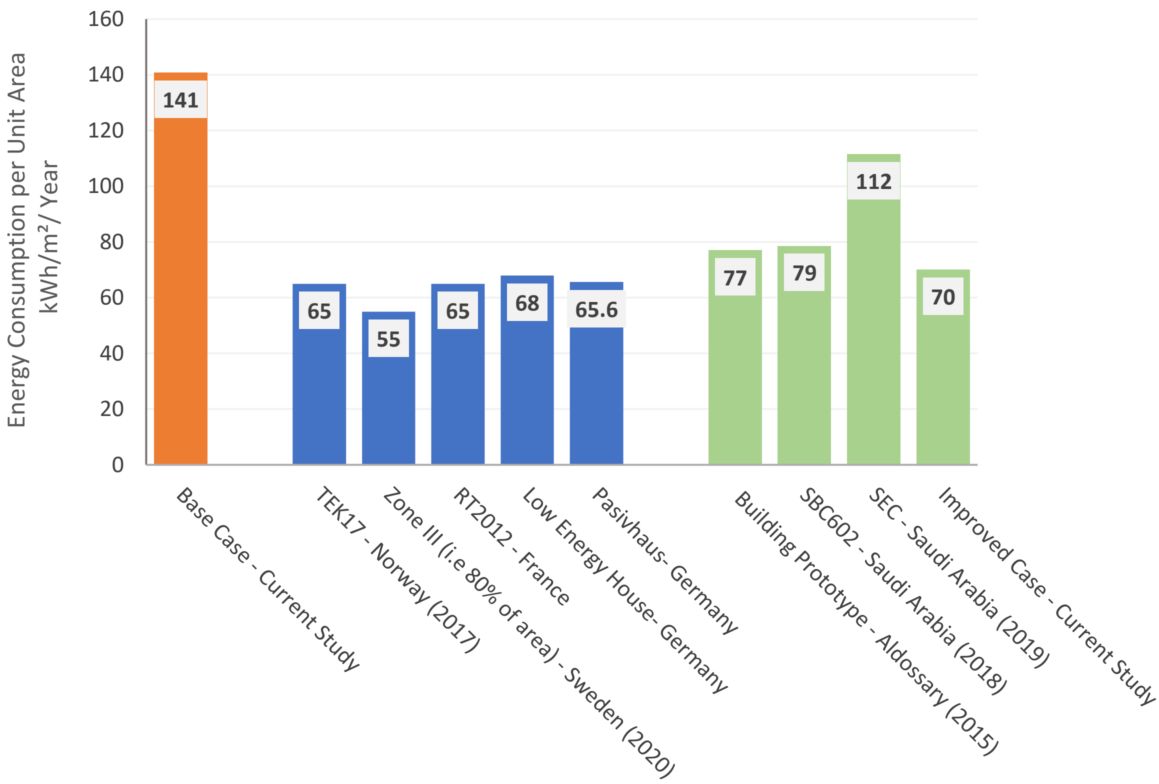


Figure 7-26: Comparison of annual energy consumption of different standards for residential buildings

These standards reflect the importance and significance of efficiency requirement in domestic houses. Comparison of the base case EUI value of 141 kWh/m²/year with those values estimated in Chapter 3 (See Table 3-8) revealed that the EUI value fell within the range of 100.1 - 227.4 kWh/m²/year for villa-type buildings in Riyadh. The EUI value investigated for the improved case in this study (70 kWh/m²/Year) is very close to the benchmark value for energy-efficient residential buildings in Norway, France, and Germany, which ranges from 65 - 70 kWh/m² (Kurnitski et al., 2018; Kurnitski et al., 2012). Furthermore, the improved case performed much better than the local standards, such as SEC and SBC602, and the prototype of a typical building of the same sized created and analysed by Aldossary (2015).

Similar analysis was conducted for the operational carbon emissions, as shown in Figure 7-27. The CO_2 emissions are expressed in tonnes per capita. The average family size (number of occupants) was set to six as per the findings of the public survey (Section 5.1.1), Aldossary (2015), and the Housing Program Statistics (2020). A substantial reduction from 4.8 tonnes/capita in the base case building was apparent in the improved case compared of 2.4 tonnes/capita, and this was the lowest across all standards. The average CO_2 emissions per capita in 25 European countries is 2.5 tonnes/capita, and this is assumed to be an international benchmark (Kurnitski et al., 2018; Aldossary et al., 2014).

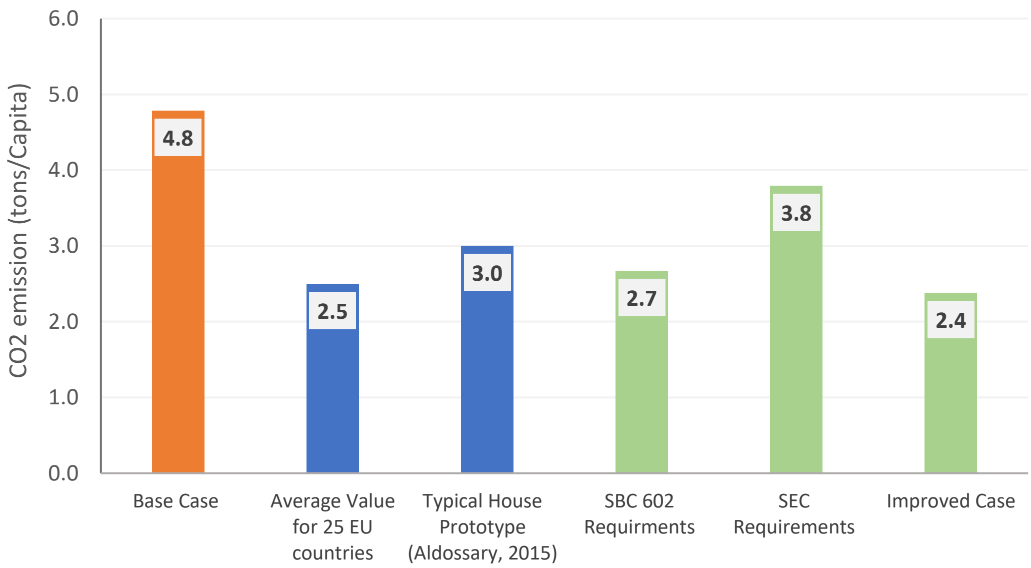


Figure 7-27: Comparison of CO_2 emissions per capita of different standards for residential buildings

The results presented above indicate that there is huge potential for energy saving in residential buildings in KSA if the improved case measures are applied. For residential buildings in Zone 1, a reduction of 68% in electricity consumption and 76% in peak electricity demand may be possible. As a result of these findings and those presented in previous chapters, it is now possible to propose a viable framework for achieving energy efficient dwellings in Saudi Arabia based on this study. The following section presents the framework and describes the way it was created.

7.10 The Proposed Framework

One of the primary objectives of this research was to create a framework which could be used to design energy-efficient dwellings that are thermally satisfying in hot climates and socio-culturally acceptable in the Saudi context. A framework has been defined as a structure which guides the development of a system and is a useful and meaningful resource which is more detailed than a protocol and more prescriptive than a structure (Akintoye, 2015). The proposed framework is informed by the data gathered from this study, which involved an in-depth investigation of the Saudi domestic building stock, a public questionnaire survey, consultation with professionals in the fields of construction and sustainable building design, an observational study of an existing representative building, and the identification of the most effective energy-performance improvement techniques via simulation and analysis. Hence, it captures the views of both building designers and occupants.

7.10.1 Creation of the Proposed Framework

This proposed framework aims to satisfy both technical and socio-cultural needs in hot climate conditions, such as those in Saudi Arabia. It addresses factors that concern the architectural and envelope design, design weaknesses, possible strategies, and the integration of on-site renewable energy, given the abundance of solar radiation found in the country. The strategies in the framework are proposed based on their proven impact on overall building performance, as demonstrated in this chapter. In addition, the experts were asked to assess the relative importance and viability of these solutions in the context of Saudi Arabia (See Section 5.3). Each criterion is intended to help civil engineers and architects to develop strategies during the design period which will meet the needs and condition of the site more efficiently without exceeding client budgets.

This study is based on detailed simulation analysis of a representative building located in Riyadh, with consideration of the prevailing climate. A whole-building energy simulation tool, DesignBuilder, was used to assess the impact of current energy efficiency options on the case study model, and, by, extension, on the wider residential building sector. Both parametric analysis and optimisation analysis were employed. Parametric analysis was used to determine which individual energy efficiency measures were most effective in reducing annual energy consumption and peak demand, while optimisation analysis determined the best combination of efficiency measures to improve the building's performance. This included the potential impacts on peak electricity demand, energy use, and carbon emissions. Optimisation analysis focuses on the application of proven and well-established measures and technologies to assess the impact of various investment options on both the individual building and the national building stock.

The optimisation analysis considered common and easily implementable design and operating EEMs to increase the energy efficiency of the prototypical residential building. EEMs considered for the optimisation analysis included adaptions to the building envelope, the temperature settings and CoP of the AC systems, and the addition of on-site renewable energy. Each EEM was compared with the baseline design option. Figure 7-28 illustrates how the research methods were correlated to produce the proposed framework

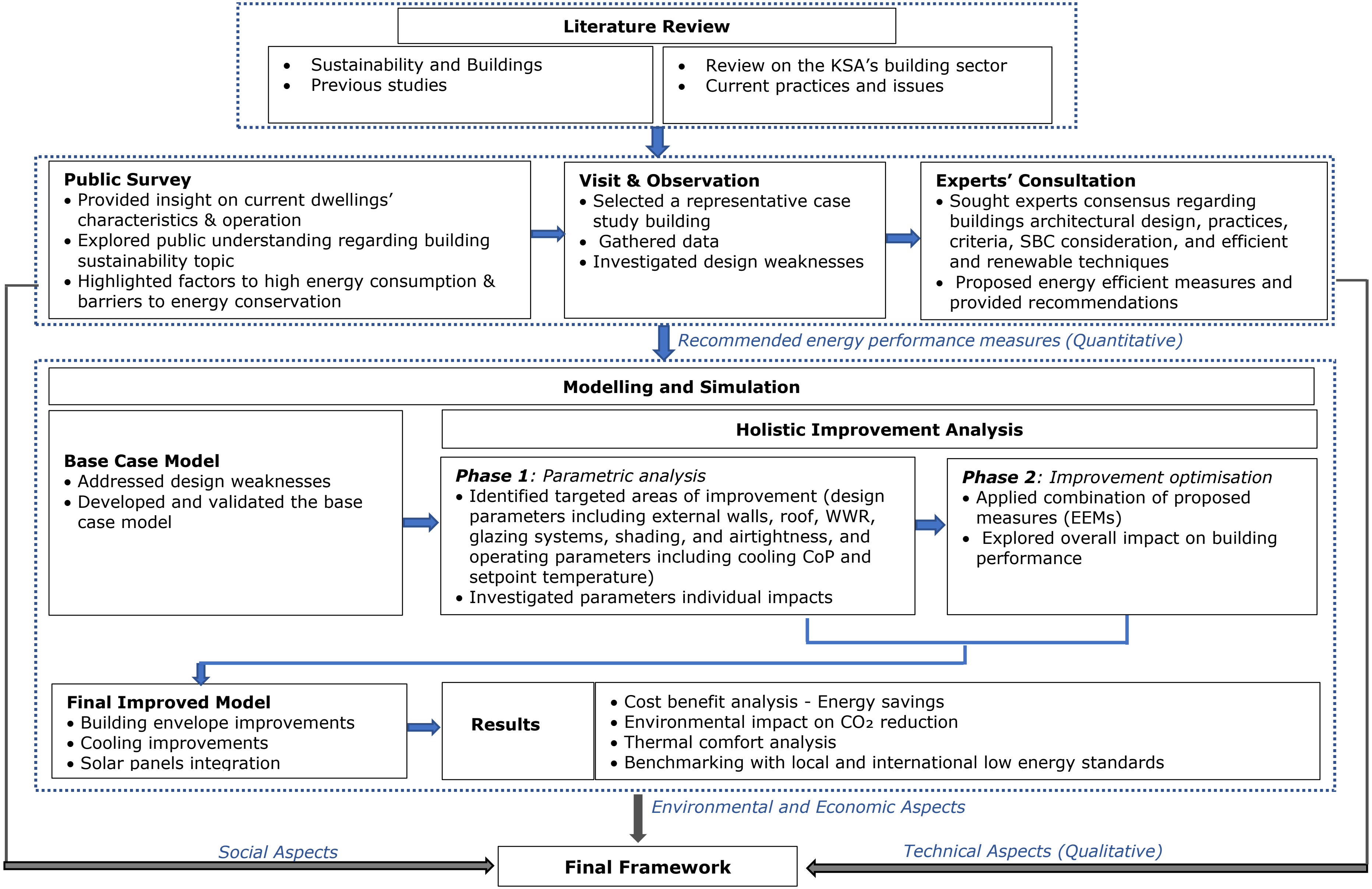


Figure 7-28: Flow chart illustrating the framework development

7.10.2 Structure of the Proposed Framework

The study examined ways to improve the energy efficiency of Saudi Arabia's residential building stock. The findings suggest that energy consumption and peak electricity demand can be reduced significantly by incorporating optimal cost-effective EEMs into residential building designs. Reducing the rapidly rising electricity demand in the country, lowering peak demand pressures and the need for new power plants, reducing utility bills, cutting carbon emissions, and improving the environment are some of the benefits identified. As a result, the proposed framework considers three main aspects: environmental, social (socio-cultural), and economic. However, the primary focus is on the environmental aspect, as this includes the most significant factors affecting building performance: the building architectural and envelope design and the EEMs.

Some of the measures proposed in the framework may only be applicable to new construction as they are not considered suitable for retrofitting. However, those which are suitable for existing buildings can also be applied in the design and construction of new buildings. The criteria used to determine if a concept is suitable only for new dwellings or could be used for retrofitting included the following:

- Viability of retrospective application with homeowners/occupants in place
- Avoidance of major alteration to the building's form
- Conservation of the property floor area
- Lower initial costs
- Need to limit reconstruction and disturbance

The issue of cost is a particularly significant consideration. Although the survey results suggested that the public believe that EEMs integration will cost more, these higher efficiency investment costs can decrease the total life cycle cost for a building (Schade, 2009). This was supported by Flanagan and Jewell (2005) who proved that an energy-inefficient building would cost three times its initial cost to operate and maintain over a period of 25 years. As Figure 7-29 demonstrates, the earlier the energy-efficiency decisions are made, the greater the impact on both the energy costs and performance of the building. Therefore, it is important to increase public understanding and awareness of the benefits of energy-efficient design and to promote the integration of EEMs at the earliest possible stage in the design of the building.

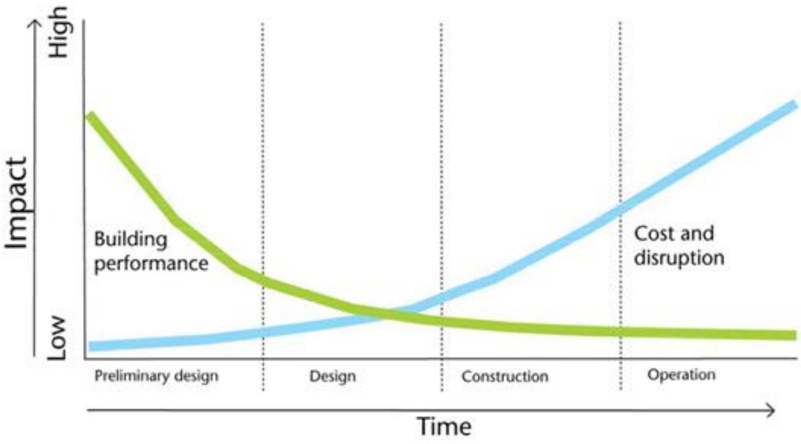


Figure 7-29: The benefits of early integration of EEMs (Source: WBCSD, 2008)

Table 7-22 presents the structure of the proposed framework. Overall, 35 techniques and strategies have been included, each related to designing efficient housing units for the hot Saudi climate. Some are included for application, either as a retrofitting solution or at the beginning of new building construction, and some should be considered at the design stage. The framework considers the environmental, social, and economic aspects in its adoption.

The architectural design aspect of the proposed framework covers the principal elements, including building form, windows design, shading, HVAC, as well as the envelope elements. The envelope design considers the following elements: roof, floor, external walls, windows glazing, and envelope fabric, all within the context of the hot climate in Saudi Arabia. As summer temperatures can reach as high as 46°C, it is particularly important to create building envelopes that are able to perform efficiently under such harsh conditions (Alrashed and Asif, 2015). Also, the well-established and validated efficient measures were also included in the framework. The hot climate also provides the country with ideal conditions to employ power generated from solar technology (Rehman et al., 2007; Hepbasli and Alsuhaibani, 2011). While the amount of natural sunlight can vary from region to region, it is possible to generate up to 2600 kWh/m² per year (Rehman et al., 2007), and this offers a clear opportunity to generate electricity for residential buildings in the Kingdom. However, despite benefits of utilising solar power, current domestic buildings in KSA have not yet started to use this option to any significant extent (Aldossary et al., 2014b). As a result, a critical consideration in future construction projects should be the addition of on-site renewable energy systems to take advantage of the abundance of solar radiation. Finally, the framework also provides some suggestions for consideration regarding socio-cultural practices and economic challenges.

Table 7-22: Proposed design framework for energy-efficient residential buildings in hot climate conditions, such as those in Saudi Arabia

Factor Category		Element Considered	Strategies and Solution				
			Description	**Thresholds**	**Significance**	**Reference**	**Suitable for**
Environmental Aspects	*Architectural Design (including Building Envelope)*	*Building Form*	Orientation of the building (south facing)		Low	Literature Review Expert consultation	New Construction
			Optimal design of building shape, i.e., use rectangular shape strategy		Low	Expert consultation	New Construction
			Reduce area of rooms that have highest use-period (e.g., bedrooms) without compromising occupant comfort		Low	Expert consultation	New Construction
			Build a house appropriate to the size of the family		Low	Expert consultation	New Construction
			Increase green areas around the building to provide shade and prevent dust		Low	Literature Review Expert consultation	Retrofit/ New Construction
		Windows Design	Reduce windows area (i.e., lower WWR) to an optimum	*WWR ≤ 10%*	Medium	Literature Review Study DB Simulation	New Construction
			Use efficient windows design to allow for air flow		Low	Expert consultation	New Construction
		Shading	Combine shading devices within the building envelope		Medium	Study DB Simulation	Retrofit/ New Construction
			Use external louvres for windows to prevent unwanted solar gains	*Projection length 0.2m*	Medium	Expert consultation Study DB Simulation	Retrofit/ New Construction
		HVAC	Design the indoor of the building to be as open plan as possible in order to promote interior airflow		Low	Expert consultation	New Construction
			Divide the internal rooms in the building into zones to create separate cooling strategies		Medium	Expert consultation	New Construction
		Roof	Design the roof structure with efficient layering and insulation materials to achieve the desired U-value. of up to.	*Current Study: 0.263 W/m²K* *SBC602: 0.272 W/m²K*	High	Study DB Simulation SBC-602	Retrofit/ New Construction
		External Walls	Use double skin walls technique in the design of external walls (DWS techniques)		High	Expert consultation Study DB Simulation	New Construction
			Ensure that the U-value of the wall assembly is obtained to meet the SBC thresholds. Alternatively, lowering the U value to this study's threshold would lead to more energy savings. This can be done by applying sufficient thermal insulation.	*Current Study: 0.246 W/m²K* *SBC602: 0.403 W/m²K*	High	Literature Review Expert consultation Study DB Simulation SBC-602	Retrofit/ New Construction
			Use of self-insulated bricks/blocks for the construction of walls	*Current Study: 0.397 W/m²K*	High	Study DB Simulation	New Construction

		Windows Glazing	Use at least double glazing with air or argon between glass layers.	*Current Study: 2.23 W/m²K SBC602: 2.67 W/m²K*	Medium	Expert consultation Study DB Simulation SBC-602	Retrofit/ New Construction
		Envelope Fabric	Apply insulation to external walls and roof to avoid high heat gains and reduce cooling load required to maintaining thermal comfort	*Current Study: 100 mm XPS (Walls) 60 mm PUR (Roof)*	High	Study DB Simulation	Retrofit/ New Construction
			Use construction materials of low thermal conductivity, i.e., that allow for better U-values to modify the building envelope		Medium	Expert consultation	Retrofit/ New Construction
			Design and construct the building envelope to be reasonably airtight	*Infiltration rate ≤ 0.5 ac/h*	Medium	Literature Review Study DB Simulation	New Construction
	EEMs	*Finishes*	Use of light colours, cool, or reflective finishes or coating for the external surfaces, such as the roof and external walls to reduce heat gain	*SR value of 0.65 at minimum*	Low	Study DB Simulation	Retrofit/ New Construction
		HVAC	Use sensors for air conditioning to control the indoor temperature of the rooms as the experts highly recommend this measure		Medium	Expert consultation	Retrofit/ New Construction
		Lighting	Use energy saving lamps (i.e., CFL and LED) and take advantage of natural daylight	*lighting power density ≤ 10 watts/m²*	Medium	Literature Review Study DB Simulation SBC-602	Retrofit/ New Construction
		Windows	Incorporate windows with reflective coating or low emissivity to reduce solar heat gain	*SHGC ≤ 0.228*	Low	Literature Review Study DB Simulation	Retrofit/ New Construction
		Ventilation	Benefit from direct ventilation, but consider dust prevention measures, for example window screens		Low	Literature Review Expert consultation	Retrofit/ New Construction
		Airtightness	Seal all possible sources of air leakage, such as window frames and gaps	*Infiltration rate ≤ 0.5 ac/h*	Medium	Literature Review Study DB Simulation	Retrofit/ New Construction
		Cooling Performance	Use cooling systems that have high efficiency	*Current Study: EER ≥ 13 SBC602: EER ≥ 11.8*	High	Study DB Simulation SBC-602	Retrofit/ New Construction
			Set the AC air temperature at appropriate values	*Cooling SPT ≥ 24°C*	Medium	SBC-602 Study DB Simulation	Retrofit/ New Construction
		Renewable Energy Integration	Incorporate rooftop PV panels oriented at optimum angles, depending on the site location, and tilted with a south facing direction to increase functionality	*PV Power ≥ 300 Wp*	Medium	Literature Review Expert consultation Study DB Simulation	Retrofit/ New Construction

Social Aspects	Consider local context (i.e., culture and religion)
	Ensure adaptability (i.e., acceptability and willingness of clients or occupants)
	Consider usability of strategies and consider occupants needs and habits (e.g., raise awareness)
Economic Aspects	Ensure affordability (i.e., products cost, budget, and financial subsidy alternative)
	Evaluate operational savings due to EEM applications (i.e., utility costs, and financial returns)
	Consider available financial incentives

The simulation results presented in this chapter show more confidence on the applicability of the proposed framework and show that simple strategies can be highly effective in reducing energy demand and addressing design issues in residential stock in hot climate conditions. Applying these measures to new residential buildings at the design stage is the best way to achieve low carbon and low energy use and improve thermal performance. However, the implementation of 'only new' building energy efficiency interventions reduces peak demand and energy consumption at a slow rate as the building stock is replaced by new construction over time. By contrast, an aggressive energy retrofit programme for existing building would have a significant and more immediate impact on both energy consumption and peak demand. A dramatic reduction in energy consumption would save electricity costs, reduce CO_2 emission and enhance the country's international sustainability profile, resulting in significant environmental, economic, and social benefits.

7.11 Summary

In this chapter, a holistic improvements analysis of the base building model was carried out to identify the most effective energy performance measures. In comparison to the base case building, these improvements resulted in significant reductions in energy consumption and potential cost savings. A cost-benefit analysis was also conducted to ensure that the proposed measures were cost-effective within the Saudi context. The final improved model was then benchmarked against local and international standards for energy conservation in residential buildings. Finally, based on the findings of this chapter and previous ones, a practical framework to promote sustainable and energy efficient construction and retrofitting of domestic buildings in the country was proposed. The following chapter concludes the study by summarising the key outcomes, answering the research questions, and providing recommendations.

Chapter Eight: Research Conclusion

8.1 Introduction

This chapter concludes the study by summarising the key research findings in relation to the research aim and questions. It demonstrates how each of the research questions has been answered and provides a number of recommendations to support the development of sustainable dwellings construction sector in Saudi Arabia. It goes on to identify the contributions to knowledge this study makes as well as setting out its limitations. The chapter concludes by considering the potential areas for further research which arise from this study.

8.2 Research Conclusions

Saudi Arabia faces severe energy and environmental challenges: it is one of the highest ranked countries in the world in terms of per capita energy consumption and CO_2 emissions, and national demand for energy is escalating rapidly due to population increases (Esmaeil et al., 2019; Alardhi et al., 2020). However, in order to fulfil the national sustainability ambitions expressed in the Saudi Vision 2030 and to meet international obligations under the Paris Climate Accord (2015), there is an increasing need to reduce domestic energy demand. The building sector has a major part to play in this respect as it consumes around 75-80% of the country's electricity production (ECRA, 2018), and residential buildings, in particular, are responsible for the largest share of this (Alshahrani, 2018). Given the fact that energy demand is set to rise in future to cope with the growing population, there is a pressing need to incorporate sustainability into the Saudi residential sector, primarily by making homes more energy-efficient.

This thesis sought to identify the most suitable energy-efficiency strategies for use in residential buildings in hot climate conditions, using Saudi Arabia as a case study country. The primary aim of this study was to develop a practical framework to promote the development of more energy-efficient housing stock within the country. The proposed framework incorporates effective design features, energy-efficiency measures, and renewable energy applications, for both new and existing dwellings, and takes careful account of the climatic, socio-cultural, and economic context in Saudi Arabia. The proposed measures have been tested in this study and shown to be effective; thus, the implementation of this framework offers a concrete way to reduce energy consumption and CO_2 emissions within the residential sector.

Driven by the shortage of experimental validated studies in the Gulf, this study adopted a mixed methods approach to investigate the factors driving high energy consumption in residential buildings, the barriers hindering sustainable building development, and the available strategies and measures which might be adopted to address them within the Saudi context. As the research sought to assess the technical and economic viability of sustainable residential buildings in Saudi Arabia, it was essential to consider the climatic conditions, both in terms of their impact on the energy consumption in buildings and the potential for domestic renewable energy generation. As a result, the city of Riyadh was selected as the study location as it is situated in Zone 1, the largest climatic zone in the country, and a representative villa was identified within the city to act as the base case model for the simulations and analysis conducted in this study.

Four research questions were established for the study, with specific objectives to guide the data collection and analysis. The conclusions that follow provide a summary of the key outcomes of the research to answer the research questions and demonstrate how the objectives were met.

8.2.1 RQ 1: What are the key factors that lead to energy intensive consumption in Saudi Arabia's residential sector?

In order to identify the causes of the high levels of energy consumption within the residential sector, this study explored both architectural design factors and the socio-cultural factors which affect building design and energy use. A review of the literature was conducted to investigate the status of current residential stock and identify potential factors, and local residents and pertinent experts were then surveyed to identify the most significant factors from their perspectives. Analysis of the findings from the literature review and the surveys were then used to identify the most significant architectural and behavioural factors within the Saudi context. The most representative type of dwelling to use for simulation was also identified at this stage. As a result, an existing occupied family villa-type dwelling in Riyadh, located in the largest climatic zone, Zone 1, was selected for observation, modelling and energy simulations. The subsequent investigation included exploration of energy consumption patterns for the representative building, the efficiency of the building mass and envelope design, the cooling load demand, and the impact of occupant behaviour on energy use.

The key factors identified can be summarised as:

- The fact that the design of buildings does not typically take the prevailing climate into account is the most significant factor in relation to high energy consumption. Housing envelopes are typically constructed from thermally ineffective building materials, such as concrete, and lack thermal insulation, double glazing, or shading devices, causing excessive heat transfer through the roof and walls. This leads to the continuous use of AC systems to achieve satisfactory levels of thermal comfort, especially in the summer months. As a result, the cooling energy demand accounts up for up to 80% of a domestic building's energy use as found in this study.

- The behaviour of building occupants also has a significant effect on a building's energy consumption, most notably their use of AC systems. Despite the impact of AC use on utility costs, the findings suggest that people try to reduce capital costs by installing cheaper, less efficient machines, and they tend to operate them continuously at the lowest temperature settings, without considering the energy implications. Another example is the extensive use of artificial lighting during the daytime, even though natural light is abundant.
- There is also a lack of understanding about the concept and importance of low-energy homes, particularly among members of the public. This is partly due to the fact that many GCC countries have only recently introduced regulations and policies to promote energy conservation in buildings. The fact that electricity tariffs in KSA are relatively low also means that people are less concerned about the cost implications of their high energy consumption.
- There is also a lack of appreciation of local buildings codes and specification within the building sector, possibly due to lax enforcement. This means that new buildings continue to be built without adequate envelope thermal insulation.
- A key socio-cultural factor is that gender mixing is not encouraged in Saudi culture for reasons of religion and tradition; thus, most homes have separate rooms for guests, one for males and another for females despite of the intermittent use of these spaces. Allocating different spaces to guests of each gender increases energy demand. Moreover, the public tend to prefer having separate bedrooms for each gender in the dwelling where sometimes a room may be occupied by just one occupant resulting in a high demand for energy.
- The number of people per household also affects energy use significantly, and family sizes tend to be large by international standards (an average of six people per household). In addition, the relatively large size of dwellings is also an issue. The cost of land encourages people to build on as much of the plot as possible, and the perception that the size of the dwelling reflect one's status in the society can lead to houses and rooms being bigger than necessary. As spacious rooms are often placed on the top floor, they are directly exposed to solar heat gain, increasing the energy required to maintain thermal comfort.
- The findings also revealed that the age of a building is often a key factor in determining its energy performance. Much of the Saudi residential building stock was built more than 10 years ago, and older houses typically lack thermal insulation and efficient glazing systems. However, the lack of awareness and enforcement of current building codes means these limitations are not solely confined to older buildings.

8.2.2 RQ 2: What are the barriers to widespread energy efficiency in dwellings in Saudi Arabia?

The results of this study indicate that a considerable share of residential buildings in Saudi Arabia do not comply with sustainability and energy conservation standards due to defects in their construction and a lack of awareness and support from stakeholders. The findings of the literature review, the public survey, and the expert consultation suggest that a number of technical, socio-cultural, and economic barriers need to be overcome before energy efficiency can be achieved within the residential sector. These barriers can be summarised as follows:

- **Technical barriers**
  - Shortage of sustainable and energy-efficient products in local markets
  - Lack of alternative efficient design as typical repeated design patterns still prevail
  - Lack of technical expertise in local sectors
  - Lack of stakeholders' engagement or interest
  - Lack of government enforcement or support, i.e., absent or poorly-defined rules and guidance documentation, limited policy frameworks, and funding difficulties
  - Limited access to information on the application, effectiveness and cost efficiency of sustainable technologies
  - Lack of public awareness of sustainability and the benefits of energy efficiency
  - Lack of promotion of building EEMs in the national media and from relevant agencies
- **Economic barriers**
  - Escalating land prices, meaning there is less money for building construction costs
  - Insufficient access to funds (limited personal or government loans)
  - High initial costs associated with EEMs
  - Lack of incentives to promote sustainable construction
  - National oil and gas subsidies which lead to low electricity tariffs
  - Low level of government and private sector investment
- **Socio-Cultural barriers**
  - Lack of acceptability of some EEMs due to concerns about privacy and preserving segregation between genders
  - Public stereotype that the building size reflects the owners’ status, leading to houses and rooms being much larger than necessary
  - Perception that it is not cost-effective to incorporate EEMs into residential buildings, despite the cost savings over the life of the building

8.2.3 RQ 3: How can the problem of energy intensive residential buildings in the KSA be addressed from a design and operational perspective?

One of the key barriers to the development of more energy efficient housing identified above is the limited access to information about the application of EEMs and the lack of clear guidance documents. As a result, one of the key objectives of this study was the creation of a practical guide to support the wider development of sustainable homes in Saudi Arabia. The expert consultation conducted for this study brought forth a number of possible strategies and solutions, ranked by order of effectiveness, which could improve a building's energy performance. Parametric and optimisation analyses were then employed to apply the suggested strategies and to assess their effectiveness and the overall building performance. The findings informed the development of the practical framework for energy-efficient residential building design which was presented in Chapter 7. Overall, 35 techniques and strategies are proposed in the framework and tested for efficiency and cost-effectiveness via the holistic improvement analysis of the selected case study model described in Chapter 7. This included the potential impact on peak electricity demand, energy use, and carbon emissions, and cost-effectiveness over the building life cycle. The framework is intended to support architects, civil engineers, and building professionals in addressing the architectural issues associated with high energy consumption, whilst also taking account of the socio-cultural and economic factors at play in the country.

Given the energy-efficiency issues associated with the current housing stock, the framework provides strategies for new build constructions and for retrofitting. These retrofitting strategies are flexible and easy to install in an existing dwelling, and prioritise: (i) applying adequate thermal insulations to the entire building envelope, (ii) replacing single glazed windows with an efficient double glazing system, (iii) installing efficient external shading devices, (iv) sealing all potential air leakage sources, (v) upgrading air conditioners to meet the recommended efficiency standards, and (vi) installing on-site renewable energy (PV panels) at the top of the building to generate electricity from the natural solar radiation. These strategies were also tested and validated via simulation and analysis of the representative base case model; when the retrofitting solutions were adopted in the existing building, reductions of up to 68% in energy consumption were noted.

While incorporating these measures into new residential buildings will achieve the greatest reductions in energy consumption and carbon emissions over the life of the building, the proposed framework is intended to enable both professionals and clients to make decisions that have synergistic effects to co-optimise building utility and energy efficiency, improving the thermal comfort of occupants and lowering energy costs.

8.2.4 RQ 4: What level of environmental and economic benefits can be achieved by improving the energy-efficiency of residential buildings and creating a sustainable building industry in the KSA?

This study has identified substantial environment and economic benefits from the development of energy-efficient buildings in Saudi Arabia; these include a) mitigating the challenges facing the energy sector by reducing the pressure from rapidly increasing energy demand; b) lowering peak demand pressures, especially in the hot summer months, c) reducing the need for new power plants, enabling the country to preserve its natural resources, and d) improving the environment by cutting carbon emissions, helping KSA to meet its international climate change commitments.

The findings indicate that energy consumption and peak electricity demand could be reduced significantly by implementing the optimal residential building design strategies proposed in the framework. For residential buildings in Zone 1, for example, a potential reduction of 68% in total electricity consumption and 74% in peak electricity demand may be possible. In particular, the proposed improvements to the thermal performance of the building envelope could reduce heat gains through walls and roof by up to 83%. This would hugely impact the demand for cooling to maintain thermal comfort, currently the highest contributor to energy consumption in the residential sector. Indeed, the simulations analysis revealed that the cooling EUI could be reduced from 115 to just 22 kWh/m^2/year (i.e., 81% saving), bringing Saudi Arabia within the range of the recommended European Standard for total annual energy for space cooling (20-30 kWh/m^2 per year) (Carmody et al., 2009). These figures suggest that the development of energy-efficient buildings could reduce energy demand considerably, enabling the country to meet its energy needs without substantially increasing national power generation capacity. As the proposed level for low energy consumption (EUI) is very close to standards in Norway, France, and Germany, it would also bring the Saudi residential sector up to European standards, a significant achievement given the extremely hot climate in the country.

Saudi Arabia has made a number of commitments to reduce its GHG emissions, both in the Saudi Vision 2030 and as a result of signing the Paris Accords. Analysis of the improvement simulations conducted for this study indicated that a reduction of 80% in carbon emissions was achieved in comparison with the base case study building. This amounted to almost 23 tonnes of CO_2 avoided annually and was equivalent to nearly five cars not being used per year. Saudi Arabia has been criticised for not making sufficient efforts to meet its international climate change commitments (Climate Action Tracker, 2020); if this level of carbon reductions could be achieved across the residential sector, the country would be in a much stronger position in respect of GHG emissions. As a rapidly developing country which is seeking to enhance its international reputation and develop its tourism sector, this would bring both environment and economic benefits.

Furthermore, the findings indicate that integrating PV arrays on as little as 7% of the roof area could generate up to 36% of the total energy consumed within the building. As the Saudi government has now introduced a solar incentive scheme, energy produced could also be exported to the distribution grid at a rate of 0.019 USD/kWh. This has clear environmental benefits and would bring immediate cost benefits to the occupiers. In addition, one of the primary aims of Vision 2030 is to shift the Saudi economy away from oil dependency (Al Harbi and Csala, 2019). Promoting the use of renewable energy in this way would directly support this long-term objective. In the short- to medium-term, substantial economic benefits could be achieved by reducing domestic petroleum consumption, thereby enabling increased sales of petroleum elsewhere at greater profit.

A key part of the improved case simulation analysis involved assessing the cost effectiveness of the proposed energy-efficiency improvements. Although high initial costs were identified as a barrier to the wider implementation of EEMs, the analysis indicated a typical payback period of 7 years, which is not unreasonable in relation to residential buildings. It also demonstrated that incorporating the improvement measures into a building would lead to average energy savings of 1,603 USD per year. Total cost-savings analysis for a building-use period of 30 years indicated total operational cost savings of up to 51%. These are significant cost savings over the life of a single building. Given the poor thermal performance of many residential dwellings in Saudi Arabia, the cost savings could be enormous if these reductions were achieved in a greater proportion of the housing stock.

Applying these measures to both new and existing dwellings would have a significant impact on Saudi Arabia's domestic sector, especially as housing demand is rising to meet population growth. Reducing the amount of residential energy required while maintaining thermal comfort would bring clear environmental and economic benefits, both to individual households and to the country at large. In supporting the shift away from high levels of energy consumption, it would help to achieve the aims of Vision 2030, boost Saudi Arabia’s environmental record, and enhance its reputation internationally.

8.3 Recommendations

Saudi Arabia is in the process of transforming from a traditional local society into an advanced modern nation. The housing sector has also undergone a transformation, prompted by the use of modern architectural construction methods and designs. However, little thought has been given to their suitability for the hot environment of Saudi Arabia and the energy performance of the resulting buildings. The framework proposed in this study provides practical guidance for professionals in the building sector, and their clients, to enhance the energy efficiency of both new and existing buildings. However, in order for the aims of the framework to be fully realised, further steps must be taken to ensure that appropriate legal provisions are in place, that sustainable products are more widely available within the Saudi market, and that members of the public and building sector professionals understand the benefits associated with EEMs and solar energy generation and are incentivised to use them. Hence, this study makes the following recommendations to support the development of a sustainable residential construction sector in Saudi Arabia based on the research findings:

- The findings of this study suggest that local building regulations are not implemented consistently, and, in some cases, not at all. The government should monitor compliance in a systematic manner and take action against parties who do not comply.
- Current building regulations have largely been derived from codes produced in other countries. The SBC in particular would benefit from further modification to meet local needs and to function more effectively within the Saudi context.
- Legislation must be enacted to encourage the Saudi construction sector to move to low energy construction policies. Without regulatory bodies taking further action, the industry is likely to continue to be reluctant to embrace sustainable techniques and renewable energy sources. Support to help professionals acquire the requisite technical skills should also be provided, including adding university curricula in the field of sustainable construction.
- The government should ensure the availability and quality of energy-efficient products in local markets and tackle price manipulation, including designating an official authority to manage this. Suppliers should also be encouraged to offer sustainable construction materials and products at prices which are affordable, especially for low- and middle-income clients.
- Governmental authorities should cooperate and encourage low-energy construction and retrofitting practices by offering incentives, such as discounts on power tariffs for energy-efficient homes, accelerating utilities connection to the national grid, and offering interest-free loans to help with initial and capital costs.
- The government should also intensify efforts to retrofit the existing housing stock to improve its energy efficiency. This, along with the enforcement of building regulations applied to new construction, would accelerate the development of sustainable construction in the country.
- All key stakeholders should be consulted to ensure that appropriate energy management strategies are put in place which can be implemented immediately to achieve the desired outcomes.
- Greater efforts must be made to raise awareness of energy efficiency and change wasteful behavioural patterns, including campaigns to raise public awareness, energy efficiency education in schools, and policies to incentivise changes in occupants' energy behaviours.
- Clients should be required to assign accredited agencies to supervise the building construction process and ensure its compliance with SBC requirements and sustainable building design

criteria. Access to information about sustainable design and energy efficiency measures for clients should also be facilitated.

- Decision makers should also invest in natural energy resources in Saudi Arabia, such as solar radiation, for future use across all sectors.

To conclude, for sustainable housing projects to become successful, major support from the government, the housing industry, and the public must be acquired.

8.4 Contribution to Knowledge

The project is timely and original in addressing the crucial issue of the sustainability of the Saudi residential building sector in light of the current pressures on energy generation caused by the rising population, the ambitions expressed in the Saudi Vision 2030, and the country's international climate change commitments. This study will contribute to the body of knowledge on sustainable residential buildings in Saudi Arabia by identifying the problems driving high energy consumption in residential buildings and proposing technical remedies which consider the local context and the Saudi Building Code. This research will also benefit building sector stakeholders and Saudi citizens by providing a practical framework to enhance the energy-efficiency of new and existing buildings. It will also help to raise awareness of the substantial benefits of sustainable development for both the environment and Saudi society. The specific research contributions made within this discipline are:

- Providing insights into widespread inefficient building practices, the factors driving intensive residential energy consumption, and the barriers preventing the spread of low-energy buildings in Saudi Arabia.
- Identifying the most effective energy efficiency measures within the Saudi context, by means of expert consultation and simulation, and assessing their cost-effectiveness. To the best of the researcher's knowledge, this study is the first to consider the updated version of the SBC and to apply cost benefit analysis in residential buildings.
- Proposing energy solutions and strategies for retrofitting existing dwellings in order to reduce their energy consumption. These solutions can also be applied to new buildings.
- Demonstrating that energy consumption levels in Saudi residential buildings (EUI) can be reduced to the level of European standards while preserving thermal comfort.
- Proposing a framework for the design of sustainable-low-energy buildings in Saudi Arabia, which could also be applied in similar contexts, notably other GCC countries.
- Assisting civil engineers, architects, building professionals, and developers to design and construct highly energy-efficient buildings with respect to the local Saudi context.

- Raising the awareness of all stakeholders of the substantial benefits of applying the proposed framework measures and promoting sustainable construction within KSA.

8.5 Research Limitations

Every research study has its limitations, and this one is no exception. This study has explored ways to enhance the energy efficiency of residential dwellings in the Kingdom of Saudi Arabia, a vast country with a variety of hot climates: (a) hot and arid, (b) hot and humid, and (c) hot arid mountainous. However, due to time constraints, only Zone 1, the largest climate zone, represented by the city of Riyadh, was used for the case study. As Zone 1 constitutes more than half of the country and covers most of the major cities, the findings of this study are widely applicable. However, to be truly comprehensive, individual study and analysis of each climate zone would be required to provide detailed and accurate results for the whole country.

Another challenge faced in this study related to finding a representative case study building that reflects the typical housing unit in Saudi Arabia. The available statistical data and the findings of this research indicated that villa-type houses and flats are the two main residential accommodation types within the country. However, blocks of flats are often built for investment purposes, and are more frequently occupied by tenants rather than owners. As they are also single apartments in structures with multiple units, rather than whole entities with their own building envelopes, they were not considered suitable for this study. However, in order for the residential sector to become truly sustainable, optimal EEMs will need to be identified for flats and other accommodation types.

The limitations also encompass a lack of recognition for regional variations, including local environmental and market conditions as reliable data regarding local climates, weather patterns, the current costs of building materials, and the availability of sustainable products were difficult to find. This could be attributed to the lack of sustainable construction or energy-efficiency projects in Saudi Arabia's market. As a result, the researcher established average costs based on recent markets quotes and recently conducted studies, and the weather data for Riyadh in DesignBuilder's extensive weather library were used for the building simulation.

Another potential limitation relates to the number of experts consulted for the study. A panel of 33 experts in the field of building construction and sustainability were identified, each with substantial experience in the Saudi context. Previous literature has claimed that this panel size is within the acceptable range for a study involving professional judgement; however, the relatively small number of experts involved may not cover all the different stakeholders in the residential building sector. Increasing the number of experts involved would have been difficult, as the researcher found it difficult to find convenient times for this number of experts to provide a response.

In addition, all the expert participants were males due to the shortage of female expertise in this field within Saudi Arabia. The public questionnaire responses were also dominated by male participants. This is due to cultural barriers relating to gender which limit interactions between unrelated males and females, as discussed in this thesis, and the fact that the householder responsible for paying the bills is usually male. As a result, the findings may not reflect behaviour variations between genders.

8.6 Avenues for Future Research

It is important to point out the potential of this research to inspire future researchers, as new studies are built upon prior work. In the light of the findings of this thesis, the following research direction could be explored.

Future work should look into other types of domestic buildings, notably flats, as they constitute a significant proportion of the housing stock. Developing guidelines for enhancing the energy performance of flats in conjunction with the current study’s proposed energy-efficiency framework for villas, could provide a huge energy savings on a national level and support the country’s 2030 vision of conserving national resources and reducing carbon emissions. Future research could also examine the other climatic zones in KSA and possibly other Middle Eastern countries with similar climatic conditions and electricity use patterns. It is important to benchmark the benefits of peak-time reductions in electricity demand to the findings of this study.

As the Saudi building codes were originally based on other international standards in developed countries, researchers could compare these standards with the nascent Saudi building standards to assess their suitability with respect to the local context. In addition, a wider expert consultation process which included all potential building stakeholder would enable experts and researchers in the field to provide insight, recommendations, and suggested amendments to current policies to those who govern and regulate the building industry.

The perception that energy-efficient buildings are more expensive than conventional buildings is an important concern; therefore, it is critical to investigate affordable solutions and financial alternatives that could motivate stakeholders to be more engaged in and committed to the concept of sustainable building development and tackle the measures application cost burden faced by house owners. Researchers in manufacturing and government institutions are the most capable party for this work.

Another area worthy of further investigation is the behaviour of building occupants which can impact total energy consumption. It has been difficult to develop a baseline to determine how much influence is normal due to societal variations; however, intensive technical-social research could be conducted in Saudi Arabia, and possibly in countries sharing similar contexts, to establish a reference for common user behaviours and their impacts on building energy performance.

The viability of other sustainable and energy-efficiency alternatives could also be explored. While this study examined the technical and economic viability of a number of proposed energy-efficient measures, investigation of other features and measures such as roof vegetation, exterior surrounding plantation, water solar-heating, and external reflective coatings can be carried out in further research.

Improving the energy-efficiency of residential buildings in Saudi Arabia will necessitate a different approach to embodied energy in sustainable home construction. Researchers should therefore focus on embodied energy when producing materials for Saudi Arabian buildings, in order to keep embodied energy and CO_2 emissions to the lowest possible levels.

8.7 Summary

This chapter has concluded the study by describing the research outcomes and demonstrating how they answer the research questions. As the findings indicate that current building regulations, practices, and available materials do not support energy efficient construction in Saudi Arabia, a number of recommendations related to these areas have also been made. The absence of a national plan for implementing sustainable strategies has also been addressed. These recommendations are intended to provide the infrastructure necessary to enable the strategies in the proposed framework, perhaps the most significant outcome of this research, to be fully implemented. The contributions to knowledge made in this study have been clearly identified, and the limitations acknowledged. The chapter has concluded by suggesting avenues for future research on sustainable residential building construction arising from this study.

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Appendices

Appendix A: Public Survey- Questionnaire

The public survey is available online at the following link:

https://documentcloud.adobe.com/link/review?uri=urn:aaid:scds:US:60bf92b5-0e03-3d4e-938d-2e09199f33c5

Appendix B: Experts Consultation

The experts' consultation survey is available online at the following link:

https://documentcloud.adobe.com/link/review?uri=urn:aaid:scds:US:f88fa71b-c123-3465-82c1-a14a6f278b1f

Appendix C: Entire Envelope Insulation Thicknesses Analysis (Both Roof and Walls)

The source of data is found in Section 7.6.1.2 - Optimum Thickness of Insulation.

Table C-1: Optimum insulation thickness identification for the entire building envelope using the XPS material for both roof and walls structures (**See Section 7.6.1.2 - Optimum Thickness of Insulation**)

Roof & Wall Construction (Both XPS Insulated)	Roof Thick (m)	Wall Thick (m)	Total Energy Consumption (kWh)	CO_2 (Kg)	Annual Energy kWh/m²/Yr	Energy Cost ($/m²/ 30 Yr)	Roof Insulation Cost ($/m²)	Wall Insulation Cost ($/m²)	Total Insulation Cost ($/m²)	Total Cost ($/m²/30 Yr)	Cost Saving (%)
R BC + EW BC	0	0	47389.5	28718.0	140.8	211.2	0.0	0.0	0.0	211.2	0.0%
R- 20mm + EW BC	0.02	0	41566.8	25189.5	123.5	185.3	2.4	0.0	2.4	187.7	11.1%
R- 40mm + EW BC	0.04	0	40432.4	24502.0	120.1	180.2	4.9	0.0	4.9	185.1	12.4%
R- 60mm + EW BC	0.06	0	39843.0	24144.8	118.4	177.6	7.3	0.0	7.3	184.9	12.5%
R- 80mm + EW BC	0.08	0	39480.3	23925.1	117.3	176.0	9.8	0.0	9.8	185.7	12.1%
R- 100mm + EW BC	0.1	0	39233.3	23775.3	116.6	174.9	12.2	0.0	12.2	187.1	11.4%
R- 120mm + EW BC	0.12	0	39056.5	23668.2	116.0	174.1	14.6	0.0	14.6	188.7	10.7%
R- 140mm + EW BC	0.14	0	38922.9	23587.3	115.6	173.5	17.1	0.0	17.1	190.5	9.8%
R BC + EW 20mm XPS	0	0.02	40737.6	24687.0	121.0	181.6	0.0	2.3	2.3	183.8	13.0%
R- 20mm + EW 20mm XPS	0.02	0.02	34277.0	20771.8	101.8	152.8	2.4	2.3	4.7	157.5	25.4%
R- 40mm+ EW 20mm XPS	0.04	0.02	33002.6	19999.6	98.1	147.1	4.9	2.3	7.1	154.2	27.0%
R- 60mm + EW 20mm XPS	0.06	0.02	32336.1	19595.7	96.1	144.1	7.3	2.3	9.6	153.7	27.2%
R- 80mm + EW 20mm XPS	0.08	0.02	31926.3	19347.3	94.9	142.3	9.8	2.3	12.0	154.3	26.9%
R- 100mm + EW 20mm XPS	0.1	0.02	31647.6	19178.4	94.0	141.0	12.2	2.3	14.5	155.5	26.4%
R- 120mm + EW 20mm XPS	0.12	0.02	31446.9	19056.8	93.4	140.2	14.6	2.3	16.9	157.1	25.6%
R- 140mm + EW 20mm XPS	0.14	0.02	31295.6	18965.1	93.0	139.5	17.1	2.3	19.3	158.8	24.8%
R BC + EW 40mm XPS	0	0.04	38724.9	23467.3	115.1	172.6	0.0	4.5	4.5	177.1	16.1%
R- 20mm + EW 40mm XPS	0.02	0.04	32005.9	19395.6	95.1	142.6	2.4	4.5	7.0	149.6	29.2%
R- 40mm + EW 40mm XPS	0.04	0.04	30683.4	18594.1	91.2	136.7	4.9	4.5	9.4	146.1	30.8%
R- 60mm + EW 40mm XPS	0.06	0.04	29978.3	18166.8	89.1	133.6	7.3	4.5	11.8	145.4	31.1%
R- 80mm + EW 40mm XPS	0.08	0.04	29550.7	17907.7	87.8	131.7	9.8	4.5	14.3	146.0	30.9%
R- 100mm + EW 40mm XPS	0.1	0.04	29260.6	17731.9	86.9	130.4	12.2	4.5	16.7	147.1	30.3%
R- 120mm + EW 40mm XPS	0.12	0.04	29050.6	17604.6	86.3	129.5	14.6	4.5	19.2	148.6	29.6%
R- 140mm + EW 40mm XPS	0.14	0.04	28892.1	17508.6	85.8	128.8	17.1	4.5	21.6	150.4	28.8%

R BC + EW 60mm XPS	0	0.06	37703.3	22848.2	112.0	168.0	0.0	6.8	6.8	174.8	17.2%
R- 20mm + EW 60mm XPS	0.02	0.06	30877.6	18711.8	91.7	137.6	2.4	6.8	9.2	146.8	30.5%
R- 40mm + EW 60mm XPS	0.04	0.06	29524.5	17891.8	87.7	131.6	4.9	6.8	11.7	143.2	32.2%
R- 60mm + EW 60mm XPS	0.06	0.06	28816.6	17462.8	85.6	128.4	7.3	6.8	14.1	142.5	32.5%
R- 80mm + EW 60mm XPS	0.08	0.06	28380.0	17198.2	84.3	126.5	9.8	6.8	16.5	143.0	32.3%
R- 100mm + EW 60mm XPS	0.1	0.06	28080.1	17016.6	83.4	125.1	12.2	6.8	19.0	144.1	31.8%
R- 120mm + EW 60mm XPS	0.12	0.06	27866.1	16886.8	82.8	124.2	14.6	6.8	21.4	145.6	31.1%
R- 140mm + EW 60mm XPS	0.14	0.06	27703.8	16788.5	82.3	123.5	17.1	6.8	23.9	147.3	30.2%
R BC + EW 80mm XPS	0	0.08	37063.1	22460.2	110.1	165.2	0.0	9.0	9.0	174.2	17.5%
R- 20mm + EW 80mm XPS	0.02	0.08	30171.6	18284.0	89.6	134.5	2.4	9.0	11.5	145.9	30.9%
R- 40mm + EW 80mm XPS	0.04	0.08	28798.3	17451.8	85.6	128.3	4.9	9.0	13.9	142.3	32.6%
R- 60mm + EW 80mm XPS	0.06	0.08	28081.7	17017.5	83.4	125.2	7.3	9.0	16.4	141.5	33.0%
R- 80mm + EW 80mm XPS	0.08	0.08	27638.6	16749.0	82.1	123.2	9.8	9.0	18.8	142.0	32.8%
R- 100mm + EW 80mm XPS	0.1	0.08	27338.6	16567.2	81.2	121.8	12.2	9.0	21.2	143.1	32.3%
R- 120mm + EW 80mm XPS	0.12	0.08	27120.9	16435.3	80.6	120.9	14.6	9.0	23.7	144.6	31.6%
R- 140mm + EW 80mm XPS	0.14	0.08	26956.8	16335.8	80.1	120.1	17.1	9.0	26.1	146.3	30.7%
R BC + EW 100mm XPS	0	0.1	36604.4	22182.2	108.8	163.1	0.0	11.3	11.3	174.4	17.4%
R- 20mm + EW 100mm XPS	0.02	0.1	29667.5	17978.5	88.1	132.2	2.4	11.3	13.7	146.0	30.9%
R- 40mm + EW 100mm XPS	0.04	0.1	28282.1	17138.9	84.0	126.0	4.9	11.3	16.2	142.2	32.7%
R- 60mm + EW 100mm XPS	0.06	0.1	27560.0	16701.3	81.9	122.8	7.3	11.3	18.6	141.4	33.0%
R- 80mm + EW 100mm XPS	0.08	0.1	27112.6	16430.2	80.6	120.8	9.8	11.3	21.1	141.9	32.8%
R100mm + EW 100mm XPS	0.1	0.1	26809.6	16246.6	79.7	119.5	12.2	11.3	23.5	143.0	32.3%
R120mm + EW 100mm XPS	0.12	0.1	26590.1	16113.6	79.0	118.5	14.6	11.3	25.9	144.4	31.6%
R140mm + EW 100mm XPS	0.14	0.1	26424.4	16013.2	78.5	117.8	17.1	11.3	28.4	146.1	30.8%
R BC + EW 120mm XPS	0	0.12	36249.1	21966.9	107.7	161.6	0.0	13.6	13.6	175.1	17.1%
R- 20mm + EW 120mm XPS	0.02	0.12	29278.8	17742.9	87.0	130.5	2.4	13.6	16.0	146.5	30.6%
R- 40mm + EW 120mm XPS	0.04	0.12	27885.9	16898.9	82.9	124.3	4.9	13.6	18.4	142.7	32.4%
R- 60mm + EW 120mm XPS	0.06	0.12	27159.2	16458.4	80.7	121.0	7.3	13.6	20.9	141.9	32.8%
R- 80mm + EW 120mm XPS	0.08	0.12	26710.0	16186.2	79.4	119.0	9.8	13.6	23.3	142.4	32.6%

R100mm + EW 120mm XPS	0.1	0.12	26403.2	16000.3	78.4	117.7	12.2	13.6	25.8	143.4	32.1%
R120mm + EW 120mm XPS	0.12	0.12	26182.6	15866.7	77.8	116.7	14.6	13.6	28.2	144.9	31.4%
R140mm + EW 120mm XPS	0.14	0.12	26016.0	15765.7	77.3	115.9	17.1	13.6	30.6	146.6	30.6%
R BC + EW 140mm XPS	0	0.14	35926.4	21771.4	106.7	160.1	0.0	15.8	15.8	175.9	16.7%
R- 20mm + EW 140mm XPS	0.02	0.14	28962.7	17551.4	86.1	129.1	2.4	15.8	18.3	147.3	30.2%
R- 40mm + EW 140mm XPS	0.04	0.14	27563.4	16703.4	81.9	122.8	4.9	15.8	20.7	143.5	32.0%
R- 60mm + EW 140mm XPS	0.06	0.14	26832.6	16260.5	79.7	119.6	7.3	15.8	23.1	142.7	32.4%
R- 80mm + EW 140mm XPS	0.08	0.14	26381.2	15987.0	78.4	117.6	9.8	15.8	25.6	143.2	32.2%
R- 100mm+EW 140mm XPS	0.1	0.14	26073.6	15800.6	77.5	116.2	12.2	15.8	28.0	144.2	31.7%
R- 120mm+EW 140mm XPS	0.12	0.14	25851.3	15665.9	76.8	115.2	14.6	15.8	30.5	145.7	31.0%
R-140mm +EW 140mm XPS	0.14	0.14	25681.3	15562.8	76.3	114.5	17.1	15.8	32.9	147.4	30.2%

Table C-2: Optimum insulation thickness identification for the entire building envelope using the PUR material for the roof and XPS for walls structures (**See Section 7.6.1.2 - Optimum Thickness of Insulation**)

Roof (PUR) & Wall (XPS) Construction	Roof Thick (m)	Wall Thick (m)	Total Energy Consumption (kWh)	CO_2 (Kg)	Annual Energy kWh/m²/Yr	Energy Cost ($/m²/ 30 Yr)	Roof PUR Insulation Cost ($/m²)	Wall XPS Insulation Cost ($/m²)	Total Insulation Cost ($/m²)	Total Cost ($/m²/30 Yr)	Cost Saving (%)
R BC + EW BC	0	0	47389.5	28718.0	140.8	211.2	0.0	0.0	0.0	211.2	0.0%
R-PUR 20mm + EW BC	0.02	0	41345.6	25063.2	122.8	184.3	2.6	0.0	2.6	186.8	11.5%
R-PUR 40mm + EW BC	0.04	0	40238.0	24391.8	119.6	179.3	5.2	0.0	5.2	184.5	12.6%
R-PUR 60mm + EW BC	0.06	0	39679.0	24053.2	117.9	176.8	7.7	0.0	7.7	184.6	12.6%
R-PUR 80mm + EW BC	0.08	0	39341.3	23848.3	116.9	175.3	10.3	0.0	10.3	185.7	12.1%
R-PUR 100mm + EW BC	0.1	0	39115.3	23710.8	116.2	174.3	12.9	0.0	12.9	187.2	11.4%
R-PUR 120mm + EW BC	0.12	0	38954.5	23613.7	115.7	173.6	15.5	0.0	15.5	189.1	10.5%
R-PUR 140mm + EW BC	0.14	0	38833.4	23540.4	115.4	173.1	18.1	0.0	18.1	191.1	9.5%
R BC + EW 20mm XPS	0	0.02	40706.8	24674.9	120.9	181.4	0.0	2.3	2.3	183.7	13.0%
R20mm PUR+EW20mm XPS	0.02	0.02	33973.4	20594.0	100.9	151.4	2.6	2.3	4.8	156.2	26.0%
R40mm PUR+EW20mm XPS	0.04	0.02	32722.5	19836.0	97.2	145.8	5.2	2.3	7.4	153.3	27.4%

R60mm PUR+EW 20mmXPS	0.06	0.02	32090.2	19452.7	95.3	143.0	7.7	2.3	10.0	153.0	27.5%
R80mm PUR+EW20mm XPS	0.08	0.02	31708.2	19221.4	94.2	141.3	10.3	2.3	12.6	153.9	27.1%
R100mmPUR+W20mm XPS	0.1	0.02	31452.6	19066.6	93.5	140.2	12.9	2.3	15.2	155.3	26.5%
R120mmPUR+ W20mmXPS	0.12	0.02	31270.3	18956.1	92.9	139.4	15.5	2.3	17.7	157.1	25.6%
R140mm PUR+W20mm XPS	0.14	0.02	31132.6	18872.6	92.5	138.7	18.1	2.3	20.3	159.1	24.7%
R BC + EW 40mm XPS	0	0.04	38687.9	23451.2	114.9	172.4	0.0	4.5	4.5	176.9	16.2%
R20mmPUR +EW40mm XPS	0.02	0.04	31688.3	19208.3	94.2	141.2	2.6	4.5	7.1	148.3	29.8%
R40mmPUR+EW40mm XPS	0.04	0.04	30375.7	18413.2	90.3	135.4	5.2	4.5	9.7	145.1	31.3%
R60mm PUR+EW40mm XPS	0.06	0.04	29716.7	18013.7	88.3	132.4	7.7	4.5	12.3	144.7	31.5%
R80mm PUR+EW40mm XPS	0.08	0.04	29318.8	17772.4	87.1	130.7	10.3	4.5	14.8	145.5	31.1%
R100mmPUR+W40mm XPS	0.1	0.04	29052.3	17610.8	86.3	129.5	12.9	4.5	17.4	146.9	30.4%
R120mmPUR +W40mm XPS	0.12	0.04	28861.0	17494.7	85.8	128.6	15.5	4.5	20.0	148.6	29.6%
R140mm PUR+W40mm XPS	0.14	0.04	28717.5	17407.7	85.3	128.0	18.1	4.5	22.6	150.6	28.7%
R BC + EW 60mm XPS	0	0.06	37661.2	22829.3	111.9	167.8	0.0	6.8	6.8	174.6	17.3%
R20mm PUR+ W60mm XPS	0.02	0.06	30551.9	18519.3	90.8	136.2	2.6	6.8	9.4	145.5	31.1%
R40mm PUR+W 60mm XPS	0.04	0.06	29217.8	17710.8	86.8	130.2	5.2	6.8	11.9	142.2	32.7%
R60mm PUR + W60mm XPS	0.06	0.06	28545.4	17303.2	84.8	127.2	7.7	6.8	14.5	141.7	32.9%
R80mm PUR + W60mm XPS	0.08	0.06	28137.7	17056.5	83.6	125.4	10.3	6.8	17.1	142.5	32.5%
R100mm PUR+W60mm XPS	0.1	0.06	27863.1	16890.1	82.8	124.2	12.9	6.8	19.7	143.9	31.9%
R120mm PUR+W60mm XPS	0.12	0.06	27667.9	16771.7	82.2	123.3	15.5	6.8	22.3	145.6	31.1%
R140mm PUR+W60mm XPS	0.14	0.06	27520.7	16682.3	81.8	122.7	18.1	6.8	24.8	147.5	30.2%
R BC + EW 80mm XPS	0	0.08	37013.2	22436.3	110.0	165.0	0.0	9.0	9.0	174.0	17.6%
R20mm PUR+ W80mm XPS	0.02	0.08	29835.8	18085.6	88.6	133.0	2.6	9.0	11.6	144.6	31.5%
R40mm PUR+W 80mm XPS	0.04	0.08	28484.1	17266.2	84.6	126.9	5.2	9.0	14.2	141.1	33.2%
R60mm PUR + W80mm XPS	0.06	0.08	27802.5	16853.4	82.6	123.9	7.7	9.0	16.8	140.7	33.4%
R80mm PUR + W80mm XPS	0.08	0.08	27389.9	16603.4	81.4	122.1	10.3	9.0	19.4	141.4	33.0%
R100mm PUR+W80mm XPS	0.1	0.08	27113.9	16436.1	80.6	120.8	12.9	9.0	21.9	142.8	32.4%
R120mm PUR+W80mm XPS	0.12	0.08	26916.2	16316.1	80.0	120.0	15.5	9.0	24.5	144.5	31.6%
R140mm PUR+W80mm XPS	0.14	0.08	26766.4	16225.3	79.5	119.3	18.1	9.0	27.1	146.4	30.7%

R BC + EW 100mm XPS	0	0.1	36554.4	22158.2	108.6	162.9	0.0	11.3	11.3	174.2	17.5%
R- 20mm + EW 100mm XPS	0.02	0.1	29324.7	17775.6	87.1	130.7	2.6	11.3	13.9	144.6	31.5%
R- 40mm + EW 100mm XPS	0.04	0.1	27961.2	16949.7	83.1	124.6	5.2	11.3	16.5	141.1	33.2%
R- 60mm + EW 100mm XPS	0.06	0.1	27273.7	16532.8	81.0	121.6	7.7	11.3	19.0	140.6	33.4%
R- 80mm + EW 100mm XPS	0.08	0.1	26858.1	16281.0	79.8	119.7	10.3	11.3	21.6	141.3	33.1%
R- 100mm + W 100mm XPS	0.1	0.1	26579.0	16111.6	79.0	118.5	12.9	11.3	24.2	142.7	32.5%
R- 120mm + W 100mm XPS	0.12	0.1	26379.4	15990.7	78.4	117.6	15.5	11.3	26.8	144.3	31.7%
R- 140mm + W 100mm XPS	0.14	0.1	26226.3	15898.0	77.9	116.9	18.1	11.3	29.4	146.2	30.8%
R BC + EW 120mm XPS	0	0.12	36195.3	21940.7	107.5	161.3	0.0	13.6	13.6	174.9	17.2%
R- 20mm + EW 120mm XPS	0.02	0.12	28931.1	17536.9	86.0	128.9	2.6	13.6	16.1	145.1	31.3%
R- 40mm + EW 120mm XPS	0.04	0.12	27560.0	16706.4	81.9	122.8	5.2	13.6	18.7	141.5	33.0%
R- 60mm + EW 120mm XPS	0.06	0.12	26867.9	16287.2	79.8	119.7	7.7	13.6	21.3	141.0	33.2%
R- 80mm + EW 120mm XPS	0.08	0.12	26447.9	16032.2	78.6	117.9	10.3	13.6	23.9	141.8	32.9%
R- 100mm + W 120mm XPS	0.1	0.12	26167.2	15861.9	77.7	116.6	12.9	13.6	26.5	143.1	32.3%
R- 120mm + W 120mm XPS	0.12	0.12	25964.3	15738.5	77.1	115.7	15.5	13.6	29.0	144.8	31.5%
R- 140mm + W 120mm XPS	0.14	0.12	25812.9	15646.9	76.7	115.0	18.1	13.6	31.6	146.7	30.6%
R BC + EW 140mm XPS	0	0.14	35868.7	21741.9	106.6	159.9	0.0	15.8	15.8	175.7	16.8%
R- 20mm + EW 140mm XPS	0.02	0.14	28608.6	17340.8	85.0	127.5	2.6	15.8	18.4	145.9	30.9%
R- 40mm + EW 140mm XPS	0.04	0.14	27231.7	16507.2	80.9	121.4	5.2	15.8	21.0	142.3	32.6%
R- 60mm + EW 140mm XPS	0.06	0.14	26536.8	16085.5	78.8	118.3	7.7	15.8	23.6	141.8	32.8%
R- 80mm + EW 140mm XPS	0.08	0.14	26115.1	15830.2	77.6	116.4	10.3	15.8	26.1	142.5	32.5%
R- 100mm + W 140mm XPS	0.1	0.14	25832.7	15658.8	76.8	115.1	12.9	15.8	28.7	143.8	31.9%
R- 120mm + W 140mm XPS	0.12	0.14	25628.1	15535.1	76.1	114.2	15.5	15.8	31.3	145.5	31.1%
R- 140mm + W 140mm XPS	0.14	0.14	25476.0	15442.7	75.7	113.5	18.1	15.8	33.9	147.4	30.2%